BOREHOLE GEOPHYSICS APPLIED TO THE EVALUATION OF GROUNDWATER MONITORING WELL CONSTRUCTION AND INTEGRITY

By

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SYMBOLS AND ABBREVIATIONS

CAL	one-arm caliper log
CAL-3	three-arm caliper log
calc	calculated
CCL	casing collar locator log
CH	cased hole
CHO	cased hole, open annulus (no annular materials installed)
cps	counts per second, cycles per second, pulses per second
d	delta (change)
dlta	delta (change)
DSPR	differential single-point resistance
EL-16N	normal resistivity log, 16-inch electrode
EL-64N	normal resistivity log, 64-inch electrode
est	estimated
g/cc	grams per cubic centimeter
GL-120D	guard log (focused electric log), 120-inch deep array
GL-55M	guard log (focused electric log), 55-inch medium array
GL-15S	guard log (focused electric log), 15-inch shallow array
GR	gamma-ray log

SYMBOLS AND ABBREVIATIONS (Continued)

HRD	high-resolution density log
IL-COND	induction log, conductivity
IL-RES	induction log, resistivity
in	inches
log	base 10 logarithm
LSD	long-spaced collimated density log
LSD-4pi	long-spaced omnidirectional density log
mmhos	millimhos
NL	thermal neutron log
NL-N	dual-spaced thermal neutron log, near detector
NL-F	dual-spaced thermal neutron log, far detector
OH	open hole
ohm-m	ohm meters
ohms	ohms
SP	spontaneous potential
SPR	single-point resistance
SSD	short-spacing collimated density log
SSD-4pi	short-spacing omnidirectional density log
-raw	raw, unfiltered data
-Xpt taper	tapered smoothing filter, X points centered on depth
-Xpt box	box smoothing filter, X points centered on depth

SYMBOLS AND ABBREVIATIONS (Continued)

-4pi	omnidirectional (360°)
-4π	omnidirectional (360°)
'1	run no. 1
'2	repeat run

Terms not listed here may be found in Appendix A.

CHAPTER 1

INTRODUCTION

Borehole geophysics can be used to identify important features of groundwater monitoring well construction, including many defects which can impair the effectiveness of a monitoring well. Similarly, water supply wells and injection wells can be evaluated to identify significant defects. The cased-hole logging methods and analytical approaches which evolved during this research are clearly demonstrated. In addition, many methods which other workers have developed and which are applicable to the study are demonstrated.

Case histories are documented to illustrate the use of borehole geophysics for monitoring well integrity assessments under diverse field conditions. Guidelines are provided for selecting the most appropriate geophysical logging methods and analytical techniques to solve specific problems for several common types of monitoring wells. A decision matrix is presented to facilitate the application of the guidelines.

Problem Statement

Proven and economical methods of evaluating well construction and integrity are needed to determine the potential for contaminant migration resulting from defective monitoring wells, water-supply wells, and certain injection wells. Methods are needed to verify that data from groundwater monitoring wells represent the subsurface interval of interest.

Poorly constructed or defective groundwater monitoring wells, water supply wells, and injection wells have the potential to cause adverse effects to public health and welfare, and the environment. As many as 20 million water wells and groundwater monitoring wells may penetrate fresh water aquifers in the United States. Small numbers of injection wells which are used for groundwater control, solution mining, or waste disposal also penetrate fresh water aquifers. If not properly constructed and maintained, most of these wells could provide a conduit through which contaminants, if present, could migrate to a fresh water aquifer.

The petroleum industry has developed effective cased-hole logging methods for evaluating the integrity of oil and gas production wells and salt water injection wells (e.g. Schlumberger, 1989 and Thornhill and Benefield, 1987). However, cost, tool size and configuration, and the operating environment generally preclude the use of oilfield logging equipment for water wells, groundwater monitoring wells, and some injection wells.

The environmental industry does not utilize borehole geophysics as effectively as do the petroleum and minerals industries. Until recently, most geologists were trained in borehole geophysics as undergraduates, graduate students, and/or as novice corporate employees. Most recent geology graduates apparently have no training in borehole geophysics, and many are not aware of the technology. The transfer of existing borehole geophysical technology from the petroleum and minerals industries to the environmental industry should be accelerated.

Many of the well logging methods which are known to be applicable to the thesis topic have not been formally presented in a journal or text, or have not been adequately documented. Such documentation of these methods is needed.

Monitoring Well Integrity

Because of poor well design or construction, or because of damaged or deteriorated well construction materials, many groundwater monitoring wells provide water samples and aquifer test data which do not represent the zones of interest. For example, a U. S. Environmental Protection Agency (EPA) study of 22 RCRA sites determined that 50% of the groundwater monitoring wells were screened incorrectly (Crowder and Irons, 1989). McCray (1986) estimates that 121,000 monitoring wells were completed in 1985. Most of these wells have not been tested to verify well construction or integrity. The total number of monitoring wells which may be improperly constructed or defective appears to be large.

Monitoring wells are generally installed because contaminated groundwater is known to be present, or because there is a potential for groundwater contamination. Defective monitoring wells have provided conduits for the vertical migration of contaminants from a contaminated zone to a previously uncontaminated aquifer (Keely and Boateng, 1987; Meiri, 1989). Cross-aquifer contamination is a concern where groundwater monitoring wells penetrate several aquifers. Specific examples are rarely published because of the sensitive and often confidential or litigious nature of the information.

Water Supply Well Integrity

Like groundwater monitoring wells, many public water supply wells are defective. A National Water Well Association (1990) study indicates that over 13 million households had private water wells in 1980. McCray (1986) reports a total of approximately 810,000 well completions for 1985, including 489,000 private household wells and 121,000 monitoring wells.

Many water supply wells have the potential to become contaminated by diverse sources of contamination. Leaking septic tanks, pipelines, underground storage tanks, agricultural spraying of pesticides and herbicides, and other potential sources of groundwater contamination may impact water supply wells. Geophysical well logging has been used for some municipal water wells to verify well construction and integrity. However, many such wells have only the driller's verification that an appropriate quantity of cement was used to grout the annulus. Geophysical well logging to document or verify well construction and integrity has been used for few domestic water wells.

Sarafolean (1993) describes examples of improperly constructed, maintained, and/or sealed water supply wells which have posed a threat to public health. During a recent environmental investigation, borehole geophysics was used to confirm that a defective domestic water well had provided a conduit through which contaminated shallow groundwater had reached a deeper confined aquifer. A nearby municipal well field produced drinking water from the deeper aquifer. The details of the latter example are confidential because of pending litigation.

Injection Well Integrity

Class III injection wells are used to inject fluids for the extraction of minerals, (e.g. at in-situ uranium mine sites). Over 21,000 such wells existed in 1989. The mechanical integrity test (MIT) which employs packers is unsatisfactory for injection wells constructed of PVC because the packer can rupture the casing or become stuck down hole (Everest Minerals, 1989).

EPA-approved MIT procedures for Class III injection wells include alternative methods which incorporate the single-point resistance log. However, the single-point resistance log does not investigate the annular space between the casing and borehole, and the logging method does not consistently detect casing couplings and holes in PVC casing.

Regulatory Compliance

The Code of Federal Regulations (40 CFR 264.97(c), July 1, 1992 edition) states: "All monitoring wells must be cased in a manner that maintains the integrity of the monitoring-well borehole. This casing must be screened or perforated and packed with gravel or sand, where necessary, to enable collection of ground-water samples. The annular space (i.e., the space between the borehole and well casing) above the sampling depth must be sealed to prevent contamination of samples and the ground water." In some instances, the EPA and/or state regulatory agencies have required that the owner of a monitoring well demonstrate that the existing monitoring well is properly sealed, or abandon and replace the well (Kwader and Leitzinger, undated).

The Underground Injection Control Act regulations as defined in the Code of Federal Regulations, 40 CFR 146.8, establish the requirement to demonstrate mechanical integrity for injection wells. According to CFR 146.8(a): "An injection well has mechanical integrity if: (1)

There is no significant leak in the casing, tubing or packer; and (2) There is no significant fluid movement into an underground source of drinking water through vertical channels adjacent to the injection well bore."

Some state and local regulatory agencies require mechanical integrity tests (MITs) for municipal water supply wells, but few (if any) require MITs for domestic water supply wells. In Oklahoma, cement bond logs have been used to evaluate well integrity for some municipal water supply wells, but most have no testing to demonstrate well integrity (L. C. Simpson, personal communication).

Oilfield Logging Equipment

The logging equipment used for evaluating the integrity of oil and gas wells and salt water injection wells (described by Schlumberger, 1989 and Thornhill and Benefield, 1987) are not appropriate for most monitoring well applications. Some of the logging methods are likewise inappropriate for most monitoring well applications. High cost, large tool diameter, tool configuration, and typical monitoring well operating environments are factors which often preclude the use of oilfield logging equipment.

In Oklahoma, the cost of logging a shallow well such as a water well or monitoring well, using leading-edge oilfield technology, can be \$3,500 to \$5,000. The deep discounts of the 1980's are being trimmed as oilfield logging activity begins to pick up, and costs can be expected to increase (Schlumberger, personal communication). The logging cost includes the setup charge, per tool depth charges, and operating charges, assuming a single logging run in a single well. Several oilfield tools which have potential environmental applications, the gamma-ray spectrometry tool and the thermal decay time tool, are among the more expensive cased-hole tools to run.

Typical oilfield logging tools have a diameter of three to more than four inches, and may have measure points which are too distant from the bottom of the tool to permit the logging of much of a monitoring well. Slimhole tools for cased-hole logging are typically less than two inches in diameter. Many oilfield slimline tools are tens of feet in length, with a measuring point located several feet above the bottom of the tool.

Most oilfield, cased-hole logging methods are designed for use in pressure-grouted steel casing. For example, acoustic methods require water-filled metallic casing which has been pressure grouted. In addition, the environments in which oilfield logging equipment operates commonly contain high concentrations of naturally occurring and synthetic hydrocarbons. Oilfield logging tools, cables, and wenches are not readily decontaminated prior to use. Most oilfield tools are not well suited for the logging of groundwater monitoring wells.

Mineral / Groundwater Logging Equipment

The logging equipment used in mineral and groundwater exploration and development (described by Hallenburg, 1993 and Keys, 1989) is much better suited to monitoring well applications than is oilfield logging equipment. Such equipment is referred to herein as mineral logging equipment. (Note that groundwater has been considered an exploitable mineral resource, historically.) Low cost, small tool size, comparatively clean equipment, and availability of operators experienced in environmental or groundwater logging are factors which favor the use of mineral logging equipment over oilfield logging equipment.

The cost of logging a water well or monitoring well using leading edge mineral industry technology, can range from $800 to $1,500 in Oklahoma (Century Geophysical Corporation, personal communication). This cost includes the mobilization and setup charge, per tool depth charges, and multiple logging runs in a single well. The cost per well drops significantly as the number of wells logged increases. In addition, the average cost per foot of logging drops as the depth of a well increases.

Many mineral logging tools are slimhole tools, with tool diameters less than two inches. However, many of the newer and technologically superior mineral logging tools exceed two inches in diameter, and are restricted to use in three-inch or larger diameter monitoring wells.

As with oilfield logging equipment, few mineral logging tools are designed specifically for the applications described herein. As a result, several tools must be run in a well to acquire the several log traces required for a complete well assessment. Several potentially useful logging methods are not generally available from mineral logging service companies (e.g. spectral gamma-ray logging). At least one method which would be useful if available, the side-collimated density log, may not be technologically feasible in a slimhole configuration.

The environments in which mineral logging equipment operates sometimes contain high concentrations of contaminants. Mineral logging tools, cables, and wenches are more readily decontaminated than are their oilfield counterparts. However, because of a lack of market demand, mineral logging companies have been slow to implement available decontamination technology (e.g. polyethylene-coated cable, or the Art's Manufacturing Company boom-mounted cable cleaning unit).

Objectives

This study is designed to identify and develop geophysical well logging methods which can be used to evaluate monitoring well construction and integrity. Objectives are:

- to verify the feasibility of using geophysical well logging to assess groundwater monitoring well construction and integrity;
- to identify the types of geophysical well logging tools which are effective in groundwater monitoring well environments, and which are cost effective and readily available to industry;
- to identify and develop analytical methods which are effective for geophysical well logs acquired in groundwater monitoring wells, and which are cost effective;
- to identify and develop well logging strategies and analytical methods to address specific problems of groundwater monitoring well construction and integrity; and
- to develop case histories which demonstrate the logging strategies and analytical methods developed during this research.

Important details of well construction and common problems with well integrity to be investigated include:

- inside diameter of casing and screen;
- casing joints;
- screened or slotted intervals;
- holes or cracks in the casing;
- casing centralizers;
- eccentered casing;
- filter (sand) pack and grout materials in the annular space between the casing and borehole; and
- voids and channels in the annular space.

Methods

This research consists of a background investigation, an experimental and design phase, and finally the verification of experimental results using case histories. The geophysical well logging methods used and their respective units of measurement, and the abbreviations used for logging methods and units are provided in this section. Definitions of selected geophysical well logging terms are taken from Ransom (1984) with permission of the publisher, the Society of Professional Well Log Analysts (Appendix A).

Standards and Terms

Geophysical well logging methods and the units of measurement produced by these logging methods are abbreviated in tables, in the headings of graphic well logs, and where appropriate, in the text. Symbols, abbreviations, and other notations used herein are included in the Table of Contents. Additional terms and definitions are provided in Appendix A.

Two similar phrases used throughout this document are easily misinterpreted. The phrases are *density trace* and *density log trace.* As used herein, density trace refers to a frequency distribution curve which is equivalent to a smoothed histogram. The phrase density log trace is used to describe the graph of the measurement produced by the geophysical well logging method, density logging. A density trace is a frequency distribution curve. A density log trace is a curve which constitutes part or all of a geophysical well log.

Background Investigation

The background investigation included a review of logging theory for selected logging methods, and an evaluation of published and unpublished examples of cased-hole logging. The purpose of the background investigation was to ensure a high probability of success for the project, and to adapt oilfield cased-hole methods where possible.

Literature Review. Several bibliographies facilitated the literature review. A subject-indexed bibliography by Prensky (1992) was acquired in computer format, and proved the most useful for this study. Several objectives were accomplished by the literature review:

- the potentially most applicable traditional analytical approaches were identified;
- published examples of the logging and analytical methods which have been used successfully in monitoring wells were documented;
- logging methods and tools which have the greatest applicability based on theory or a demonstrated and similar use were reviewed; and,
- approaches to logging and log analysis which might be applied to the current problems were reviewed.

Technical Feasibility. Well logs made available by the thesis advisor (Kent, Hall, and Biyikoglu, 1990) were evaluated to verify that geophysical well logging can be used to identify well construction features in groundwater monitoring wells. (See Case History No. 2.) This preliminary study of technical feasibility was conducted prior to soliciting industry support for the drilling, installation, and logging of the experimental control wells described as Case History

No. 1. As described herein, Case History No. 2 provided clear evidence that geophysical well logging, and more specifically slim-hole well logging, is applicable to groundwater monitoring well studies. Subsequent to the completion of the experimental control wells, Yearsley, Crowder, and Irons (1991) provided additional evidence that the research under way would be successful. (See Case History No. 3.)

Data Acquisition and Conversion

Geophysical well logs for this study were acquired in analog and digital format. Analog logs were digitized using a digitizing tablet and an ACL™ utility, DIGITIZE. All well log data were recorded in or converted to digital format in 0.1 foot depth increments. Digital data were transformed to VIEWLOG™ format using the VIEWLOG utility program, VLIO. ACL and VIEWLOG are general purpose well log interpretation and graphics programs.

The several logs acquired in analog format were manually digitized. Each curve was digitized by "clicking" a digitizing puck at, and on either side of, each inflection point and at additional points. These irregularly-spaced data were then interpolated and resampled at regular intervals. An iterative procedure of overlaying irregularly-spaced and resampled data was used to determine the optimal regular spacing for the data to be retained. After resampling each curve from a suite of well logs, the data files were converted to ACL or VIEWLOG format. The largest resampling interval for any of the files was used for the conversion for all files, so that all logs combined in a single file had the same sampling intervals.

Century Geophysical Corporation logging equipment produces a computer file in Century's RMX data format for each logging tool run in a well or borehole. All geophysical well log data were transformed from the RMX data format to PCL format and then imported into the program ACL or VIEWLOG.

Mr. Robert Crowder of Colog provided digital log data for Case History No. 3 in ASCII format. These data were transformed to VIEWLOG format using the VIEWLOG utility VLIO.

Where several logging tools were run, each producing several log traces, log traces selected from each logging run were merged to form a single computer file before final interpretations were made.

Graphical Presentation of Well Logs

The experimental control wells (Case History No. 1) were used to confirm or establish the region of investigation for each of the 13 logging tools used. This experimental work and modifications to available graphics software resulted in the graphic log presentation format described here.

Graphical log data were manipulated and displayed using the computer programs ACL or VIEWLOG and their associated utility programs. ACL was used during the preliminary phases of the investigation. As a result of the preliminary feasibility study, it became apparent that the program could be improved by permitting three graphics columns to be displayed to permit a log presentation which is based on the region of investigation concept described herein. A VIEWLOG upgrade incorporated these and other suggestions. After the VIEWLOG upgrade was acquired, that program was used for the remainder of the study.

A well log graphics format was developed to facilitate interpretation of the logs from the experimental control wells. The well log graphics format was based on the concept that each logging method used has a method- and tool-specific region of investigation, extending outward from the tool's measuring point within the casing. Log traces are presented according to the relative depths of their regions of investigation.

Four regions of investigation have been defined for geophysical well logging methods (Smolen, 1987). These regions are:

- Region I - the region within the casing which includes all fluids found within the casing;
- Region II - the casing and/or well screen;
- Region III - the annular space between the casing or well screen and the formation; and

○ Region IV - the formation, including all unconsolidated soils and sediments and consolidated rock units.

The concept of the region within a specified cased-hole environment which a particular logging method investigates, guided the selection of logs for detecting or characterizing each feature of interest, the graphical data presentation, and the final analysis and conclusions. Logging methods and specific objectives for well logging were categorized according to their respective regions of investigation.

The American Petroleum Institute (API) graphical well log formats and formats used by various mineral exploitation companies and logging contractors were determined to be inappropriate for this project. A graphical well log presentation format was developed to present the log traces and the graphic columns showing interpretations organized according to the region of investigation for the log traces and graphic columns (Figure 1).

The log traces and graphic columns representing Region IV, the formation, are shown at the left side of the well log. This places the gamma-ray log in the log track at the extreme left side of the well log, following oilfield and mining industry conventions. Logs with progressively smaller volumes of investigation are presented correspondingly farther to the right. Logs and the graphic column representing Region III, the annulus, occur in the approximate center of the well logs. The depth column is to the right of the Region III graphic column. The Region II, or casing and screen, graphic column is to the right of the depth column. Finally, logs which evaluate Region II are shown at the right side of the well log.

Only Regions III, II, and I are displayed because the program VIEWLOG can display only three graphic columns, and because these were the principal regions of interest for this study. Any logs representing Region I would have been displayed to the right of all other logs. The water level within the casing is indicated in the graphic column for Region II.

Well Name: MW-X
File Name: LITHEXPL
Location: CASE HISTORY NO. X
Elevation: 0 Reference: TOC
Information on well construction

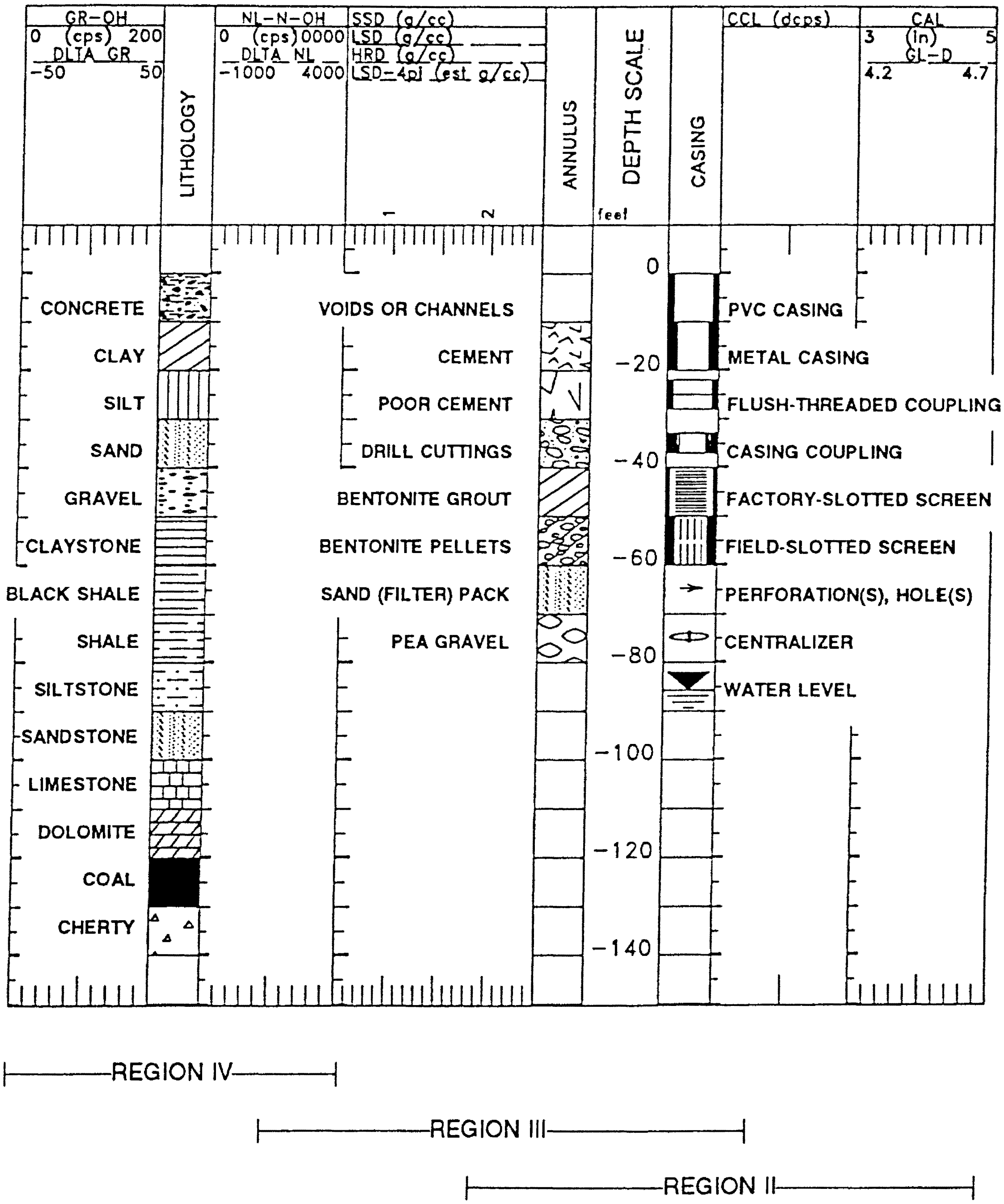


Figure 1. Typical Well Log Format Showing Graphics Symbols and Regions of Investigation

Quality Assurance

Quality assurance measures were implemented for the geophysical well logging of the experimental control wells (Case History No. 1) and at Case History No. 6. Two quality assurance measures were utilized, tool calibration and repeat logging runs.

All logging tools used (13 tools for Case History No. 1 and 3 tools for Case History No. 6) were calibrated prior to initiating well logging. Recalibration for the purpose of determining tool drift was discussed, but costs, logistics, and scheduling precluded such recalibration. Calibration was performed by Century Geophysical Corporation at their Tulsa, Oklahoma headquarters, and using water tanks, assayed calibration blocks, and mechanical devices which Century uses for all commercial logging work.

For the experimental control wells in Case History No. 1, a repeat run was made for each logging run from total depth to the top of casing. For Case History No. 6, a repeat run was made for only the compensated density run, also from total depth to the top of casing. Repeat runs were used to verify any log responses which appeared anomalous.

Numerical Data Analysis

Numerical analyses of data were performed using the program VIEWLOG and the statistical program SOLO™. Most numerical analyses, including summary statistics and log calibration, were performed within VIEWLOG. SOLO was used for statistical normality tests and produced graphs of data distributions to facilitate well log analysis.

Transformations. Prior to their final analysis, most well logs underwent a preliminary screening, followed by one or more numerical transformations as deemed necessary. The types of transformations used included smoothing, depth corrections, horizontal and vertical scale changes, and algebraic transformations. Algebraic transformations were performed on single log traces, and using several log traces as multiple variables in an equation.

The nuclear logging methods produce raw data which contain significant noise. A smoothing filter was used to filter these logs and reduce the noise to data ratio. An odd number of data points centered on each depth increment were averaged. Generally seven data points were averaged using a tapered filter which gives greater weights to the nearer neighbors (Figure 2). Experiments similar to Figure 3 resulted in the selection of seven data points for most smoothing operations.

Depth corrections are desirable where log traces have been merged from several files produced by more than one logging run in a well, if the tools were not precisely zeroed at the surface, or if the depths for any logging runs erred for any reason. Figure 4 illustrates a depth correction. Such depth corrections are essential prior to any cross-plotting or numerical transformations which involve more than one log trace.

Log responses to small features are generally more noticeable at large scales. The depth scale was often expanded to from one to five feet per inch to locate small-scale features such as cracks and holes in casing (see Figure 5). The horizontal well log scale was varied to produce the optimal response, although noise increased in the same proportion as the useful data. Figure 6 compares two horizontal scales for the same casing collar locator log.

Algebraic transformations used included the logarithmic transformation of data, especially where a empirical relationship containing such a transformation is commonly used; for example, in the calibration of density data in counts per second to units of grams per cubic centimeter. Figure 7 shows a side-collimated, long-spacing density log (LSD) in track 1, an omnidirectional density log (LSD-4pi) in track 2, and the two-step transformation of the omnidirectional density log from units of counts per second (cps), first to the base 10 logarithm of counts per second (log cps), and finally to an estimated grams per cubic centimeter (est g/cc), using coefficients derived during a calibration procedure. For selected logs, VIEWLOG calculated differences between log responses for the same logging method used at different stages of completion. Figure 8 illustrates a depth corrected, open-hole gamma-ray log

Well Name: OSU/CGC CW-3
File Name: TF_SMTH
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

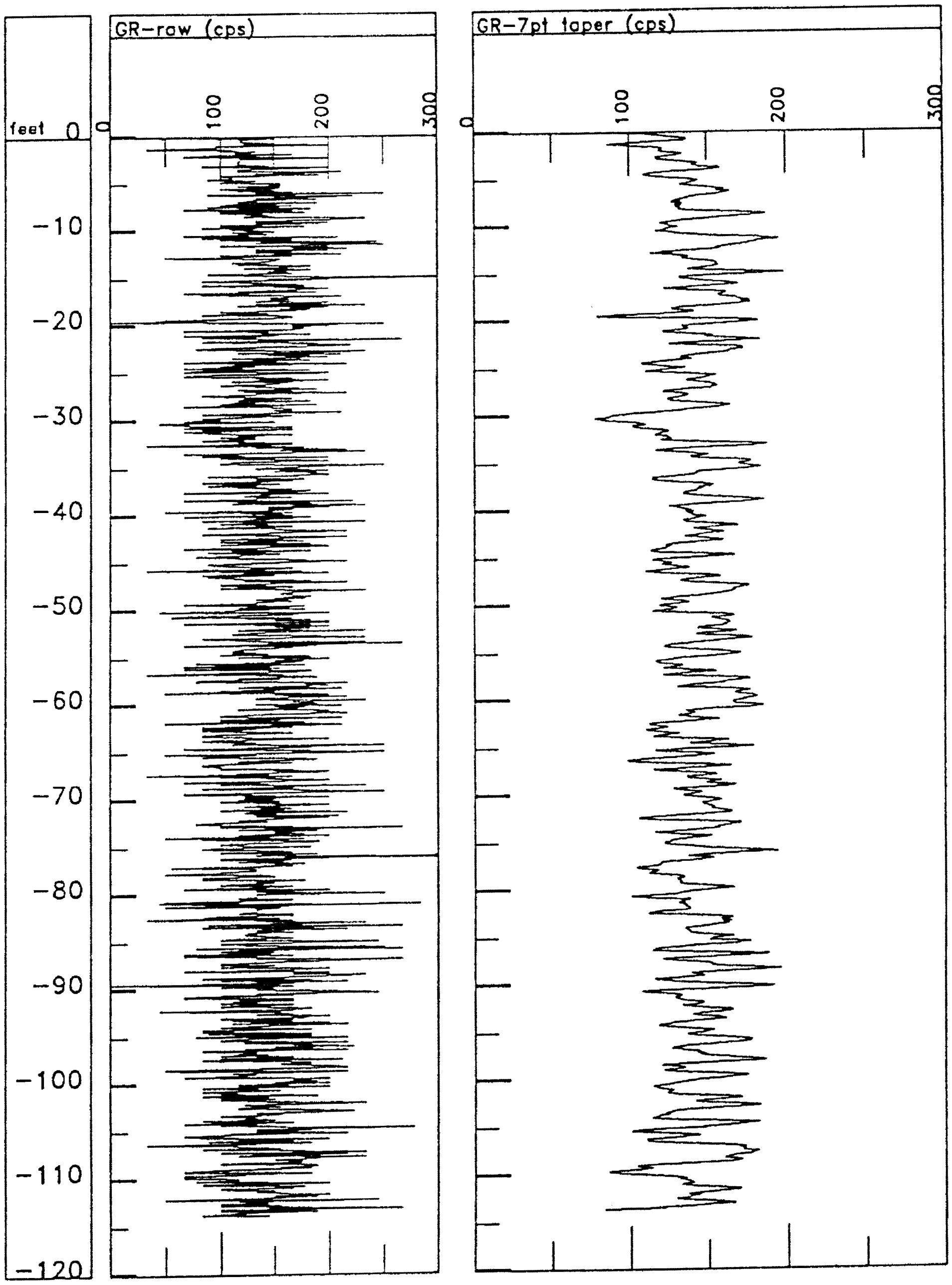


Figure 2. Seven-Point Tapered Smoothing Filter, Applied to Gamma-Ray Log

Well Name: OSU/CGC CW-2
File Name: TF_SMTH
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC
PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

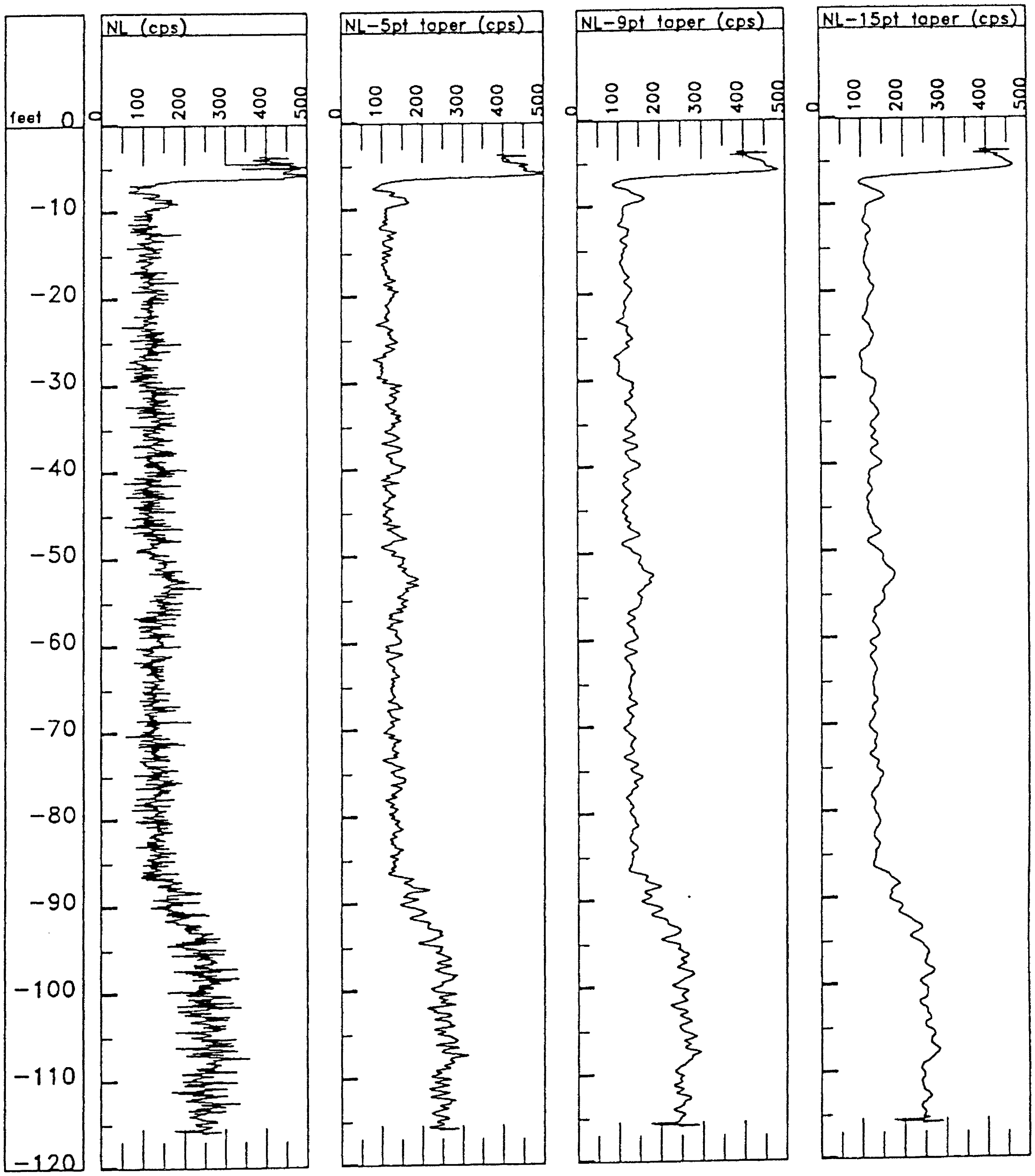


Figure 3. The Effect of Increasing the Number of Points used by a Smoothing Filter

Well Name: OSU/CGC CW-3
File Name: TF_DEPTH
Location: CASE_HISTORY NO. 1
Elevation: 0 Reference: MUD PIT / TOC
OPEN HOLE AND CASED HOLE LOGS

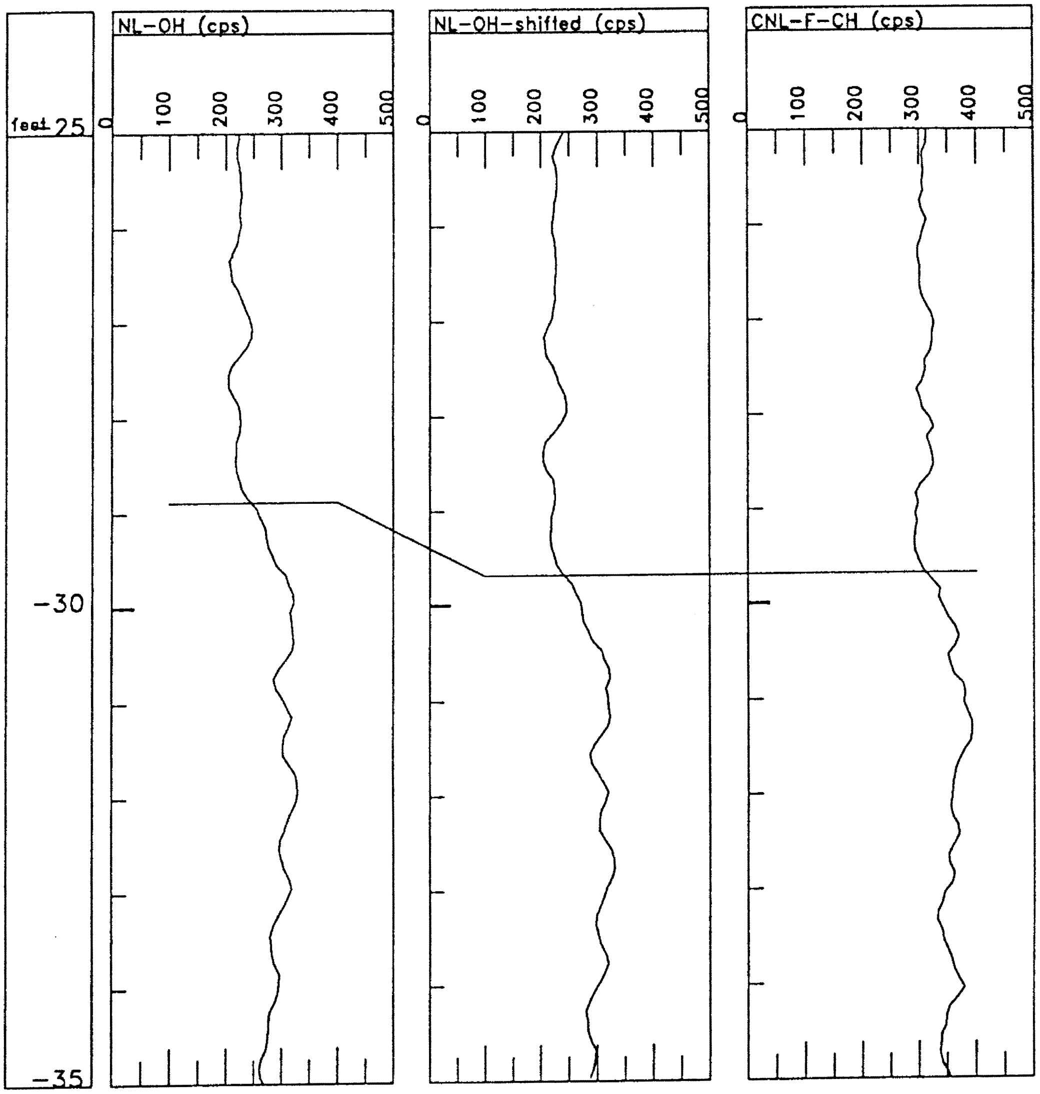


Figure 4. An Example of a Depth Correction for the Open-Hole Neutron Log

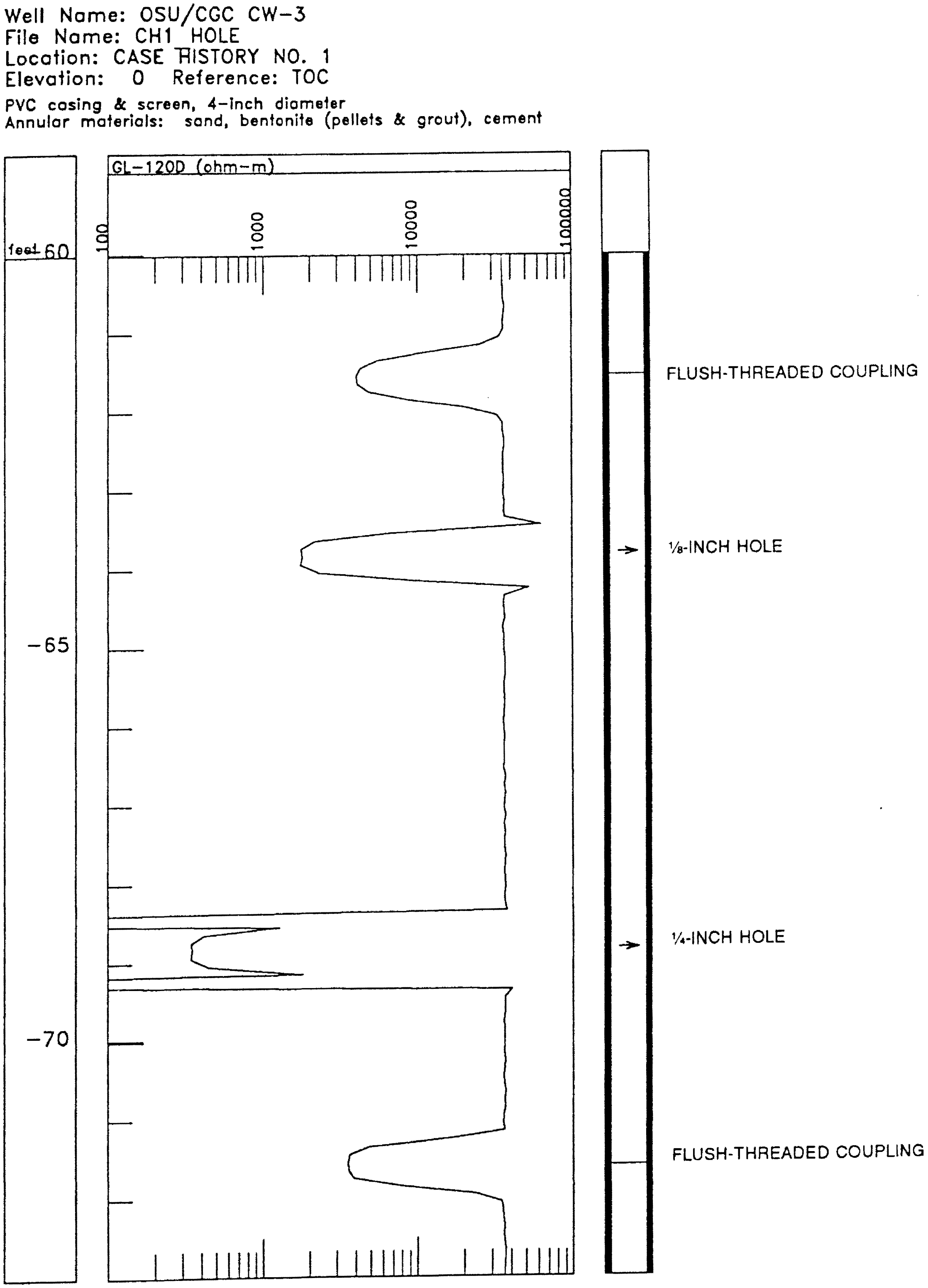


Figure 5. An Example of Expanding the Depth Scale to Accentuate Small Features

Well Name: OSU/CGC CW-3
File Name: TF_SCALE
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

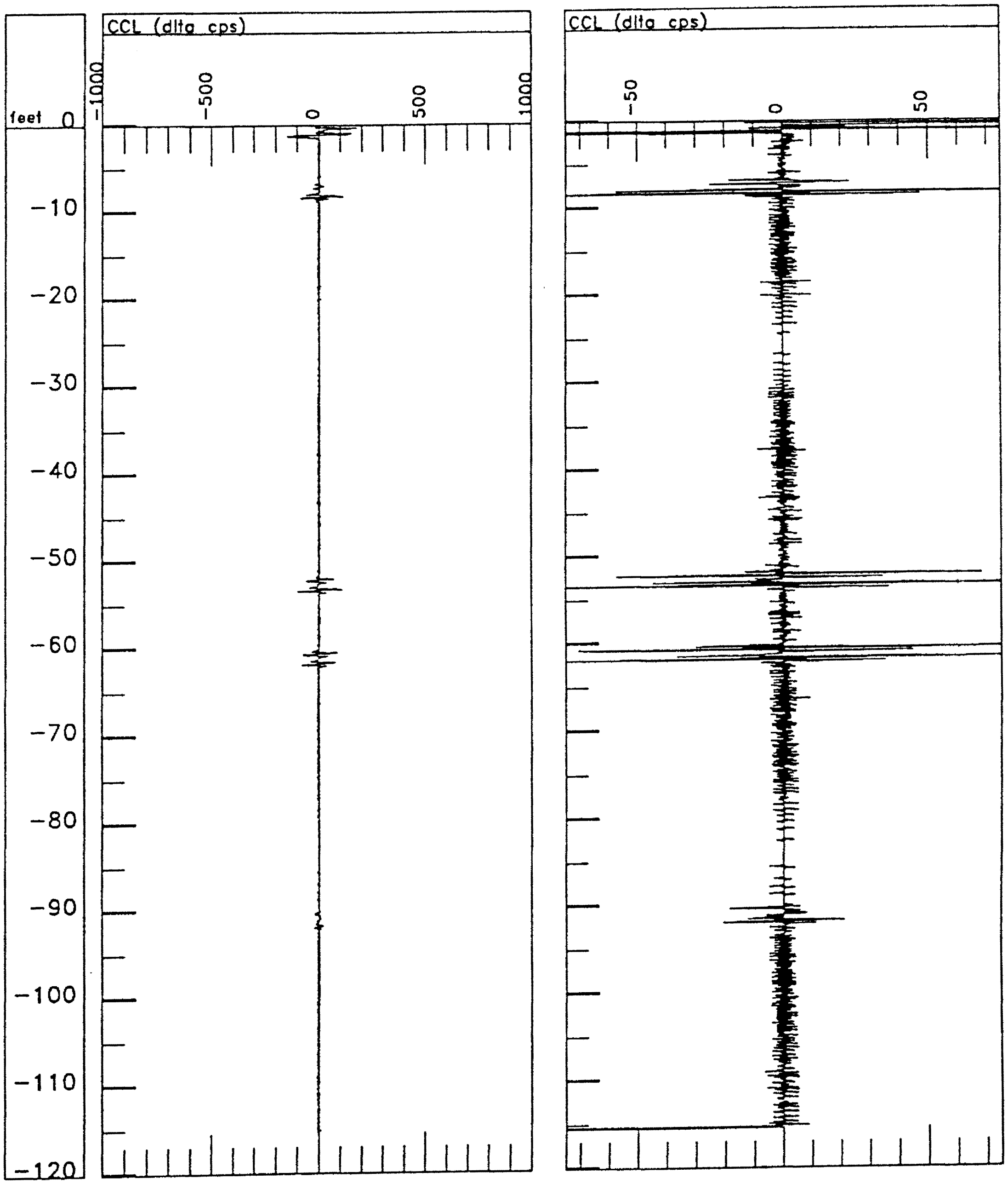


Figure 6. An Example of Expanding the Horizontal Scale to Increase Amplitude

Well Name: OSU/CGC CW-3
File Name: TF DL
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

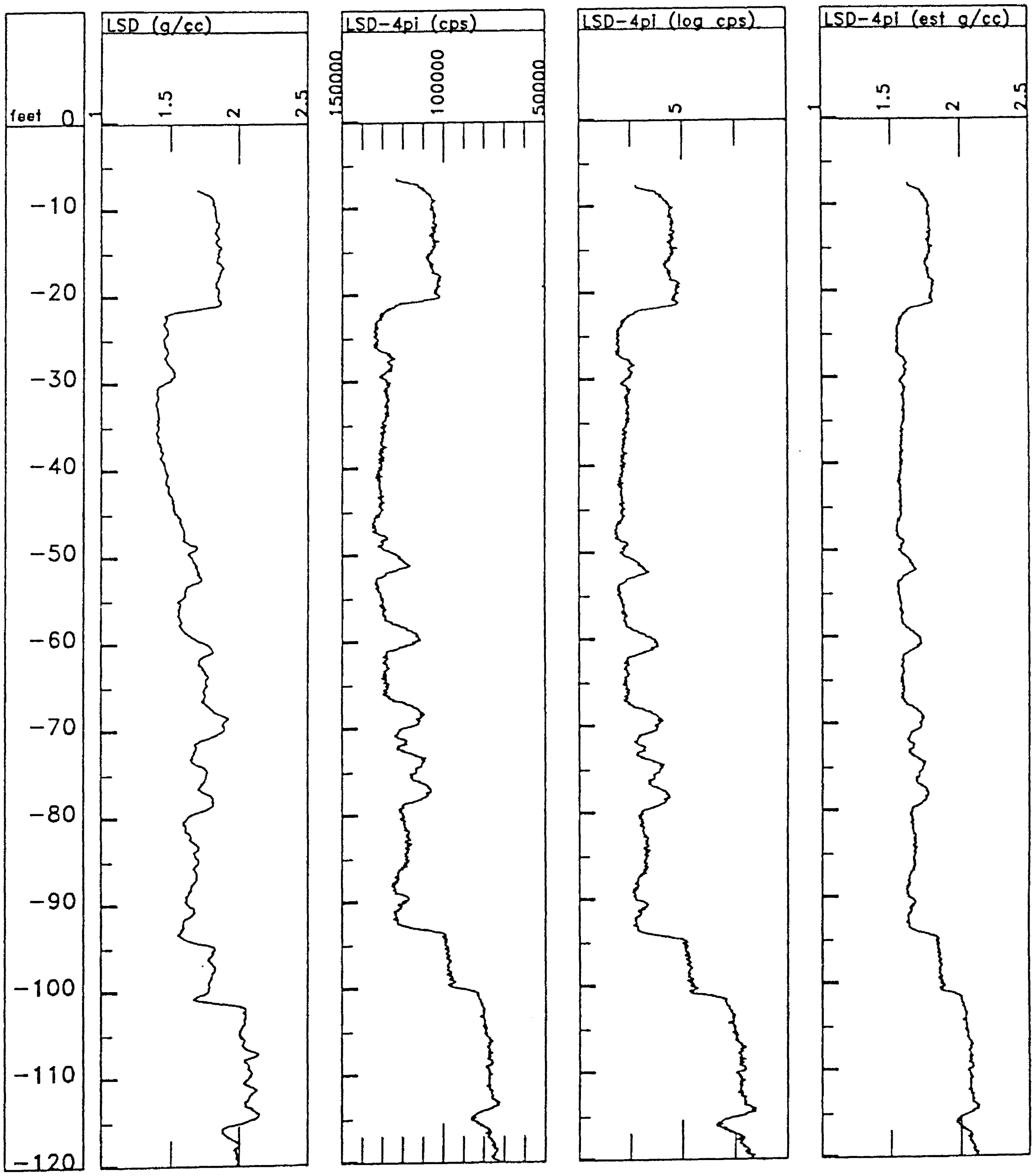


Figure 7. The Transformation of the LSD-4pi Response from CPS to G/CC for Comparison to the LSD Log

Well Name: OSU/CGC CW-3
File Name: TF_GR
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

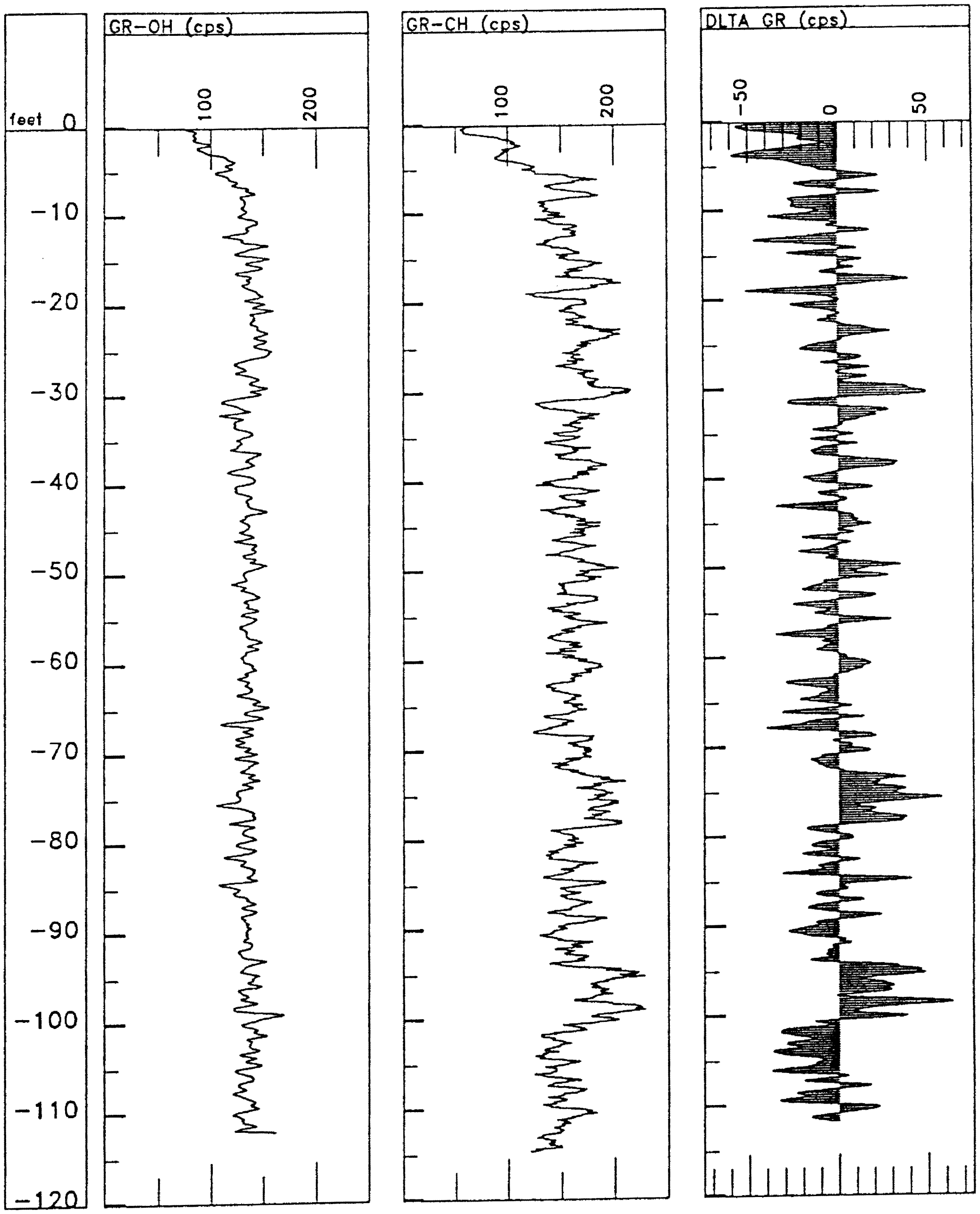


Figure 8. The Difference (DLTA GR) between Open-Hole (GR-OH) and Cased-Hole (GR-CH) Gamma-Ray Logs

(GR-OH) in track 1, a cased-hole gamma-ray log (GR-CH) in track 2, and the value of the cased-hole gamma-ray counts minus the open-hole gamma-ray counts (DLTA GR) in track 3.

Omnidirectional Density Log Calibration. Density logging and related terms are defined in Appendix A. Three methods of density log calibration are performed, two using linear regression, and a third using two calibration points in the form of a straight line equation.

Density logging tools are manufactured in nonfocused or omnidirectional (4-pi) and in focused or side-collimated configurations. The omnidirectional density logging method measures in units of counts per second. The side-collimated density tools are calibrated to the more easily interpreted units of grams per cubic centimeter.

Cross-plots of the omnidirectional density log data in counts per second versus the side-collimated density data in grams per second indicate a log-linear relationship. This finding is consistent with the density response curves described by Hearst and Nelson (1985, Figure 6-15) and by Hallenburg (1993, Figure 16-10). The log-linear relationship between density and density tool response in counts per second is the basis for logarithmic graphic display of omnidirectional density log data, and for several calibration techniques which were used to convert omnidirectional density log data from counts per second to grams per cubic centimeter. (See Case History Nos. 1, 2, 3, and 5.)

The first calibration method was applied to a dual-spacing omnidirectional density tool to fit the short-spacing log trace to the long-spacing log trace, both measured in counts per second. These logs produce measurements which differ by several orders of magnitude and are difficult to compare without such a conversion. The logarithm of the short-spacing log was set as the independent variable and fit by linear regression to the logarithm of the long-spacing log.

The second calibration method fits an omnidirectional density log trace measured in counts per second to a side-collimated density log trace measured in grams per cubic centimeter, to facilitate comparison of the two logs. The omnidirectional density response in counts per second was transformed to its base 10 logarithm. The side-collimated density response, expressed in grams per cubic centimeter, was used as the dependent variable in the linear regression. VIEWLOG produced a slope and a y-intercept which were used to convert the omnidirectional density response to grams per cubic centimeter. If the resulting calibrated response did not match the independent variable extremely well, as determined empirically by goodness-of-fit coefficients and by visual comparison of the log traces, zones which appeared similar were selected to use in a second iteration of the procedure. A second pass always produced an excellent fit, except for zones where the annular materials were heterogeneous as described in Chapter 3 and Chapter 4.

Finally, a density log trace measured in counts per second was calibrated to grams per cubic centimeter using the known densities of water and an aluminum block as calibration points. The Z/A (defined in Appendix A) for water and for the aluminum block were used to correct the calibration constants to apparent densities.

The calibration methods used the cross-plotting module of VIEWLOG to produce a linear regression equation, to determine the goodness of fit of the estimate, and to calibrate one curve to another. Most density log data failed several measures of normality, even after data transformations were used to better approximate normality. Individual modes from the multimodal density distributions also failed normality tests. Measures of normality examined included skewness, kurtosis, the Martinez and Iglewicz normality test, and the Kolmogorov-Smirnov normality test. Thus, a fundamental assumption for linear regression is violated.

The use of linear regression for curve fitting is empirical as applied here, and is not used as a statistical method. The calibration method is simple and effective. In addition, the goodness-of-fit calculation will be shown to be useful as an empirical check of the validity of the calibration.

The calibration method using water and an aluminum block as standards has practical flaws:

- The borehole in the aluminum calibration block is larger in diameter (5.125 inches) than the casing (2 inches), so that a proportionately greater volume of water is being measured within an undetermined total volume of investigation; and
- Because the borehole in the aluminum calibration block was water-filled, the calibration would be applicable to the water-filled part of the casing. The calibration was applied to the entire well, below and above the water level.

The side-collimated density log calibration, performed by the logging contractor, also contains false assumptions for cased-hole logging. No tool-specific corrections are available for the several casing and screen materials, for percentage of open area in the screens, or for casing and screen thickness. As with the calibrated omnidirectional density logs, the side-collimated density log does not provide corrected densities.

The advantage of these calibration methods for density logging is that the relative densities of annular materials are easily compared when units of grams per cubic centimeter are used. It is recognized that the quantification in terms of grams per cubic centimeter represents an apparent density. In the writer's opinion, the advantage of comparing several apparent density measurements justifies the nonrigorous application of statistical methods for curve fitting and calibration.

Probability Density Estimation. The histogram is often used for the analysis of the frequency distribution of data. The choice of origin and the number and width of histogram intervals has a significant impact on the appearance of a histogram. Rosenblatt (1971) introduced a probability density function which he termed the kernel estimator. This method was used to produce a density distribution graph referred to as a density trace by BMDP Statistical Software, Inc., the publisher of the program SOLO.

The density trace is analogous to a smoothed histogram which is independent of the histogram origin and the number and width of bins. The term density in this context refers to the relative frequency or concentration of data points along the data range. The phrase density trace is unrelated to the geophysical density log trace.

The kernel density estimate has been used for geophysical well log analysis (Mwenifumbo, 1993). In this study, the density trace was used where the geophysical log of apparent density proved difficult to interpret. The density trace was used to display the multimodal distributions in a manner which is less biased and more easily interpreted than the histogram.

Silverman (1978) compared window widths for estimating density, and selected the optimal window width empirically by visually comparing the graphic results. The analogous smoothing function in SOLO, the percent of the range of data that is used in computing the density (density percent), was empirically set at 15 percent for this study. The density computation was performed at 50 points along the total data range.

The annular materials believed to have been used during well construction were ranked according to their relative densities. Then an effort was made to assign peaks in the density trace to the corresponding annular materials.

Because the pore or void space contains more water below the water level, the bulk density of any material which has porosity is greater below the water level. Therefore, it is useful to separate the density data above the water level from the density data below the water level. No such analyses are known to have been performed where an artesian water level within the casing was above the water saturated portion of the annular space. Such an occurrence may complicate this analytical method.

Experimental Design

Three experimental control wells were constructed and logged to develop well logging strategies for identifying specific features and defects in monitoring well construction, for wells constructed with PVC casing and screen. A well logging strategy includes both logging tool selection and interpretive methodology.

Two wells, a two-inch diameter well and a four-inch diameter well, were constructed of PVC casing and screen and with similar designs and with no intentional defects. A third well, four inches in diameter, was also constructed using PVC casing and screen, but with features designed to simulate common defects. Details of well construction are described in Chapter III.

These three wells provide experimental control for the project. The wells provided an opportunity to evaluate thirteen mineral logging tools and to experiment with analytical approaches. In addition, the experimental control wells establish the first case history which is documented herein.

Verification of Results Using Case Histories

Additional case histories were developed to serve as analogs for cased-hole log interpretation. Many of the case histories provided incomplete logging suites due to well design, logging tool availability, or other reasons. Techniques were developed to make the most complete analysis possible with the available data.

Documentation includes open-hole logs, cased-hole logs, logging tool specifications, data processing methods, interpretive methods, and detailed well construction records, where such information is available.

Previous Studies

Bibliographies on Geophysical Well Logging

Prensky (1992) published the most recent update to a comprehensive set of bibliographies on geophysical borehole logging. The Prensky bibliographies were acquired in computer format and were the principal source of published references. Other significant bibliographies (Keys, 1988; Smolen, 1987; Taylor and Dey, 1985) were reviewed.

Logging for Well Construction and Integrity

The petroleum industry has used cased-hole logging methods to evaluate well integrity for over 30 years. In 1933, Schlumberger introduced the continuous thermometer log, which could be used to pick the top of curing cement. Commonly, cased-hole applications for logging methods lag several years behind the open-hole applications. Gamma-ray logging was introduced commercially in 1939. Four years later, Layne-Wells introduced the use of gamma-ray logs for locating cement tops (Hughes, 1943). Similarly, the cement bond log was introduced by Schlumberger in 1960 (Grosmangin et al, 1961), following the introduction of acoustic methods for open-hole logging about 10 years earlier.

Nuclear methods developed for open-hole logging have been adapted for evaluating annular materials. Ahmed (1977) describes the use of the neutron log for locating the top of cement behind casing. Gravel-pack logging using density (gamma-gamma) logging, neutron logging, or both methods in combination, is described by Neal and Carroll (1985) and by Sollee (1985).

Several published papers (Yearsley, Crowder, and Irons, 1991, and Darr, Gilkeson, and Yearsley, 1990) and several unpublished reports discuss the use of borehole geophysics for identifying annular materials in monitoring wells. Darr, Gilkeson, and Yearsley recognized the effects of monitoring well completion on the gamma-ray and neutron logs. Yearsley, Crowder, and Irons (1991) demonstrated that the density log (gravel-pack log) is not only applicable to steel casing but also can be used in monitoring wells constructed of PVC casing.

Most environmental industry research replicates practices which have been used for many years in the mineral and/or petroleum industries. Several proved logging methods applicable to groundwater monitoring wells (e.g. neutron, temperature, caliper, flowmeter) are not mentioned or are only briefly described in the environmental literature. No research was found which uses well logging to identify the clay mineralogy of bentonites used as annular seals in monitoring wells.

Mechanical Integrity Testing of Injection Wells. Several research efforts have evaluated methods of demonstrating the mechanical integrity of injection wells. Two such efforts were conducted by the E.P.A. and by a uranium mining company, Everest Minerals Corporation, Glenrock, Wyoming.

The E.P.A. conducted noteworthy research involving mechanical integrity testing for Class II injection wells (Thornhill and Benefield, 1987). The E.P.A. research focused on wells used to dispose of salt water produced by oil wells. Because the E.P.A. test wells were constructed with steel casing, oilfield logging methods developed for such applications were employed. The research was significant because it documented logging tool responses to artificial features built into the test wells, including simulated channeling and fluid flow behind pipe. The experimental design of the E.P.A. test wells influenced the design of the experimental control wells at Century Geophysical Corporation headquarters (Case History No. 1).

Everest Minerals Corporation developed an alternative mechanical integrity test (MIT) for Class III injection wells which incorporates borehole geophysics (Morzenti, 1989). Everest Minerals Corporation conducts uranium solution mining and must re-inject groundwater recovered in this operation. Pressure tests using a full-bore packer proved unsatisfactory as an MIT in PVC casing because of casing rupture and sticking of the packer. An alternative test was developed which utilized the single-point resistance log to verify anomalies indicated by a cement pressure test. Hairline cracks, major ruptures, and probable holes were identified in PVC casing. The method is directly applicable to groundwater monitoring wells constructed of PVC casing and screen. (Although a February 9, 1989 letter from the U. S. Environmental Protection Agency, Region VIII states that the method is approved subject to certain limitations and conditions, the method is not mentioned in the July 1, 1992 edition of 40 CFR 146.8.)

Water Supply Well and Groundwater Monitoring Well Logging. Geophysical well logs have been used in water supply wells by the U. S. Geological Survey and others for decades (Keys and MacCary, 1971; Campbell and Lehr, 1973; and Keys, 1988). The similar application of geophysical well logs for groundwater monitoring wells has evolved over the past several years (Kwader, unpublished, 1987; Darr, Gilkeson, and Yearsley, 1990; Yearsley, Crowder, and Irons, 1991). The foregoing references have had a significant impact on this research.

Keys and MacCary (1971) compiled, and Keys (1988) revised and updated a comprehensive reference on borehole geophysics applications for groundwater investigations. The reports include some discussion of logging in steel and plastic casing, but because of the broad scope of these reports, statements and examples are general and log responses to specific conditions are not quantified. Keys (1980) mentions that borehole geophysics has been used to locate cement and gravel pack behind casing, but notes that interpretation may be ambiguous.

Keys and MacCary (1971, p. 72, Fig. 46) illustrate an example of the density (gamma-gamma) log response to grout behind casing. The casing in this example appears to be PVC because casing collars are not evident and attenuation of the density curve appears minimal in the ungrouted zone as compared to the open hole log (although the gamma-ray scales are not shown). Keys (1988, p. 181) notes that casing, cement, and gravel pack all introduce large errors in density logging. Features such as the tops of cemented zones, gravel pack, and multiple casing strings can be identified according to Keys.

Among the methods discussed by Keys (1988), the acoustic televiewer is described as a very costly alternative for well inspection. The method has been described extensively, it is costly, and it was not available for this study.

Keys (1988) notes that the use of borehole television is limited by its requirements for nonstandard logging cable and clear water. The method is in widespread use, but does not provide data on the annular space behind casing.

Findings of the current research have been presented at technical meetings (Kent, Hall, and Biyikoglu, 1990; Kent and Hall, 1993). These presentations demonstrated the use of a variety of geophysical logs, especially the density and the guard resistivity logs, for the verification of well construction and the identification of defects.

Miscellaneous Logging. Fertl (1984) summarized spectral gamma-ray applications documented in the literature, including in-situ clay typing, cation exchange capacity estimates, and channeling behind pipe. A slimhole tool was developed in response to the uranium boom in the late 1960's.

Ahmed (1977) described the characteristic cased hole responses of the neutron tool for materials filling the annular space. A "left-hand-shift" was observed as the tool was pulled up hole past cemented casing and into a zone of fluid filled annulus. A "right-hand-shift" was observed as the tool was pulled past the top of fluid in the hole into air-filled hole.

Findings

This study has demonstrated that geophysical well logging, especially using tools available from mineral logging service companies, provides an effective means of evaluating well construction and integrity. Techniques were developed to investigate three regions of investigation, the formation, the annular space between the formation and well casing, and the well casing or screen. A fourth region of investigation, the volume within the well casing, was not within the scope of this study. The well casing and screen materials, the well diameter, and the logging objectives influenced the selection of geophysical logs for evaluating each region of investigation.

Logging Methods for Formation Evaluation (Region IV)

The gamma ray log proved effective in determining formation lithology in both nonmetallic and metallic casings. The induction log was effective for determining formation lithology and relative fluid resistivity only in nonmetallic casings. Both methods were used to determine the relative locations of the formation and well construction features. The best formation evaluation is made possible by a combination of gamma-ray, density, neutron, and electrical logging in a fluid-filled uncased borehole.

Logging Methods for Annular Space Evaluation (Region III)

Several nuclear logging methods proved effective for evaluating the annular space. The several density logging tools were most effective. Neutron logs generally provided additional useful information. Annular materials, including sand, bentonite pellets, bentonite grout, and cement grout were distinguished. Void spaces and eccentered casing were detected, although log responses to eccentered casing were not unique. The high-resolution density log, the casing collar locator log, and the induction log detected metallic centralizers attached to the outside of PVC casing. The dual-spacing density logs detected features which are probably massive metallic centralizers attached to carbon steel casing.

Logging Methods for Well Casing and Screen Evaluation (Region II)

For nonmetallic casing and screen (e.g. PVC), where water is present within the casing, guard logs (focused resistivity logs) proved most effective in determining the locations of flush-threaded couplings, bell couplings, holes, and slots. The casing collar locator, the high-resolution density, and the induction electric logs were effective in locating metallic centralizers attached to nonmetallic casing and screen.

For metallic casing and screen, the casing collar locator and the high-resolution density logs were generally effective for locating threaded couplings, and apparently indicated the presence of scaling and corrosion where severe. Butt-welded casing joints were detected by the casing collar locator log but not by the high-resolution density log. The combined responses of the casing collar locator log and the high-resolution density log were used to determine whether a coupling was threaded or welded.

Torch-cut slots in metallic casing were difficult to distinguish from corrosion using the casing collar locator and high-resolution density logs. Slots in manufactured metallic well screen were readily identified using the high-resolution density log, and in one instance using the side-collimated, dual-spacing density logs.

Casing diameter was determined with both one-arm and three-arm calipers. The three-arm caliper has a greater possibility of locating a squeezed-in section of casing, because it cannot easily rotate so that none of the caliper arms contact the narrow dimension. The three-arm caliper requires an additional logging run, thereby increasing cost, and has a greater likelihood of becoming lodged in the well, especially in torch-slotted casing.

Analytical Methods

The completeness of the log suite, the quality of the logs, and the logging objectives determined the analytical strategy for each well. A fundamental problem of well log analysis was significant for this study. For open-hole logging, the number of rock types which can be distinguished is constrained by the degrees of freedom, or the number of log responses. The number of unique solutions for cased-hole logs is similarly constrained, but is additionally complicated because each of the logging devices has its own characteristic region of investigation.

Thus, the region of investigation for each method and tool must be considered to determine which methods can be used in combination to distinguish materials occurring in a specified region. Because of dissimilar regions of investigation, the open-hole cross-plotting methods such as the neutron-density cross plot cannot be used.

Density classification and the analysis of heterogeneity, radially and with depth, proved very useful in characterizing the annular space. The analysis of heterogeneity identifies zones which represent potential problems such as eccentered casing and channeling. These analytical techniques require interpretations, the reliability of which varies according to the quality of the logging data, the details of well construction, and the ability of the log analyst to model or envision geophysical logging tool responses to the features of interest.

CHAPTER 2

BACKGROUND

The well logging methods described herein are limited to the methods available for this research. Tool design features are characteristic of logging tools used in the mineral and groundwater industries, and differ in design from analogous oilfield tools in some instances.

The principals of geophysical well logging are described in detail in comprehensive texts, in service company manuals, and in numerous published papers. The sources of technical information on borehole geophysics which proved most useful for this research were: Doveton (1986), Hallenburg (1993), Hearst and Nelson (1985), and Keys (1989). Numerous service company technical manuals were quite useful as well.

Well logging methods available for this research can be classified as nuclear, electrical, magnetic, and mechanical methods. Each logging method used is briefly described with references to Appendix A or literature sources where a more detailed explanation is located. The casual user of well logs should be cautioned that some familiarity with basic logging theory and tool design factors is required for the successful use and interpretation of well logs.

The descriptive literature on geophysical well logging methods is voluminous. The literature has summarized each method effectively, and in much greater depth than is appropriate here. Background information for each method utilized is available from the following sources: Doveton (1986), Hallenburg (1984), Hallenburg (1993), Hearst and Nelson (1985), Hoffman, Jordan, and Wallis (1982), Keys (1989), and others as noted.

Geophysical Well-Logging Methods Used

The well logging methods which were tested and which proved effective during this research include nuclear or radiation logging methods, electrical logging methods, magnetic logging methods, and mechanical logging methods. The nuclear logging methods used included gamma-ray logging, thermal neutron logging, and density logging (omnidirectional and side-collimated). The electrical logging methods used included induction logging, guard (focused resistivity) logging, normal resistivity logging, and differential single point resistance logging. The magnetic logging method used was casing collar locator logging. The mechanical logging methods used were the one-arm and three-arm mechanical caliper logs.

These methods and related abbreviations and units of measurement are summarized in Table 1. Table 2 lists the 13 Century Geophysical Corporation logging tools which were used for the experimental control wells (Case History No. 1) and the logging method or methods which each tool incorporates.

Well logging methods which did not prove useful for this study include the fluid resistivity log, the temperature log, the spontaneous potential log, and the deviation survey log. These logs were evaluated for the control wells, and could prove useful elsewhere to solve specific problems. For example, the fluid resistivity and temperature logs have been demonstrated to be useful in detecting fluid movement and inflow/outflow at perforations and slots. None of these tools, however, are used in this study.

The characteristics of each logging method which proved useful in this research are summarized in a table. These tables are found in Appendix B. Each table describes:

- the class or category of the method (i.e., nuclear, electrical, magnetic, mechanical);
- the names and abbreviations used for the method by the mineral industry;
- the names and abbreviations used for the method by the petroleum industry;
- the properties which are measured by the method;

- the units of measurement in which the data are recorded;
- the principals of operation of the method;
- the common tool configurations for the method (mineral logging only);
- the methods most commonly combined on the same logging tool;
- the estimated volume of investigation for the method;
- the estimated vertical resolution of the method;
- factors which influence log response;
- conventional applications of the method;
- applications of the method which are described in this research; and
- related terms found in Appendix A.

The logging methods which are summarized in the tables in Appendix B are caliper, casing collar locator, density, differential single point resistance, gamma-ray, guard, induction, and neutron logging.

Density and Neutron Logging

Region of Investigation III, the annular space, is the most difficult region to characterize and perhaps the most important for well integrity assessment. The density and neutron logging methods are described in more detail than other methods, because these methods are key elements of the well integrity evaluations, and because additional information is required to use and interpret density and neutron logs. Correct interpretation of density and neutron logs requires not only an understanding of the methods (see Tables 34 and 39, Appendix B), but also information about the properties of materials and substances which affect the density and neutron log responses.

Density Logging. In an uncased or open borehole, the calibrated density logs produce apparent density values which correlate to bulk densities after correction with an index, Z/A. Matrix density, bulk density, apparent density, and Z/A for selected annular materials, elements,

TABLE 1

SELECTED LOGGING METHODS, TOOL CONFIGURATIONS, ABBREVIATIONS, AND UNITS OF MEASUREMENT

LOGGING METHOD	ABBREVIATED METHOD NAME	UNITS OF MEASUREMENT	
		ABBREVIATION	DESCRIPTION
CALIPER			
decentralized, one-arm, 8"/14" arm	CAL	in or cm	inches or centimeters
centralized, three-arm	CAL-3	in or cm	inches or centimeters
CASING COLLAR LOCATOR			
free swinging	CCL	(arbitrary)	delta ± millivolts
DENSITY (GAMMA-GAMMA)			
free swinging & omnidirectional (4π)			
single spaced, 15"	LSD-4pi	cps	counts per second
dual spaced, 9.8" & 18.9"	LSD-4pi & SSD-4pi	cps	counts per second
decentralized & side collimated			
single spaced, 1.75"	HRD	cps	counts per second
single spaced, 8"	LSD	g/cc	grams per cubic centimeter
dual spaced, 5.9" & 12.2"	SSD & LSD	g/cc	grams per cubic centimeter
DIFFERENTIAL SINGLE POINT RESISTANCE			
free swinging & omnidirectional	DSPR	ohms	ohms
GAMMA RAY (GROSS-COUNT NATURAL GAMMA)	GR	cps or API	counts per second or API$_\gamma$
free swinging			
decentralized			
GUARD LOG (FOCUSED RESISTIVITY LOG)			
decentralized, 15"	GL-15S	ohm-m	ohm-meters
decentralized, 55"	GL-55M	ohm-m	ohm-meters
decentralized, 120"	GL-120D	ohm-m	ohm-meters
INDUCTION LOG			
free swinging	IL-COND	mmhos (conductivity)	millimhos
	IL-RES	ohm-m (resistivity)	ohm-meters
NEUTRON (THERMAL NEUTRON)			
free swinging & omnidirectional (4π)			
single spaced, 14"	NL	cps or API$_N$	[counts per second]
single spaced, 16.75"	NL	cps or API$_N$	or
dual spaced, 10.8" & 24.5"	NL-N & NL-F	cps or API$_N$	[API$_N$ units]
NORMAL RESISTIVITY			
free swinging, 16"-64"	EL-16N & EL-64N	ohm-m	ohm-meters

TABLE 2

CENTURY GEOPHYSICAL CORPORATION LOGGING TOOLS

TOOL NUMBER	TOOL DIMENSIONS (INCHES)		POSITION AND ORIENTATION	LOGGING METHODS	
	DIAMETER	LENGTH		MEASUREMENT	SPACING OR LENGTH (INCHES)
9030	2.2"	121"	Decentralized & Side-Collimated	Gamma Ray	
				Density	8"
				Guard Log	55"
				One-Arm Caliper	8" or 14"
9030H	2.2"	121"	Decentralized & Side-Collimated	Gamma Ray	
				Gamma-Gamma Density	1.75"
				Guard Log	55"
				One-Arm Caliper	8" or 14"
9035	2.8"	118"	Decentralized & Side-Collimated	Gamma Ray	
				Density	5.9" & 12.2"
				Guard Log	15"
				One-Arm Caliper	14"
9041	2.5"	84"	Free-Swinging & Symmetrical	Gamma Ray	
				Spontaneous Potential	
				Normal Resistivity	16" & 64"
				Fluid Resistivity	40"
				Temperature	
9051	1.7"	96"	Free-Swinging & Symmetrical	Gamma Ray	
				Casing Collar Locator	
				Thermal Neutron	16.75"
9055	1.8"	114"	Free-Swinging & Symmetrical	Gamma Ray	
				Thermal Neutron	16.75"
				Spontaneous Potential	
				Single Point Resistance	
				Temperature	
				Deviation Survey	
9060	1.4"	88"	Free-Swinging & Symmetrical	Gamma Ray	
				Spontaneous Potential	
				Single Point Resistance	
9064	1.5"	86"	Centralized	Three-Arm Caliper	
9067	1.25"	98"	Free-Swinging & Symmetrical	Gamma Ray	
				Thermal Neutron	14"
9068	1.25"	98"	Free-Swinging & Symmetrical	Gamma Ray	
				Density	15"
9069	1.25"	94"	Free-Swinging & Symmetrical	Gamma Ray	
				Dual-Spaced Density	9.8" & 18.9"
9072	2.5"	122"	Free-Swinging & Symmetrical	Gamma Ray	
				Thermal Neutron	10.8" & 24.5"
				Guard Log	120"
9510	1.625"	89"	Free-Swinging & Symmetrical	Gamma Ray	
				Induction	

fluids, minerals, rocks and soils, and well casing materials are provided in Table 40, Appendix C. The terms *apparent value*, *bulk density*, *matrix*, and *Z/A* are defined in Appendix A.

Cased-hole density logging produces apparent densities which cannot be readily corrected to bulk densities without test models which simulate the well construction of interest or correction curves which are based on such test models. The test models or correction curves must have been based on the specific logging tool used. Because these types of models and correction curves are not generally available for mineral logging tools, interpretation relies on the relative densities of materials rather than the absolute determination of density.

The densities of materials listed in Table 40 enable the log analyst to estimate the relative densities of emplaced annular materials, caved annular materials, and fluids filling void space. In addition, the several casing materials influence the density response as a function of their respective densities and thicknesses. Nuclear log responses to casing also depends on the spacing between the radioactive source and the detector. For the omnidirectional density logs, the density of the fluid within the casing, the casing diameter, and the volume of investigation are additional factors.

Neutron Logging. In an uncased or open borehole, and in saturated materials, the neutron logs used in this study produce apparent porosity values or counts per second which correlate to the capacity of materials to absorb thermal neutrons. For elements, the microscopic thermal neutron capture cross sections are a measure of this capacity to absorb neutrons. Table 41 lists selected elements, their typical concentrations in water and in well casing materials, and their microscopic thermal neutron capture cross sections.

For mixtures, compounds, and other materials of interest in cased-hole logging, the measures of the neutron absorbing capacity are the hydrogen index and the macroscopic thermal neutron cross section. Table 42 lists selected materials, their hydrogen indices, and their macroscopic thermal neutron cross sections.

The borehole camera and the acoustic televiewer are methods which were not available for detailed evaluation, but which have proven effective for certain of the objectives of this thesis. The borehole camera has been used extensively in water-supply wells. Keys (1989) reports that "The acoustic televiewer is probably the highest resolution logging system for obtaining information on steel and plastic casing and screens, but it may be too expensive for some operators." Both of these methods are well documented in the literature. Because neither type of log or record was available for the wells used in this study, neither logging method was evaluated.

CHAPTER 3

EXPERIMENTAL CONTROL WELLS (CASE HISTORY NO. 1)

Purpose

Three experimental control wells, designated CGC/OSU CW-1 (or CW-1), CGC/OSU CW-2 (or CW-2), and CGC/OSU CW-3 (or CW-3), were constructed and logged under controlled conditions during the preliminary phase of the research. These data provide a baseline for comparison to geophysical well logs from other sites.

In addition to establishing experimental control, the control wells at Century headquarters provided an opportunity to evaluate and compare 13 logging tools. Most of these tools produce more than one measurement or response, so that a wide range of nuclear, electrical, magnetic, and mechanical logs were evaluated. During the development of Case History No. 1, the most effective geophysical logs were identified for assessing well construction and integrity for the most commonly encountered well construction materials. These results in combination with techniques adapted from oilfield logging were used to select the logging methods to use or evaluate in depth for wells constructed with steel screen and casing.

A third function of the control wells was to provide an opportunity to develop analytical techniques and graphical log display standards to be used for the case histories developed to demonstrate well logging applications.

Finally, experiments and tests were conducted to facilitate the development of analytical techniques. The control wells were designed to:

- Compare open-hole logs with cased-hole logs to determine the influence of the formation on the cased-hole responses;

- Compare log responses for screen intervals to log responses for casing (unslotted) intervals;
- Compare log responses to the several annular sealants and filter (sand) pack materials used;
- Compare log responses for a well constructed using best available methods and materials (CW-2) with log responses from a similar well which is constructed to include simulated or actual flaws which adversely affect well integrity (CW-3); and
- Compare the quality and detail of interpretations using:
    1) All available logging tools in a four-inch diameter well (CW-2); and
    2) Available slimhole logging tools in a two-inch diameter well (CW-1).

Location

Experimental control wells CW-1, CW-2, and CW-3 were installed at the headquarters of Century Geophysical Corporation in the SE/4 Sec. 26, T20N, R13E, Tulsa County, Oklahoma. Several factors influenced site selection:

- The subsurface rock units have permitted open-hole logging without the loss or sticking of tools down hole;
- The subsurface stratigraphy is relatively uniform; and
- Drilling services and extensive geophysical well logging services would not have been contributed by industry at any other site.

The control wells penetrate approximately ten feet of clay soil and the upper part of the Nowata Shale. The boreholes were drilled to total depths of 122 feet, placing the bottom of each well at an estimated 60 feet above the top of the Oologah Limestone. The Nowata Shale is of Pennsylvanian age and is of a nearly uniform dark gray shale lithology. The depth to water is an estimated ten feet below ground level. The geological uniformity made any influence of lithology on log responses constant, thereby minimizing the potential effect of one variable for these experiments.

Experimental Control Well Construction

Experimental control well construction consisted of five principal elements:

- ○ Drilling;
- ○ Running the casing string into the borehole;
- ○ Emplacement of annular materials; and
- ○ Installation of a protective manhole and concrete pad.

As-built well construction diagrams for control wells CW-1, CW-2, and CW-3 are shown in Figures 9, 10, and 11 respectively. Geophysical well logging was coordinated with the well installation activity and is described in the Data Acquisition section in this chapter.

Drilling

Drilling and well construction were performed by Winnek Environmental Drilling, Inc. of Tulsa, Oklahoma, a water well drilling contractor licensed by the State of Oklahoma. A Failing Model 1250 rotary drilling rig was used. The rig was equipped with a mud pump and auxiliary equipment including a portable mud pit, a steam cleaner, a 150-gallon mixing tank, a grout pump, and tremie pipes. Drilling began on January 13, 1990 and was completed on January 21, 1990. On January 26, 1993, Winnek completed the installation of cement aprons (pads) and protective manholes. Control wells CW-1, CW-2, and CW-3 were drilled to total depths of 122 feet with a medium formation rock bit. After drilling the 6¼-inch pilot holes, wells CW-2 and CW-3 were reamed with an 8½-inch medium formation rock bit. The circulating fluid was a very low viscosity drilling mud made up of tap water and bentonite. After drilling and reaming to total depth, the mud was thinned and circulated out for one hour prior to geophysical well logging.

During the drilling of control well CW-3, a problem was encountered which affected the subsequent geophysical well logging. The driller was working at an accelerated pace because of the imminent deadline for completion of the project. To expedite drilling, no short trips were

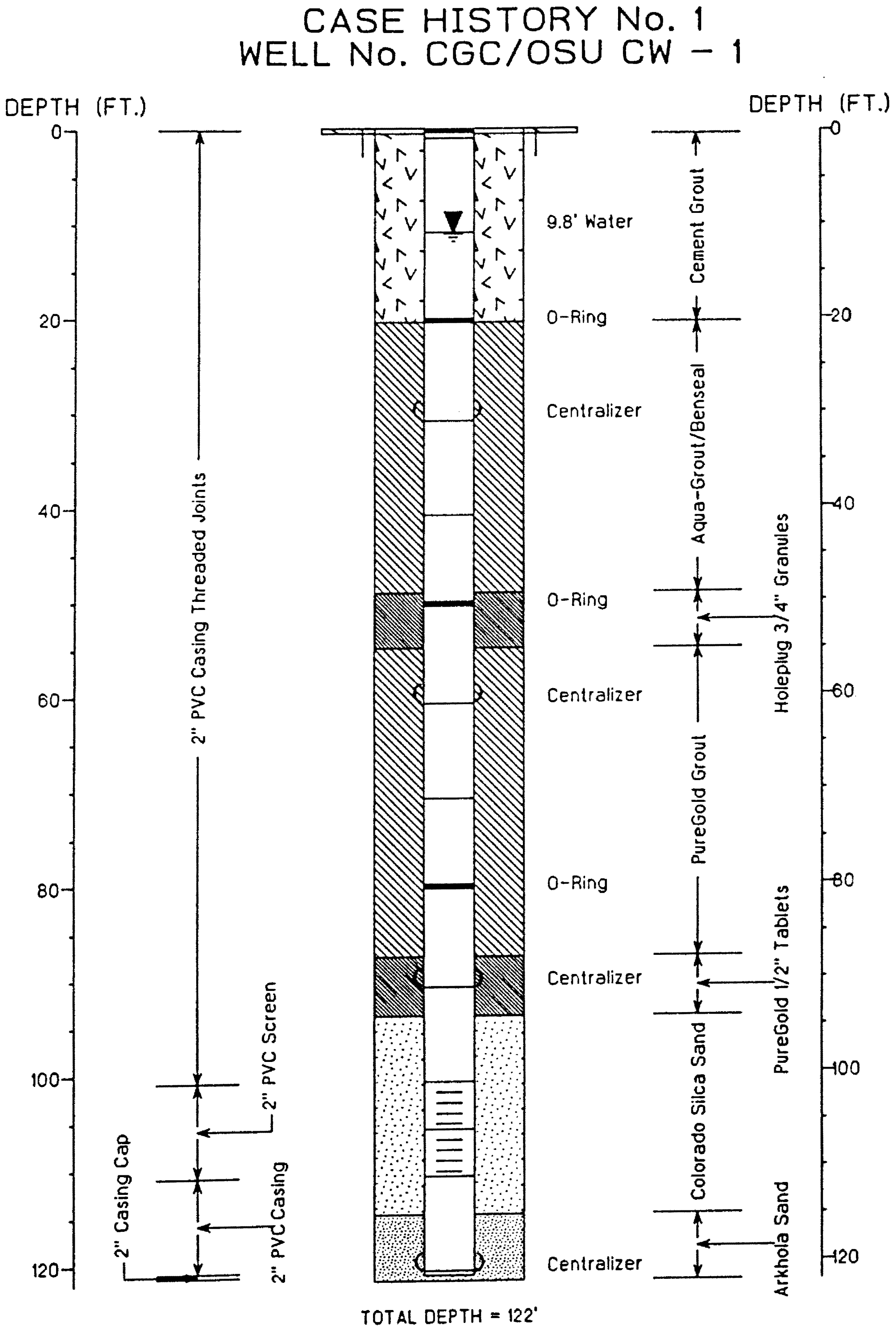


Figure 9. As-Built Diagram, Experimental Control Well CW-1

CASE HISTORY No. 1
WELL No. CGC/OSU CW – 2

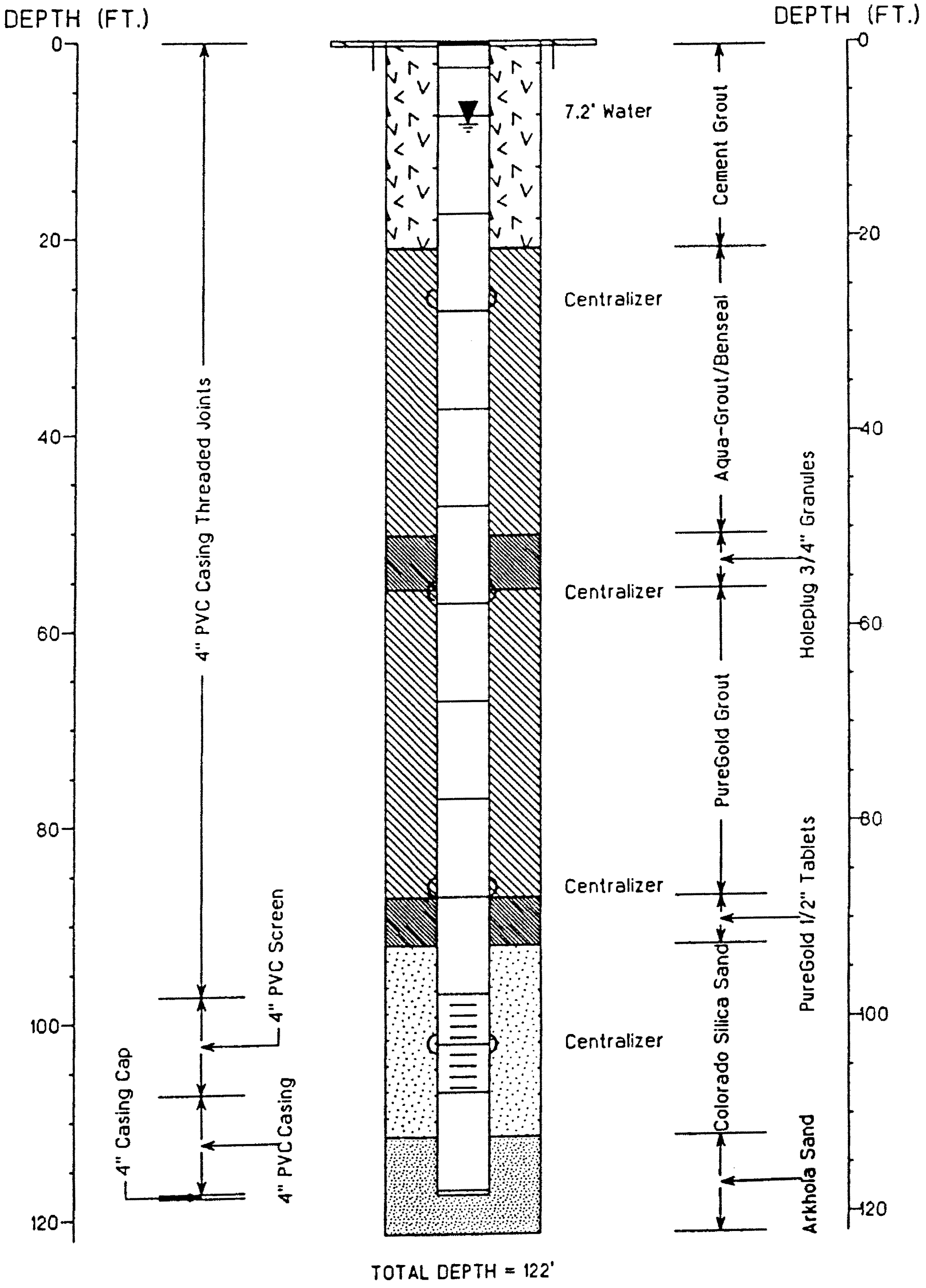
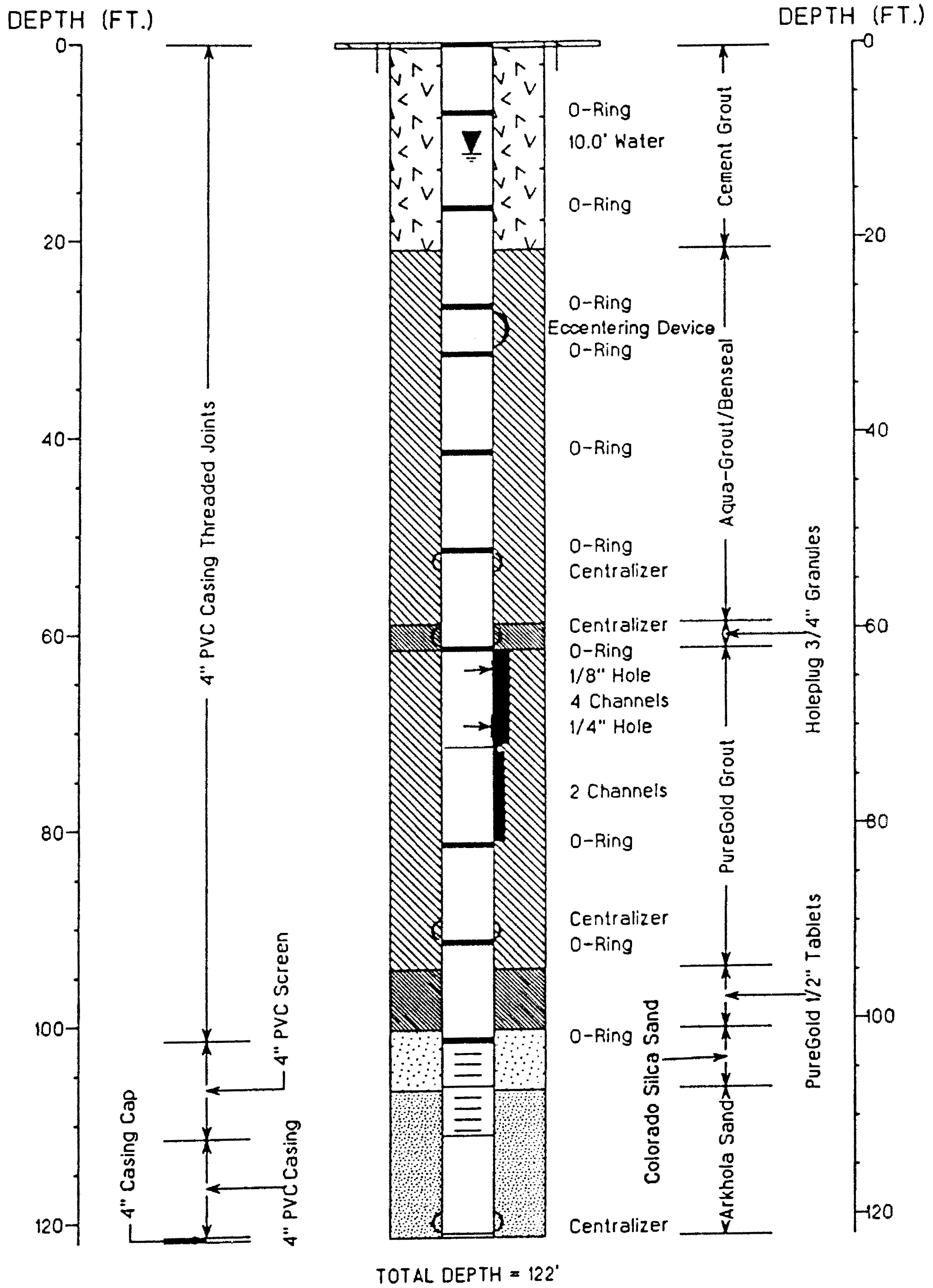


Figure 10. As-Built Diagram, Experimental Control Well CW-2



CASE HISTORY No. 1
WELL No. CGC/OSU CW - 3

TOTAL DEPTH = 122'

Figure 11. As-Built Diagram, Experimental Control Well CW-3

made during reaming with the 8½-inch bit. After reaching total depth and circulating for one hour, the trip out of the hole began. The bit became stuck near total depth. The rig worked for three or four hours during the trip out, becoming stuck intermittently all the way out. As the bit neared the surface, a clay boot or a donut-shaped clay ring was visible on top of the bit. The clay boot became dislodged as the bit was withdrawn from the hole, and sank to bottom. Rig scheduling did not permit a trip in the hole to clean out the clay.

Cuttings were collected at five-foot intervals for control well CW-1, washed with a sieve and tap water, and classified according to U.S.C.S. soil type or lithology. Cuttings at wells CW-2 and CW-3 were checked at approximately 20-foot intervals to ensure that any lateral variability in the stratigraphic section would be noted.

Installation of the Well Screen and Casing

The driller installed schedule 80 PVC casing and machine-slotted screen in all three wells. The well casing and screen were manufactured by Brainard-Kilman, Atlanta, Georgia. Most casing joints were ten feet in length. One five-foot casing joint was used in constructing an experiment, and the uppermost casing joint for each well was cut at the approximate ground level. The O-rings supplied by the casing manufacturer were installed at selected couplings, as indicated in Figures 9, 10, and 11.

Well screen was in five-foot joints and had a slot size of 0.010 inches. The length of each joint of screen and pipe was measured to the nearest 0.01 foot prior to installation. For well screen, the distance between each end and the nearest slot was measured.

Stainless steel centralizers, manufactured by Diversified Well Products, Orange, California, were installed at approximately 30-foot intervals, and at closer-spaced locations where necessitated by experimental design. The location of each centralizer was measured to the nearest 0.01 feet from the nearest joint end. Finally, the casing joints were lowered in the prescribed sequence, as each joint was carefully threaded to the preceding joint.

Control well CW-3 was modified to include several experiments involving modifications to the casing string, as shown in Figure 11. These experiments were to create or simulate 1) holes in the casing, 2) channels in the annulus, and
3) eccentered casing.

First, two holes, ⅛-inch and ¼-inch in diameter, were drilled in a casing joint. After running the casing into the well, the holes were at the approximate depths indicated in Figure 11. The simulated channels described below were placed over the holes to prevent bentonite slurry from entering the casing. A minor amount of bentonite mud was packed around the channels at the locations of the holes and allowed to dry prior to casing installation.

To simulate small-scale channeling in the annulus, ten feet of ½-inch diameter PVC water pipe was filled with water, capped, and strapped to the outside of two casing joints. The upper section of casing had four such pipes arranged immediately adjacent to one another. The lower section of casing had two such pipes, also arranged immediately adjacent to one another, and on the same side of the casing string as the four pipes. Filament-reinforced strapping tape was used to attach the ½-inch pipe to the well casing.

An eccentering device was constructed and attached to a five-foot casing joint. A sheet of PVC, ¼-inch in thickness, was cut into one-inch wide bands. These bands were cut into the desired lengths, and heated in a pot of boiling water until plastic. Two bands were shaped to the outside diameter of the four-inch PVC casing. A third band was shaped into a bow, such that the radius of the bow was four inches. The casing diameter plus the radius of the bow was eight inches, approximately ½-inch smaller than the bit diameter.

The PVC bow was attached to the outside of a five-foot section of casing at the upper end of the bow, using the two bands which had been shaped to the four-inch casing. PVC solvent and filament-reinforced strapping tape were also used to attach the device. The downward end of the bow remained free, to allow flexing of the bow in tight spots as the pipe was lowered into the borehole.

Emplacement of Annular Materials

Annular materials in each of the control wells were, in ascending sequence:

- Sand (filter pack) - Arkhola arkosic quartz sand;
- Sand (filter pack) - Colorado Silica high-purity quartz sand;
- Bentonite tablets - American Colloid PureGold ½-inch tablets;
- Bentonite slurry - American Colloid PureGold grout;
- Chipped bentonite - Baroid Holeplug ¾-inch granules;
- Bentonite slurry - Baroid Aqua-Grout/Benseal (bentonite with catalyst);
- Cement-bentonite grout - neat cement with five percent bentonite grout; and
- Neat cement grout.

Each annular material was emplaced by the most feasible means. The driller followed mixing instructions provided by manufacturers to the extent possible. As each annular material was introduced into the annulus, the depth to the material was measured continuously with a weighted tape measure.

Sand was poured into a ¾-inch diameter tremie pipe which was raised in five-foot increments to the top of the sand interval. Two types of sand were used in each of the control wells. A double screened (12-28), arkosic quartz sand marketed by Arkhola, Inc. was used from total depth upward to the overlying sand interval. A double-screened (10-20), high-purity quartz sand marketed by Colorado Silica, Inc. was used for the remainder of the sand pack interval.

Repeated efforts to pour bentonite tablets and chips through tremie pipe failed due to plugging of the pipe. Therefore bentonite tablets and chips were poured at a very slow rate into the open annulus from the surface.

Bentonite grouts were mixed in a water-filled 150 gallon tank. Two grout pumps were damaged during attempts to pump bentonite grouts mixed according to manufacturers' specifications. The maximum pumpable viscosity was generally reached at bentonite to water ratios less than the ratios specified by the manufacturers. Bentonite grouts were pumped through a ¾-inch diameter tremie pipe. Samples of each bentonite grout mixture were placed in styrofoam cups, to observe the gelling of the grout prior to the subsequent stage of completion. After pumping the upper bentonite grout interval in each of the control wells, the wells were prepared for the pumping of a cement-bentonite seal. After samples of the grout had gelled, tremie pipe was lowered to depths of 20 feet. Tap water was pumped through the tremie pipe as it was raised to the surface, to clear any bentonite in suspension from the annulus.

Cement-bentonite grout was mixed in two steps. Bentonite grout was added to water in a proportion to yield a final slurry containing five percent by volume of bentonite. After the bentonite began to gel, neat cement was added to the slurry. The cement-bentonite slurry was pumped into the annulus with the ¾-inch diameter tremie pipe.

Installation of Protective Manholes and Concrete Pads

Approximately two inches of gravel and soil were removed from an area around each wellbore. Forms were constructed of 2"x6" lumber and measured four feet on each side. Neat cement was mixed with tap water and pumped into the annulus of each well and into the form in a nearly continuous pour until the form was filled. The pour was interrupted briefly to make the final saw cuts on the casing stickups and to place the manholes over each well.

Data Acquisition

Century performed all geophysical well logging for the control wells. For control wells CW-1 and CW-2, geophysical well logs were run at three stages of completion:
in open hole, after screen and casing were installed but prior to emplacement of annular materials, and after annular materials were emplaced.

For control well CW-3, geophysical well logs were run in open hole and after final well completion, but not in casing prior to the emplacement of annular materials. The experimental design included the intermediate logging runs for all three control wells. The driller's schedule necessitated the emplacement of annular materials and the expedited completion of the control well CW-3 before intermediate logs could be run.

For quality control, pre-logging and post-logging calibration and bottom to top repeat runs were requested for each logging run. Due to budgetary and scheduling constraints, tool calibration was limited to one calibration per tool prior to the initiation of the project. Repeat runs were run for nearly all logs.

A total of 13 logging tools were tested. Because of the two-inch casing diameter for control well CW-1 and availability, only five tools were run in CW-1 after casing was installed. Most of the 13 tools produce more than one geophysical response or curve. Table 2 describes the logging tools which were tested. Century performed the logging when logging equipment and personnel were available, and at times which would not conflict with drilling and well installation operations. Most of the logging was performed at night. Because work at the project site was nearly continuous day and night for nine days, most logging activity was not supervised.

Geophysical Well Log Analysis

All geophysical well logs for each of the experimental control wells were reviewed. For each well, the log traces which best responded to the known features of well construction were merged into computer files for analysis. The evaluations for the control wells are summarized below, followed by a discussion of selected analytical strategies, especially those which were successful, or have potential application elsewhere.

Control Well OSU/CGC CW-1

Well construction and integrity for control well CW-1 was evaluated using open-hole and cased-hole logs. Cased-hole logs were run before and after annular materials were emplaced. For cased-hole logging, five of the six tools capable of running within the two-inch diameter well casing were run. All logs were run by Century, were obtained in digital format, and were of excellent quality. Each region of investigation is evaluated as shown in Figures 12, 13, and 14.

Region IV. Lithology was interpreted using open-hole logs, principally the gamma-ray logs shown in Figures 12, 13, and 14. Approximately 6.6 feet of clay fill and soil is present at the surface. The clay is underlain by a uniform shale to the total drilled depth of 122 feet. This interpretation is consistent with the descriptions of drill cuttings which were collected at five-foot intervals.

Region III. The annular space was interpreted using the neutron log (NL), omnidirectional long- and short-spacing density logs (LSD-4pi, SSD-4pi), and gamma-ray (GR) logs. The SSD-4pi log was calibrated to the LSD-4pi log, both in units of counts per second, using a calibration technique described in the Methods section of Chapter 1. (See Figure 15.)

Three alternative graphical presentations are provided for gamma-ray and neutron log interpretation. Figure 12 displays the open-hole (GR-OH, NL-OH) and completed cased-hole (GR-CH, NL-CH) gamma-ray and neutron logs. Figure 13 displays the cased-hole gamma-ray and neutron logs prior to installing annular materials (GR-CHO, NL-CHO), and after completion (GR-CH, NL-CH). In Figure 14, the calculated differences between the cased-hole and open-hole gamma-ray and neutron logs (DLTA GR, DLTA NL) are displayed in the tracks with the respective open-hole gamma-ray and neutron logs.

Bentonite pellets are indicated by an increase in gamma-ray counts in the completed cased hole as compared to the open hole or the cased hole prior to installing annular materials. The neutron logs reflect the percent of apparent porosity, all of which is water-filled. Therefore the counts increase in proportion to the net water volume decrease as annular materials are installed. Because sand has less apparent porosity than the other annular materials, the top of sand is apparent on the DLTA NL log trace. Annular materials are shown in the graphics columns of Figures 12, 13, and 14 labelled "ANNULUS" and are explained in Table 3.

Region II. The well casing and screen were interpreted using the differential single-point resistance (DSPR) and caliper (CAL) logs. Region of Investigation II interpretations are illustrated in the graphic columns of Figures 12, 13, and 14 labelled "CASING" and are explained in Table 4.

TABLE 3

REGION III INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	6.0		Not logged.
6.0	20.4	cement	Higher apparent density (LSD-4pi, SSD-4pi) than bentonite pellets, comparable or slightly lower density than sand pack.
20.4	49.4	bentonite grout slurry	Lower apparent density (LSD-4pi, SSD-4pi) than bentonite pellets.
49.4	54.8	bentonite pellets	Slight increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs. Lower density (LSD-4pi, SSD-4pi) than sand, higher density than bentonite slurry grout.
54.8	87.8	bentonite grout slurry and bentonite pellets	Lower apparent density (LSD-4pi, SSD-4pi) than bentonite pellets. Pellets settled into grout slurry near top of interval.
87.8	93.9	bentonite pellets	Increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs. Lower apparent density (LSD-4pi, SSD-4pi) than sand, higher apparent density than bentonite slurry grout.
93.9	118.6	sand	Higher apparent density than other annular materials (LSD-4pi, SSD-4pi). Lower apparent porosity than other annular materials (NL-CH). The sand pack appears uniformly distributed based on the similarity of the omnidirectional long- and calibrated short-spacing density logs (LSD-4pi, SSD-4pi).
118.6	121.4		Not logged.

Well Name: OSU/CGC CW-1
File Name: CH1 CW1G
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 2-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

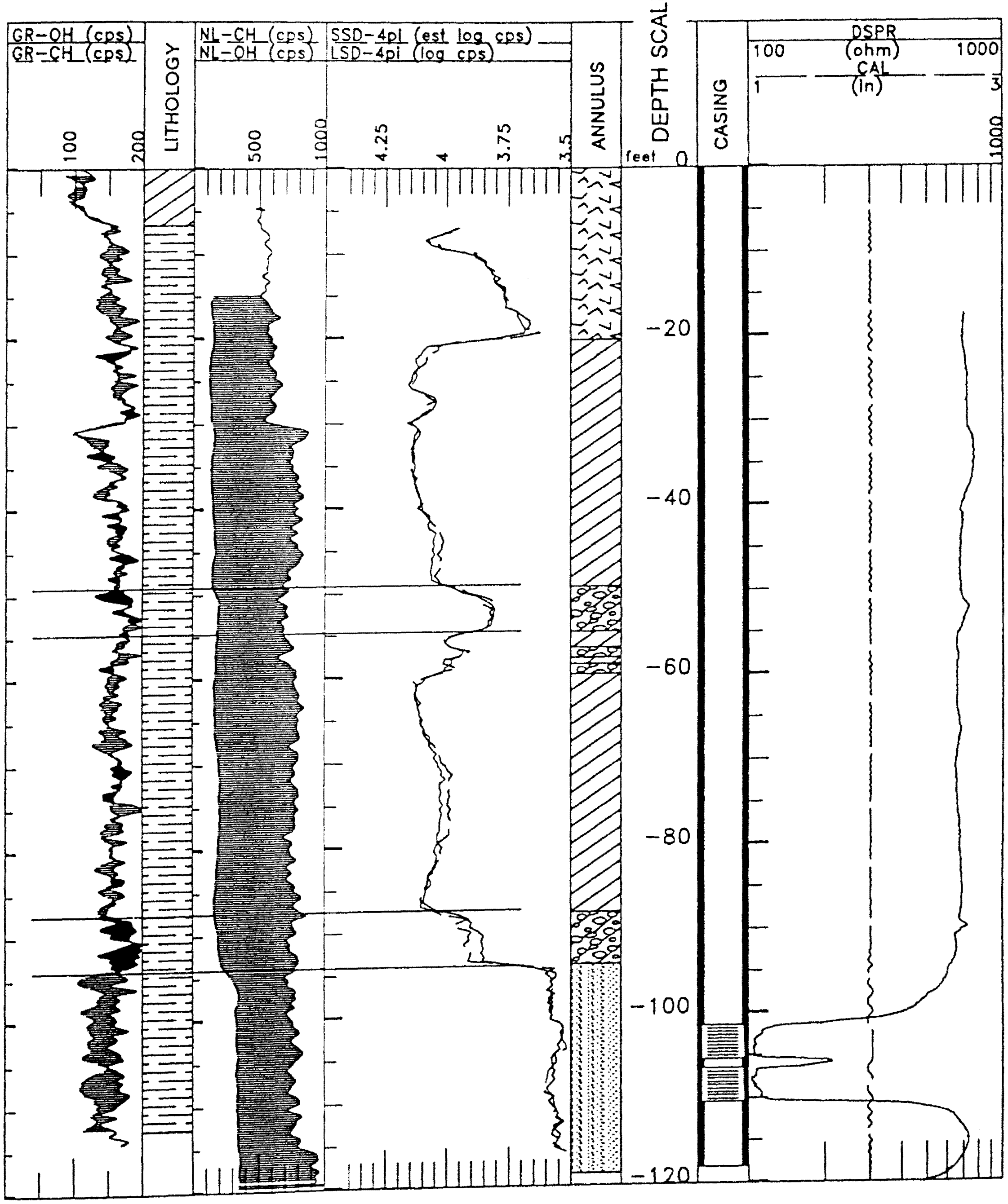


Figure 12. Open-Hole and Completed Cased-Hole Geophysical Well Logs, Control Well CW-1

Well Name: OSU/CGC CW-1
File Name: CH1_CW1X
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 2-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

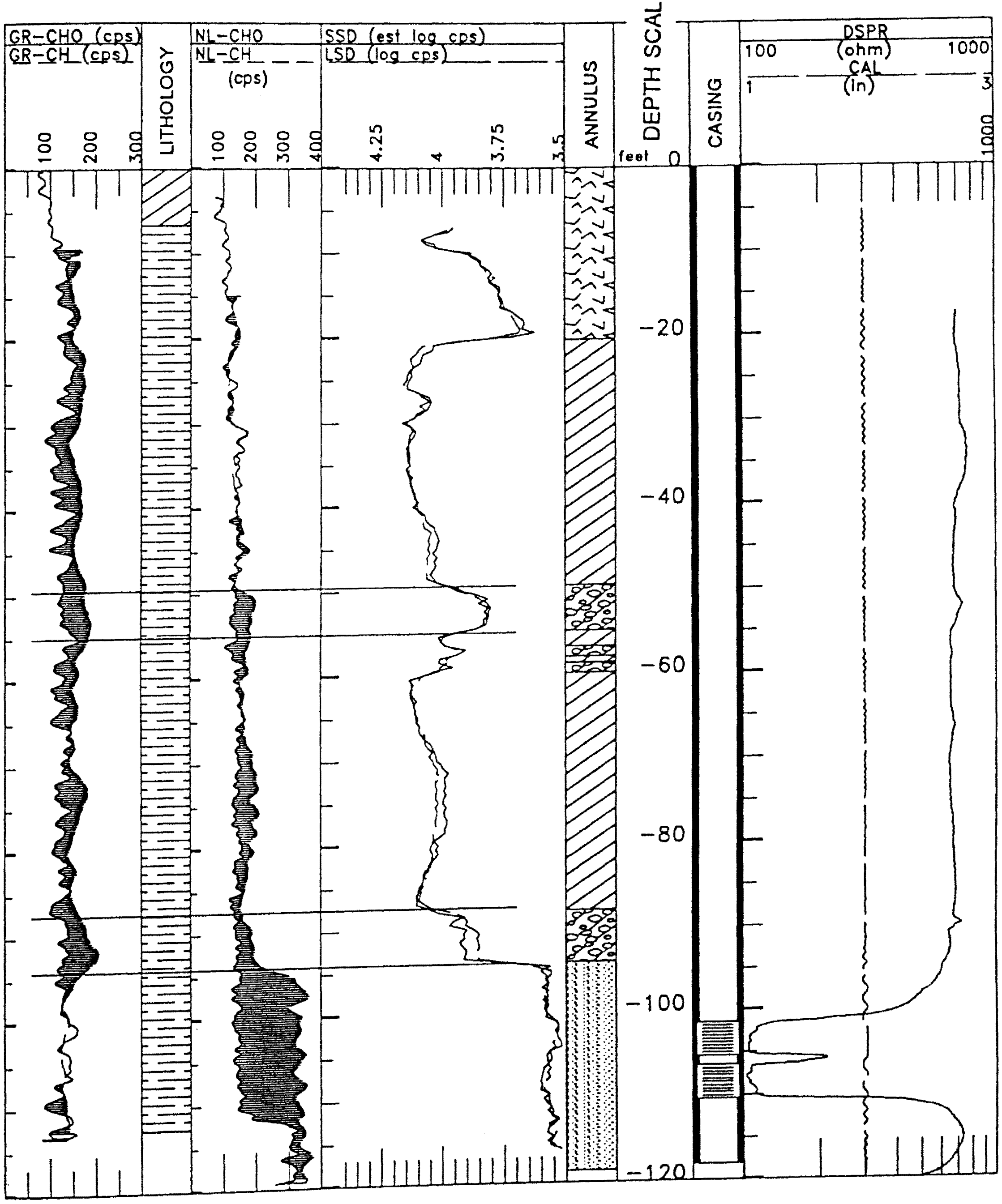


Figure 13. Open-Hole and Cased-Hole, Open-Annulus Geophysical Well Logs, Control Well CW-1

Well Name: OSU/CGC CW-1
File Name: CH1 CW1H
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC
PVC casing & screen, 2-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

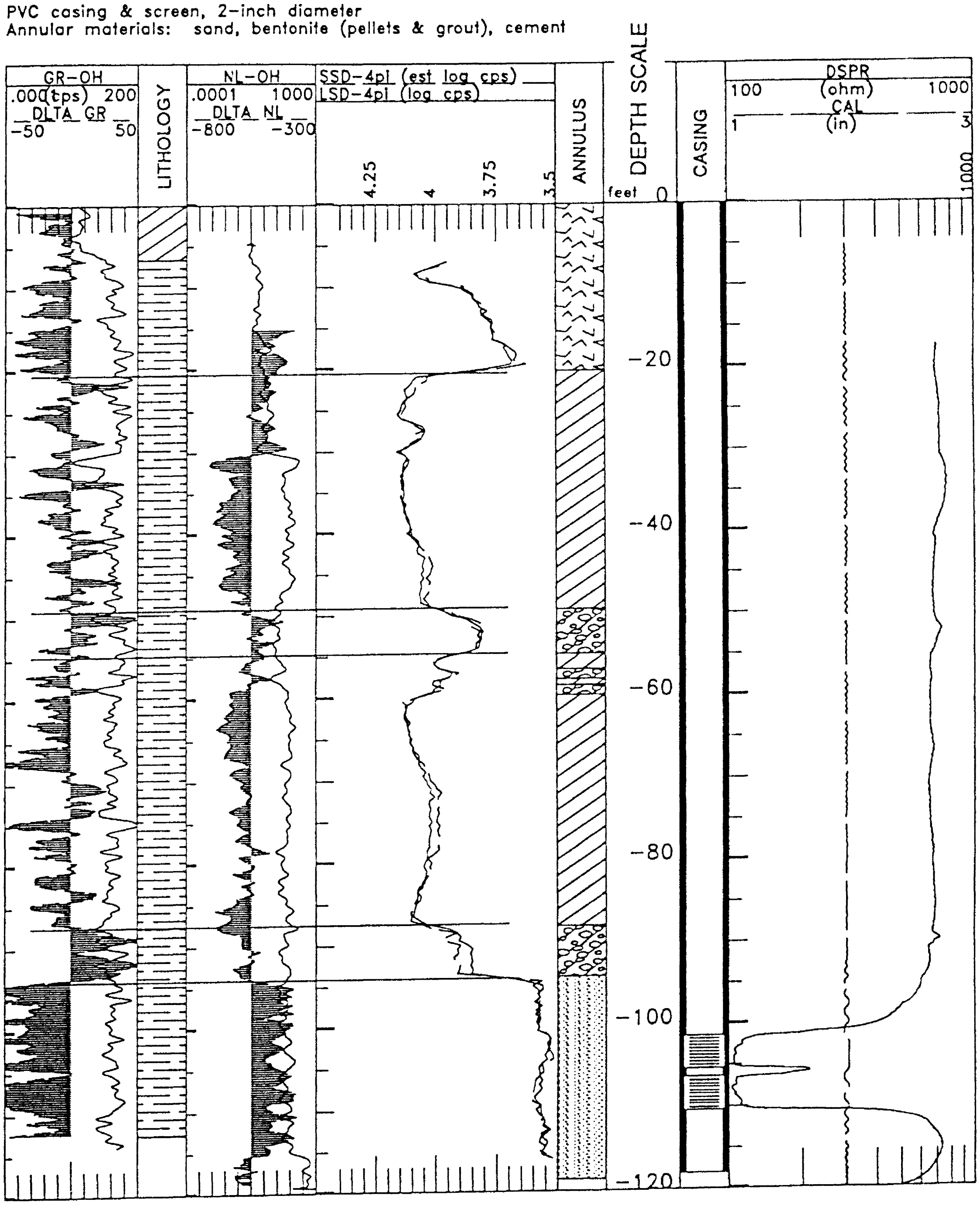
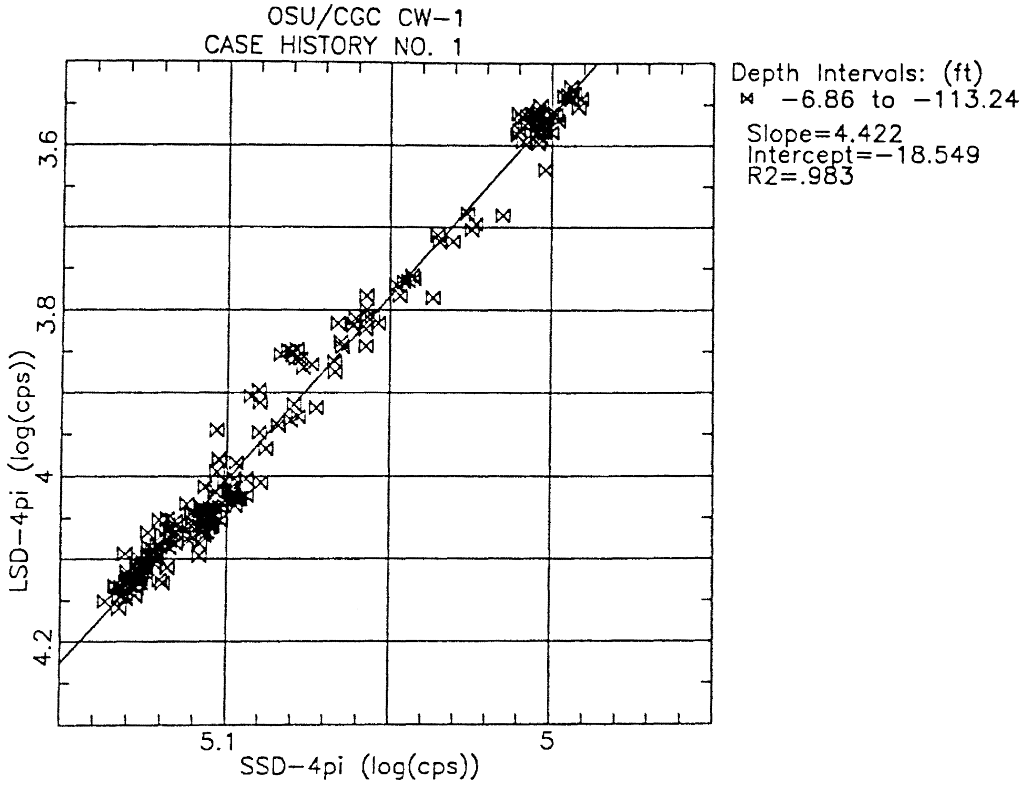


Figure 14. Open-Hole and DELTA Open-Hole/Cased-Hole Geophysical Well Logs, Control Well CW-1



CALIBRATION EQUATION

SSD-4pi (est log(cps)) = 4.422 [SSD-4pi (log(cps))] - 18.549

Figure 15. Calibration for Short-Spacing Omnidirectional Density, Control Well CW-1

TABLE 4

REGION II INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	17.7		Not logged.
17.7	101.4	2" PVC casing	Some flush-joint couplings are subtly indicated by the DSPR but probably would not be correctly interpreted if locations were not known in advance.
101.4	110.4	2" PVC screen	Slotted interval indicated by DSPR with unslotted interval at base of upper 5' section and at top of lower 5' section from 105.4 to 105.5 feet, but couplings not evident.
110.4	118.1	2" PVC casing	
118.1	121.4		Not logged.

Control Well OSU/CGC CW-2

Well construction and integrity for control well CW-2 was evaluated using open-hole and cased-hole logs. Cased-hole logs were run before and after annular materials were emplaced. For cased-hole logging, twelve tools were run in the four-inch diameter well casing. All logs were run by Century Geophysical Corporation, were obtained in digital format, and were of excellent quality. Each region of investigation is evaluated as shown in Figures 16 and 17.

Region IV. Lithology was interpreted using open-hole logs, principally the gamma-ray logs shown in Figures 16 and 17. Approximately 10.1 feet of clay fill and soil is present at the surface. The clay is underlain by uniform shale to the total drilled depth of 122 feet. This interpretation is consistent with the descriptions of drill cuttings collected at five-foot intervals for control well CW-1.

Region III. The annular space was interpreted using the neutron log (NL), the side-collimated, long- and short-spacing density logs (LSD, SSD) the omnidirectional long-spacing density log (LSD-4pi), and the open-hole and cased-hole gamma-ray (GR) logs. The omnidirectional long-spacing density log was calibrated to the side-collimated, long-spacing density log using a calibration technique described in the Methods section of Chapter 1. (See Figure 18.) The resulting units for the calibrated omnidirectional density log are in grams per cubic centimeter. Annular materials are shown in the graphics columns of Figures 16 and 17 labelled "ANNULUS" and are explained in Table 5.

Two alternative graphical presentations are provided for gamma-ray and neutron log interpretation. Figure 16 displays the open-hole (GR-OH, NL-OH) and completed cased-hole (GR-CH, NL-CH) gamma-ray and neutron logs. Figure 17 displays the cased-hole gamma-ray and neutron logs prior to installing annular materials (GR-CHO, NL-CHO), and after completion (GR-CH, NL-CH).

TABLE 5

REGION III INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-2

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	6.0		Not logged by density logs.
6.0	20.8	cement	Higher apparent density (SSD, LSD, LSD-4pi) than bentonite pellets, comparable or slightly lower density than sand pack. Apparent density of 1.92 g/cc (LSD), 1.70 g/cc (SSD).
20.8	27.4	cement settling into bentonite grout	Transitional apparent densities (SSD, LSD, LSD-4pi) between overlying cement grout and underlying bentonite slurry grout.
27.4	50.3	bentonite grout slurry	Lower apparent density (SSD, LSD, LSD-4pi) than bentonite pellets. Apparent density of 1.57 g/cc (LSD), 1.27 g/cc (SSD).
50.3	55.9	bentonite pellets	Slight increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs. Lower density (SSD, LSD, LSD-4pi) than sand, higher density than bentonite slurry grout. Apparent density of 1.87 g/cc (LSD), 1.59 g/cc (SSD).
55.9	87.8	bentonite grout slurry	Lower apparent density (SSD, LSD, LSD-4pi) than bentonite pellets. Apparent density of 1.62 g/cc (LSD), 1.30 g/cc (SSD).
87.8	92.5	bentonite pellets	Increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs. Lower apparent density (SSD, LSD, LSD-4pi) than sand, higher apparent density than bentonite slurry grout. Apparent density of 1.92 g/cc (LSD), 1.64 g/cc (SSD).
92.5	117.0	sand	Higher apparent density than other annular materials (LSD-4pi, SSD-4pi). Lower apparent porosity than other annular materials (NL-N-CH). The sand pack appears uniformly distributed based on the similarity of the LSD-4pi and SSD-4pi. Apparent density of 2.12 g/cc (LSD), 1.85 g/cc (SSD).
117.0	117.8		Not logged by density logs.

Well Name: OSU/CGC CW-2
File Name: CH1 CW2G
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

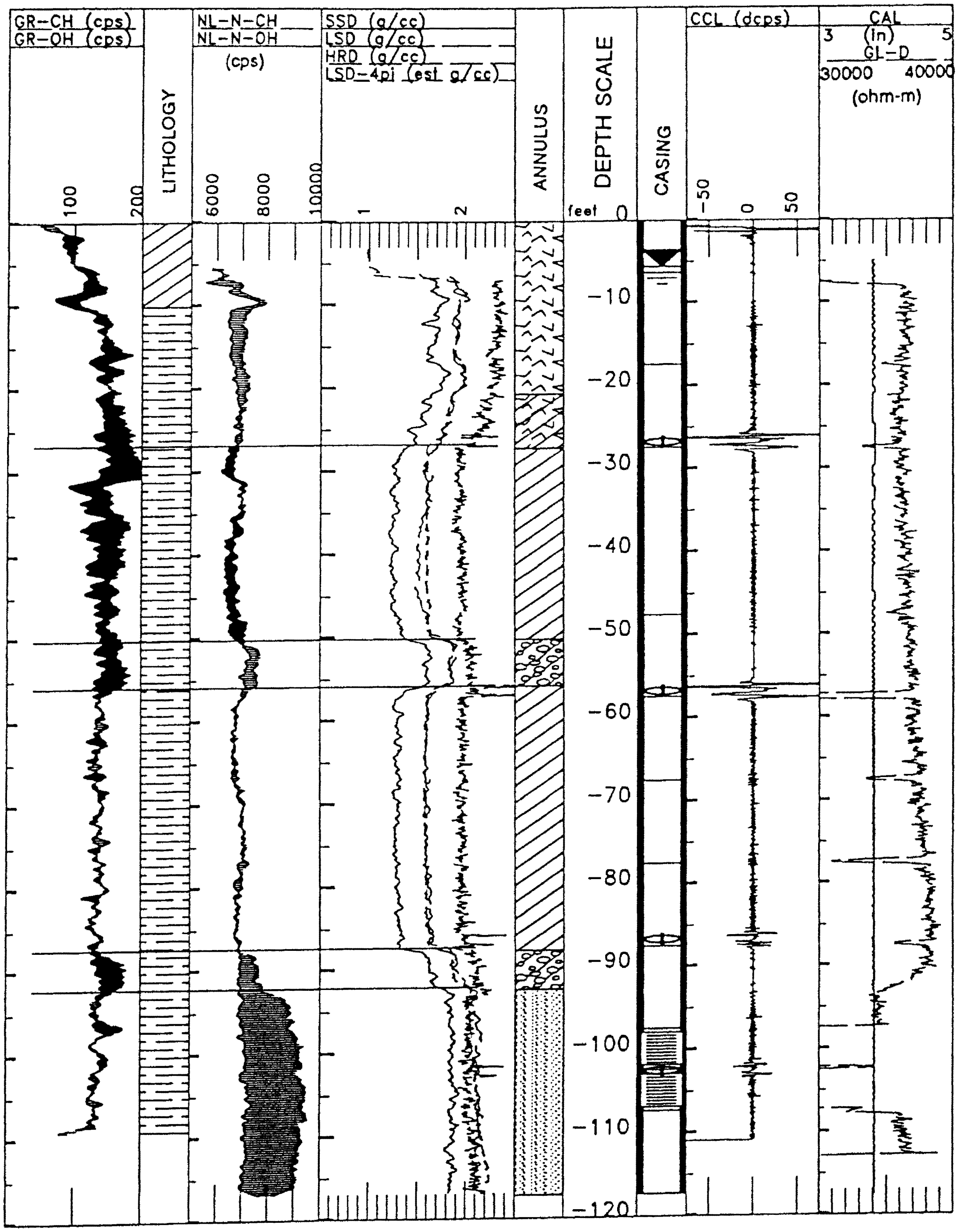


Figure 16. Open-Hole and Completed Cased-Hole Geophysical Well Logs, Control Well CW-2

Well Name: OSU/CGC CW-2
File Name: CH1 CW2X
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

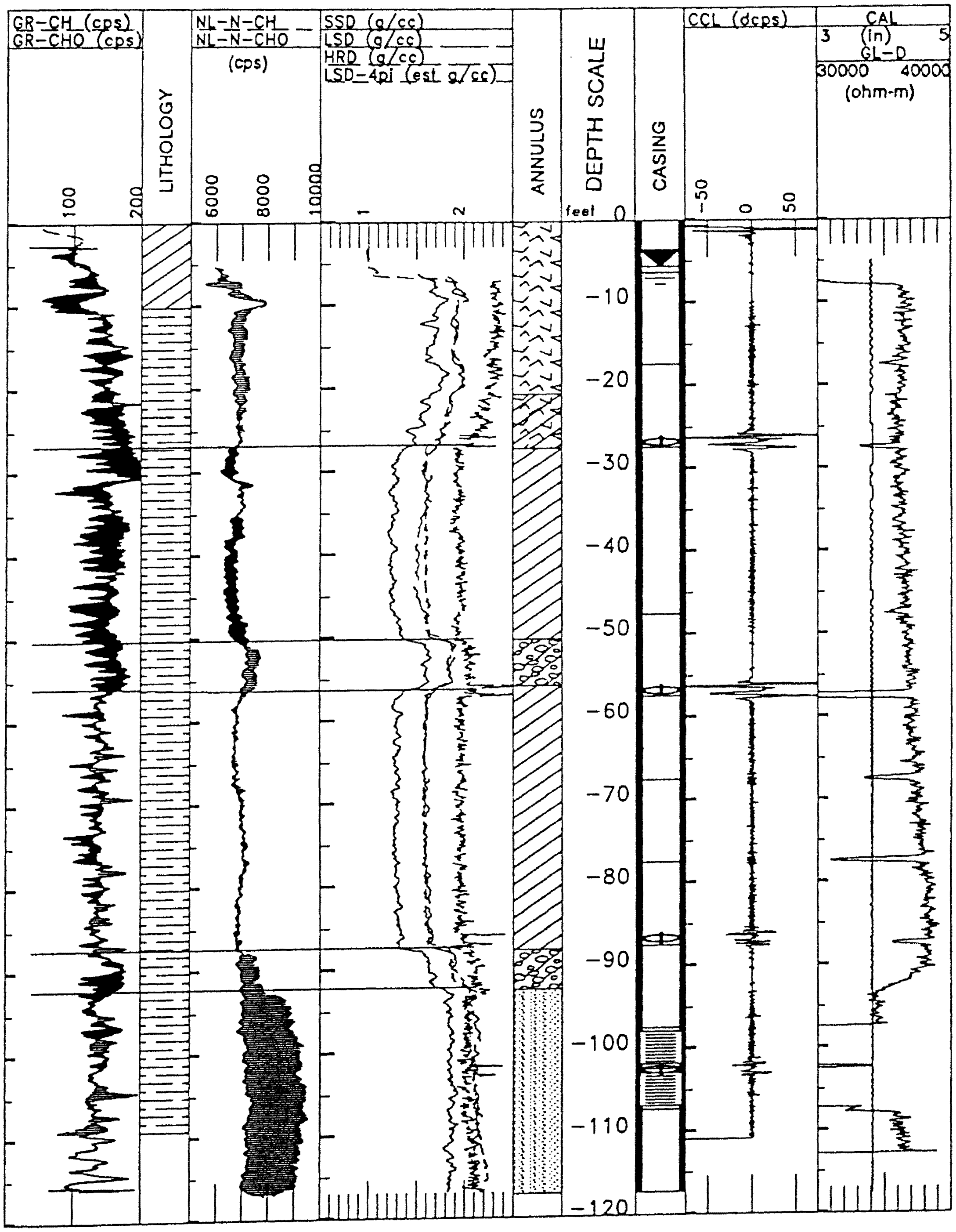
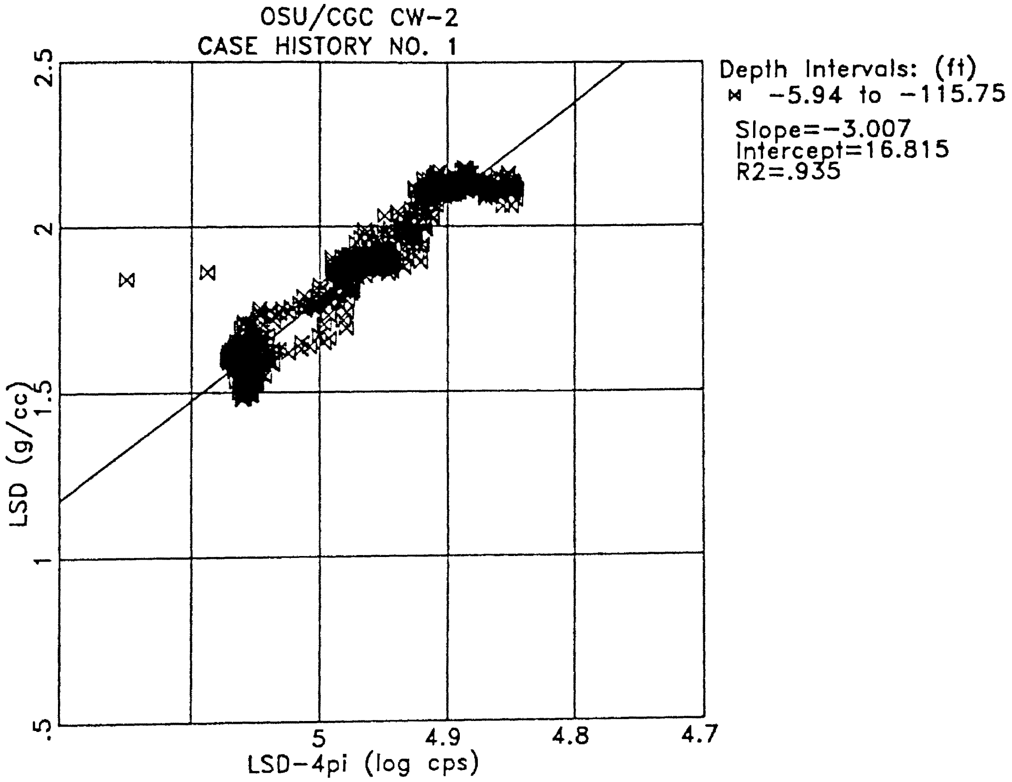


Figure 17. Open-Hole and Cased-Hole, Open-Annulus Geophysical Well Logs, Control Well CW-2



CALIBRATION EQUATION

LSD-4pi (est g/cc) = -3.007 [LSD-4pi (log(cps))] + 16.815

Figure 18. Calibration for Long-Spacing Omnidirectional Density, Control Well CW-2

Region II. The well casing and screen were interpreted using the high-resolution density (HRD), the casing collar locator (CCL), the deep or 120" guard (GL-D), and the caliper (CAL) logs. Region of Investigation II interpretations are illustrated in the graphic column of Figures 16 and 17 labelled "CASING" and are explained in Table 6.

TABLE 6

REGION II INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-2

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	5.6		Not logged with guard log above water level.
5.6	97.9	4" PVC casing	Flush-joint couplings indicated by GL-D at 17.4', 27.4', 47.6', 57.4', 67.5', 77.5', 87.5', and 97.5'. GL-D responses to couplings at 37.4' and 97.4' are obscured by noise. CCL indicates manhole near surface. CCL and HRD indicate centralizers at 26.7', 86.6', and 102.5'.
97.9	106.8	4" PVC screen	GL-D indicates slotted intervals at 97.9' to 101.8' and 102.9' to 106.8', but coupling between 5' joints not evident.
106.8	116.0	4" PVC casing	GL-D response to coupling at 107.3' obscured by noise.
116.0	117.8		Not logged by GL-D.

Control Well OSU/CGC CW-3

Well construction and integrity for control well CW-3 was evaluated using open-hole and cased-hole logs. Cased-hole logs were run after annular materials were emplaced. For cased-hole logging, thirteen tools were run in the four-inch diameter well casing. The induction log (IL) was available for the logging of control well CW-3, but not for wells CW-1 or CW-2. All logs were run by Century Geophysical Corporation, were obtained in digital format, and were of excellent quality. Each region of investigation is evaluated as shown in Figures 19 and 20.

Well Name: OSU/CGC CW-3
File Name: CH1 CW3I
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

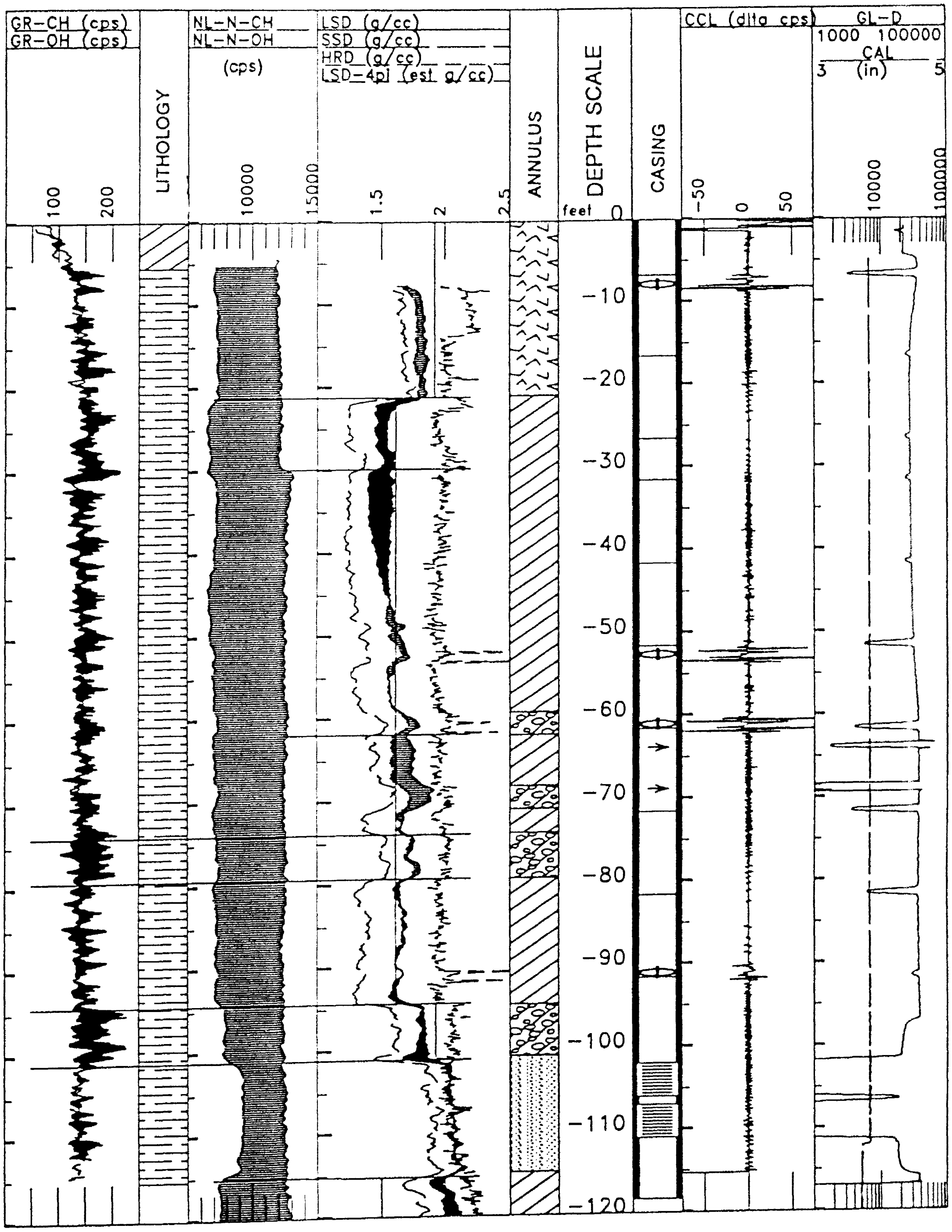


Figure 19. Open-Hole and Completed Cased-Hole Geophysical Well Logs, Control Well CW-3

Well Name: OSU/CGC CW-3
File Name: CH1 CW3H
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

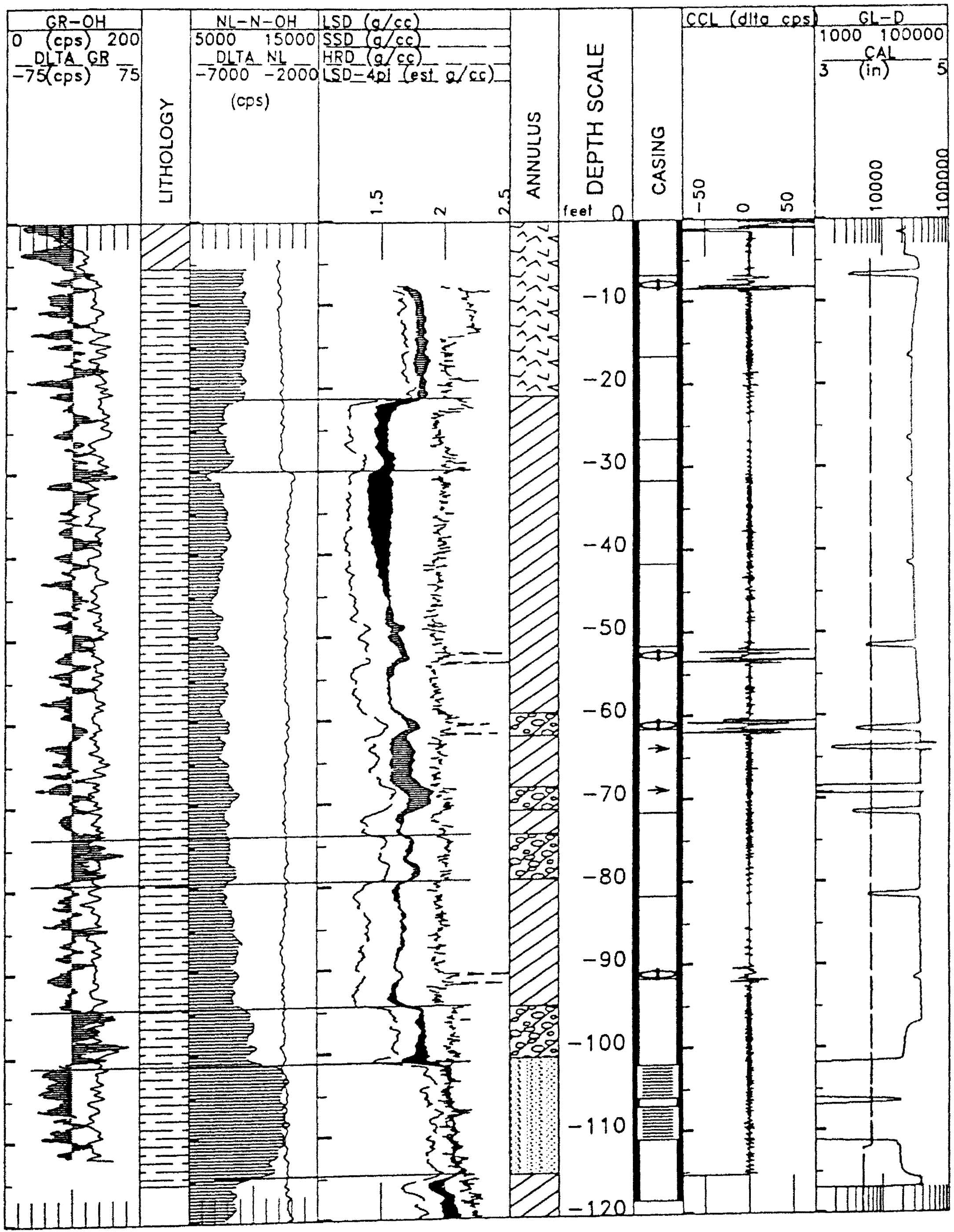
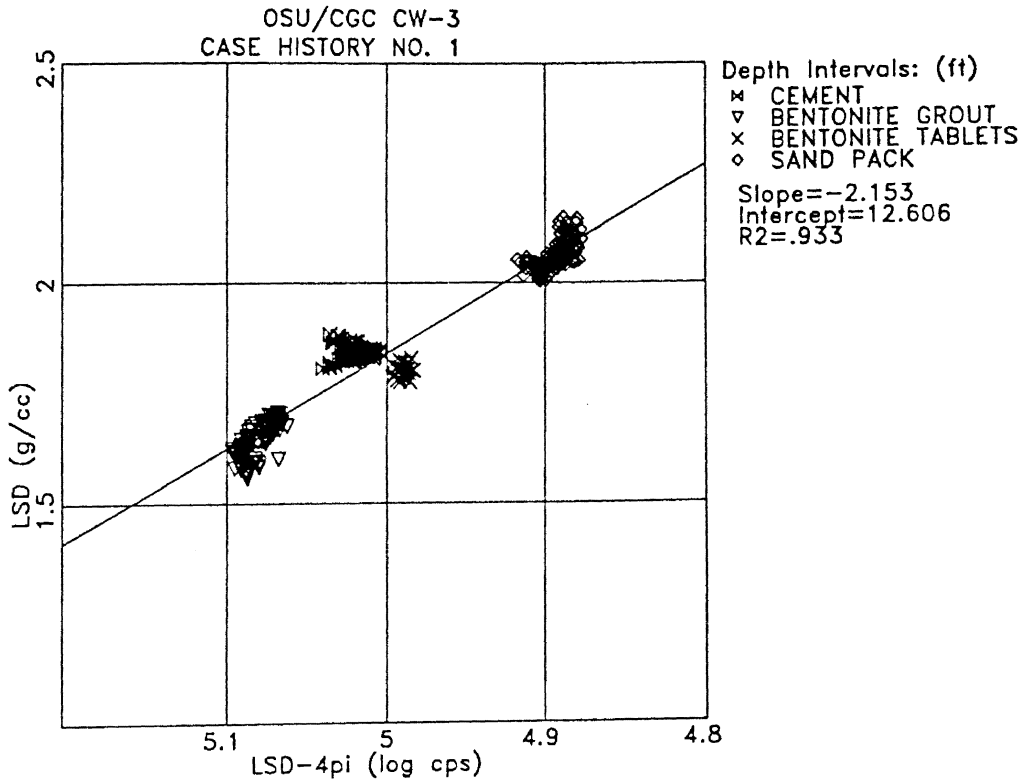


Figure 20. Open-Hole and DELTA Open-Hole/Cased-Hole Geophysical Well Logs, Control Well CW-3

Region IV. Lithology was interpreted using open-hole logs, principally the gamma-ray log shown in Figures 19 and 20. Approximately 5.6 feet of clay fill and soil is present at the surface. The clay is underlain by uniform shale to the total drilled depth of 122 feet. This interpretation is consistent with the descriptions of drill cuttings collected at five-foot intervals for control well CW-1.

Region III. The annular space was interpreted using the neutron log (NL), the side-collimated, long- and short-spacing density logs (LSD, SSD) the omnidirectional long-spacing density log (LSD-4pi), and the open-hole and cased-hole gamma-ray (GR) logs. The LSD-4pi log was calibrated to units of grams per cubic centimeter using a calibration technique described in the Methods section of Chapter 1. (See Figure 21.) Annular materials shown in the graphics columns of Figures 19 and 20 labelled "ANNULUS" are explained in Table 7.



CALIBRATION EQUATION

LSD-4pi (est g/cc) = -2.153 [LSD-4pi (log (cps))] + 12.606

Figure 21. Calibration for Long-Spacing Omnidirectional Density, Control Well CW-3

TABLE 7

REGION III INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-3

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	8.0		Not logged by density logs.
8.0	21.0	cement	Higher apparent density (SSD, LSD, LSD-4pi) than bentonite pellets, comparable or slightly lower density than sand pack. Apparent density of 1.84 g/cc (LSD), 1.68 g/cc (SSD).
21.0	59.3	bentonite grout slurry	Lower apparent density (SSD, LSD, LSD-4pi) than bentonite pellets. Apparent density of 1.58 g/cc (LSD-4pi), 1.52 g/cc (LSD), 1.29 g/cc (SSD). Eccentered casing and position of side-collimated density tool caused divergence of LSD and LSD-4pi values.
59.3	79.3	bentonite pellets and bentonite grout slurry	Bentonite pellets indicated by slight increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs, and by lower apparent density (SSD, LSD, LSD-4pi) than sand, higher apparent density than bentonite slurry grout. Pellets initially installed at 59.3'-62.0', but apparently settled in slugs to 68.2'-70.9' and 73.8'- 79.3'. Apparent densities of 1.75-1.87 g/cc (LSD), 1.50-1.58 g/cc (SSD).
79.3	94.6	bentonite grout slurry	Lower apparent density (SSD, LSD, LSD-4pi) than bentonite pellets. Apparent density of 1.64 g/cc (LSD), 1.35 g/cc (SSD).
94.6	100.8	bentonite pellets	Increase in gamma-ray counts (GR) in cased-hole logs as compared to open-hole logs. Lower apparent density (SSD, LSD, LSD-4pi) than sand, higher apparent density than bentonite slurry grout. Apparent density of 1.78 g/cc (LSD), 1.60 g/cc (SSD).
100.8	114.8	sand	The sand pack appears uniformly distributed based on the similarity of the density logs (SSD, LSD, LSD-4pi). Apparent density of 2.04 g/cc (LSD), 1.87 g/cc (SSD).
114.8	121.0	clay	Clay boot which fell from drilling bit as described in text indicated by lower apparent density than sand (SSD, LSD, LSD-4pi). Apparent density of 1.97 g/cc (LSD), 1.80 g/cc (SSD).
121.0	122.0		Not logged by density logs.

Region II. The well casing and screen were interpreted using the high-resolution density (HRD), the casing collar locator (CCL), the deep or 120" guard (GL-D), and the caliper (CAL) logs. Region of Investigation II interpretations are illustrated in the graphic column of Figures 19 and 20 labelled "CASING" and are explained in Table 8.

TABLE 8

REGION II INTERPRETATION FOR CASE HISTORY NO. 1
CONTROL WELL CW-3

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	5.6		Not logged with guard log above water level.
5.6	101.45	4" PVC casing	Flush-joint couplings indicated by GL-D at 6.7', 16.5', 26.6', 31.5', 41.5', 51.5', 61.6', 71.6', 81.6', and 91.6'. GL-D response to coupling at 101.5' is obscured by noise. CCL indicates manhole near surface and centralizer at 7.8'. CCL and HRD indicate centralizers at 52.6', 61.0', and 91.0'.
101.45	111.45	4" PVC screen	GL-D indicates slotted intervals at 102.0' to 106.0' and 107.0' to 111.0', but coupling between 5' joints not evident.
111.45	118.4	4" PVC casing	GL-D response to coupling at 111.45' obscured by noise.
118.4	122.0		Not logged by GL-D.

Discussion of Experimental Control Wells, Case History No. 1

The quality of the assessments for control wells CW-2 and CW-3 was superior to the quality of the assessment for control well CW-1. The four-inch diameter wells (CW-2 and CW-3) permitted the use of more logging methods, newer logging technology (more recently-developed tools), and more sophisticated analytical methods than did the two-inch well (CW-1). A variety of logging methods were compared and analytical techniques for evaluating specific features of well construction were developed.

Logging methods and analytical techniques for evaluating the several regions of investigation are described and compared here. These methods and techniques are proven to be applicable only in wells similar to those described in Case History No. 1, unless proven to be more broadly applicable by other case histories.

Logging Methods and Analytical Techniques, Region IV. Region IV or formation evaluation with cased-hole logs was conducted using traditional logging and analytical methods, many of which have been in widespread use in the Midcontinent for over 50 years. Methods described in texts by Pirson (1977), Doveton (1986), and others, were found to be applicable to cased-hole formation evaluation in monitoring wells constructed of PVC casing and screen. However, the stratigraphy at the site of Case History No. 1 exhibits little variability. Therefore, Case History No. 1 does not provide a good example of an evaluation of Region IV.

The logging methods which evaluate Region IV are the gamma-ray log the induction log, and the neutron log. The neutron is strongly influenced by Region III, Region II, and Region I, and is commonly of limited value for Region IV evaluation. The gamma-ray log and the induction log are influenced by Region III and Region II in predictable ways, and are useful for Region IV evaluation in wells constructed of PVC casing and screen.

The gamma-ray log is influenced by annular materials which emit gamma rays due to their potassium, uranium, or thorium content (e.g. bentonite pellets). With the use of logs which interpret the annular materials, the effect of the annular materials on the gamma-ray response can be discounted. The total gamma-ray counts reflect the potassium, uranium, and thorium content, and generally are proportional to the clay or shale content of the formation.

The induction log is so strongly influenced by metallic objects (e.g. steel centralizers) that the induction log response to Region IV is completely masked adjacent to such features. Other factors which could limit the usefulness of the induction log include highly conductive fluids within the casing, invasion of drilling fluids into the formation, and highly resistive formations such as limestone or very dry formations. The induction log appears to be influenced by the eccentered casing in control well CW-3. Additional tests or case histories are required to confirm this observation.

The induction log responds to the formation conductivity which is a function of formation fluid resistivity, the amount of formation fluid present, and the geometry of interconnected void spaces. Clays and shales provide a source of ions which make formation fluids more conductive. Therefore, clays and shales commonly exhibit comparatively low resistivities.

Logging Methods and Analytical Techniques, Region III. Cased-hole methods which have been used to evaluate Region III, the annular space, in oil and gas wells (i.e. density and neutron logging) worked well in the experimental control wells. The effects of well completion on gamma-ray and neutron logs, described by Darr, Gilkeson, and Yearsley (1990), were apparent in Case History No. 1.

Open-hole logs, cased-hole logs before emplacement of annular materials, and cased-hole logs after emplacement of annular materials were compared for the gamma-ray and neutron logs. The comparison of cased-hole logs before and after the installation of annular materials is better suited for Region II interpretation than the comparison of open and completed cased-hole logs. However, where two logging events have taken place, the simpler and more common practice is to log open hole and after well completion.

Density logging was the most effective logging for Region III assessment. The several density tools have volumes of investigation which appear to include much of the annular space and very little or none of the formation. Therefore, variations in apparent density as measured by a density tool result mostly from density changes in the annulus, provided that the fluid in the casing is of constant density, the casing is of constant density and thickness, and the casing is centered in the borehole. The side-collimated tools minimize the effects of fluids within the casing, because they are focused sidewall tools designed to minimize borehole effects.

Only the omnidirectional density logs were run in control well CW-1 because the side-collimated tools are too large in diameter to run in two-inch casing. The several annular materials could be qualitatively identified, based on their relative densities. The dual-spacing omnidirectional density tool permitted the analysis of heterogeneities in the annulus at varying distances from the well casing. The calibration of the short-spacing detector to the response of the long-spacing detector made this analysis possible.

Side-collimated and omnidirectional density logging tools proved most effective when used in combination. Dual-spacing density logging tools were more effective than single-spacing tools. The comparison of density tools which measure properties of materials in different areas of the annulus permits an assessment of heterogeneity. Heterogeneity is an indication of potential problems such as channeling or eccentered casing.

In Case History No. 1, two density log calibration methods were used to assess heterogeneity in the annular space. In control well CW-1, the short-spacing omnidirectional density log was calibrated to the omnidirectional long-spacing density log. In control wells CW-2 and CW-3, the omnidirectional long-spacing density log was calibrated to the side-collimated, long-spacing density log. The curve-fitting method used for both calibrations was linear regression, because of its effectiveness, ease of use, and availability an integral part of the computer program used for well log analysis. Both of these calibration methods greatly enhanced the ability to detect heterogeneity in the annular space.

The comparison of the calibration attempts for the omnidirectional long-spacing density log was useful in distinguishing heterogeneous zones. Eliminating such zones from the regression improved the best fit (R^2) from 0.79 for the entire well (Figure 22) to 0.93 for the homogeneous zones only (Figure 21). The zone which had two simulated channels had an R^2 of 0.81 (Figure 23), which is significantly poorer than homogeneous zones. The obviously heterogeneous zones, such as the zone with four simulated channels, all simulated channels, and eccentered casing exhibited no meaningful correlation (Figures 24, 25, and 26).

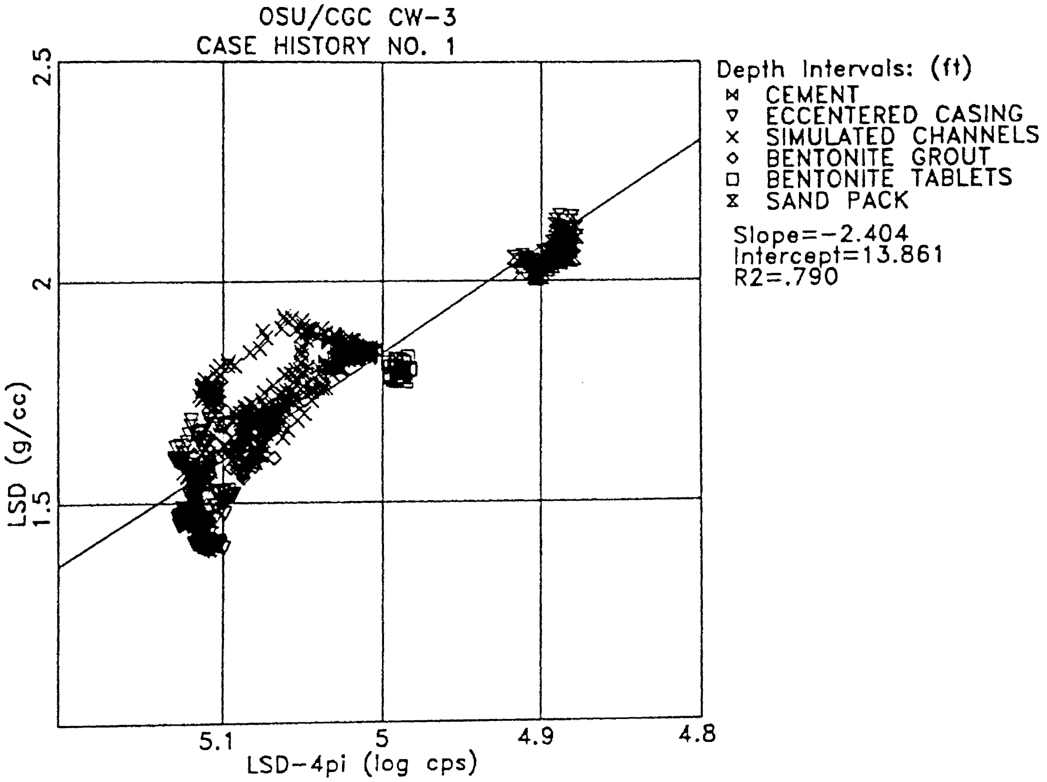


Figure 22. Curve Fit for Long-Spacing Omnidirectional Density, Control Well CW-3, All Intervals

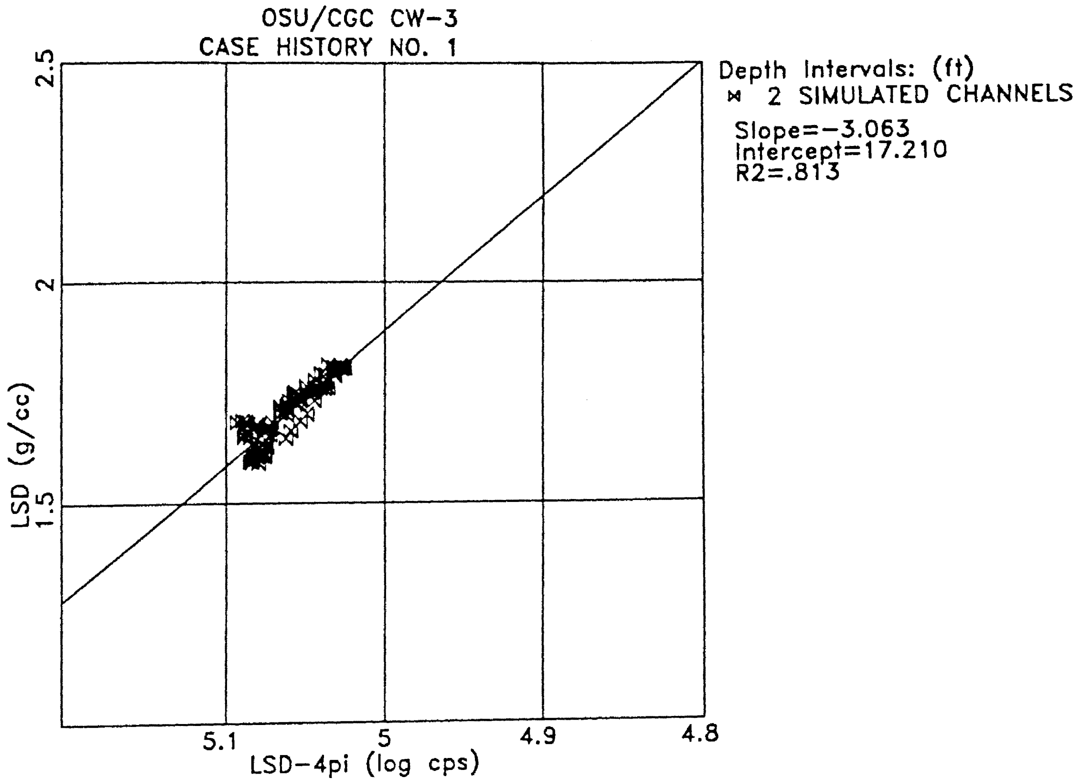


Figure 23. Curve Fit for Long-Spacing Omnidirectional Density, Control Well CW-3, Two Simulated Channels

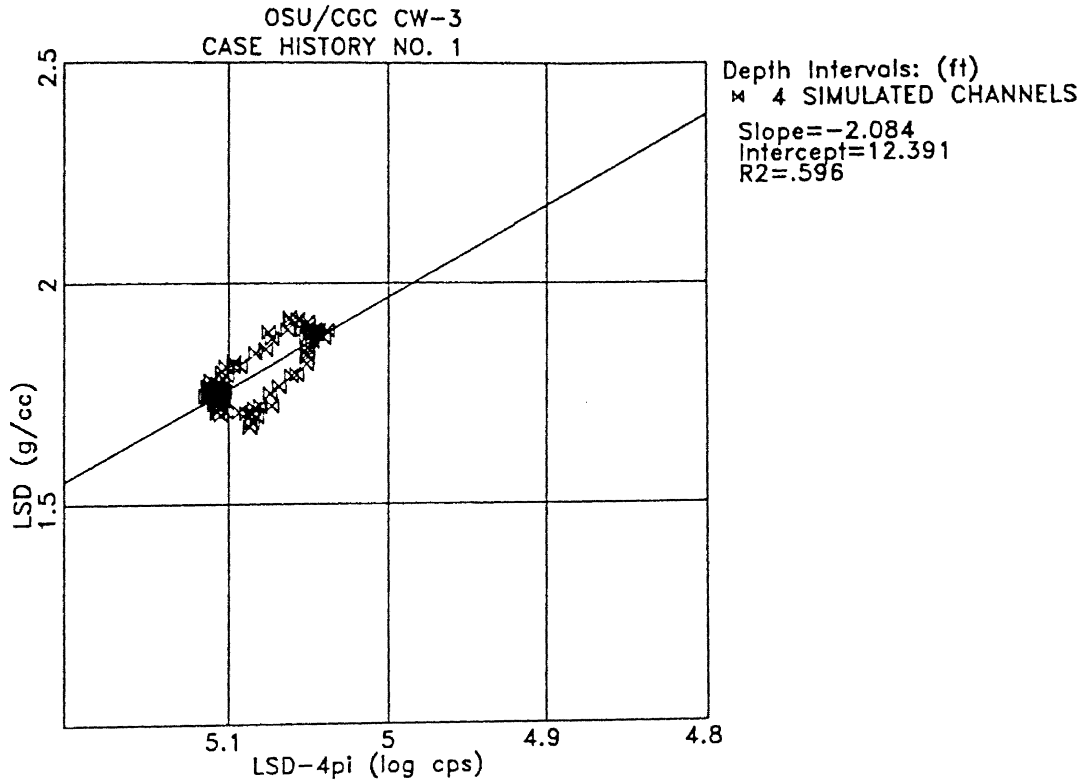


Figure 24. Curve Fit for Long-Spacing Omnidirectional Density, Control Well CW-3, Four Simulated Channels

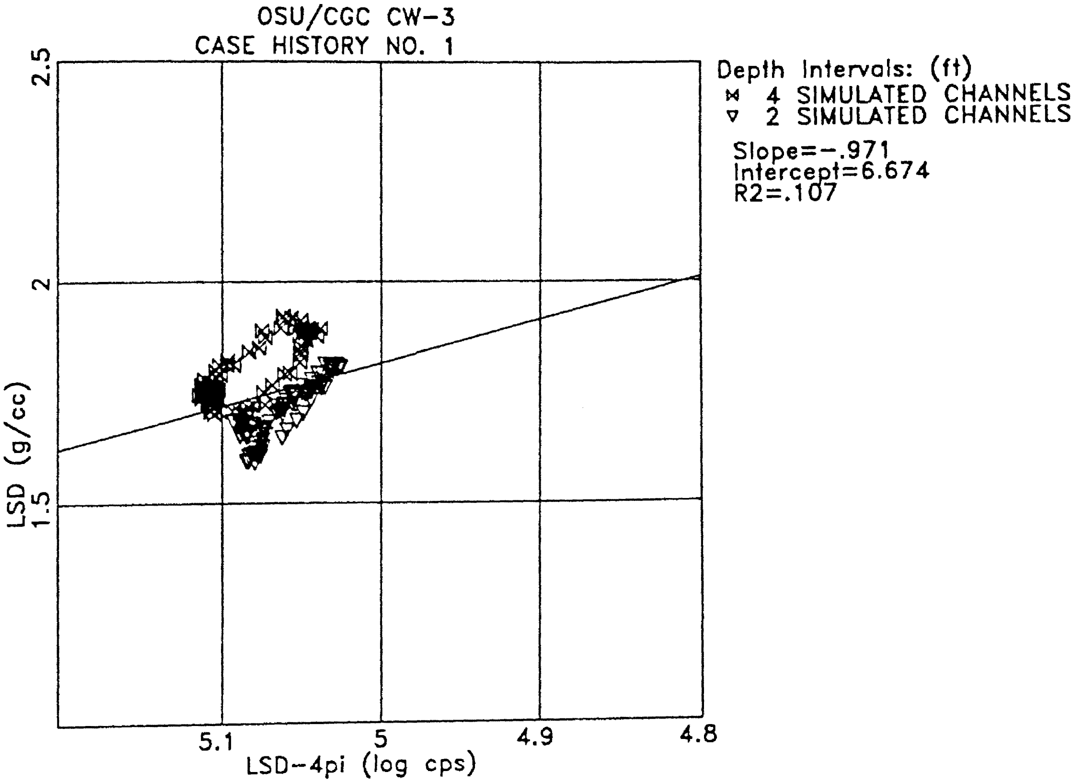


Figure 25. Curve Fit for Long-Spacing Omnidirectional Density, Control Well CW-3, Two and Four Simulated Channels

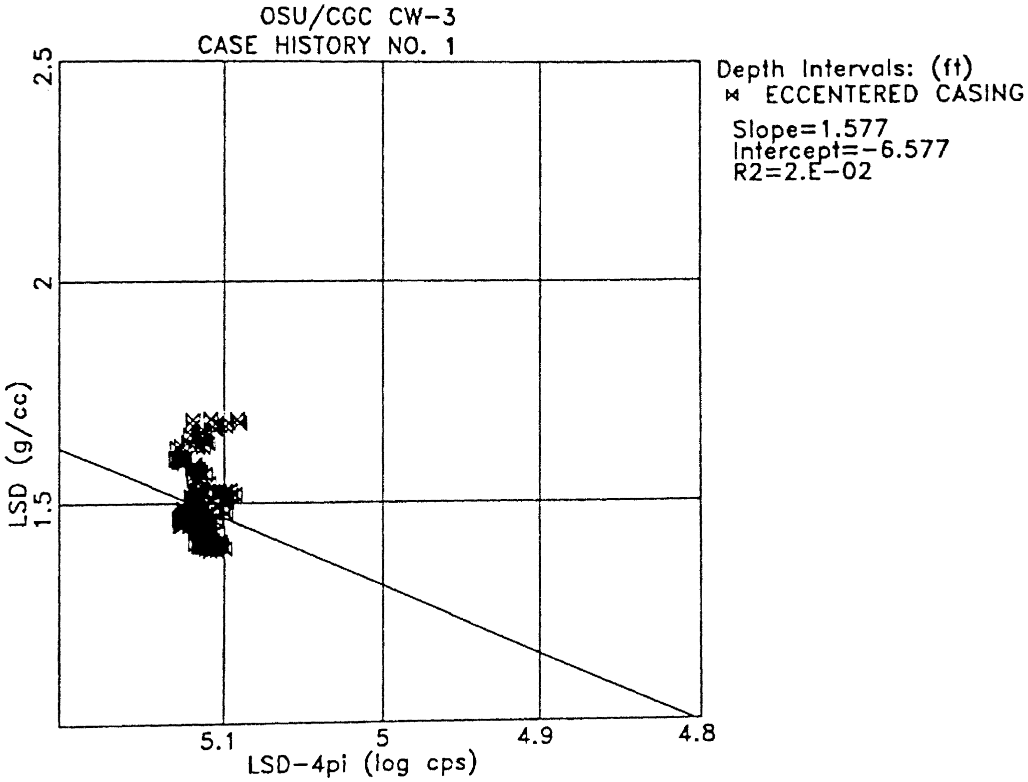


Figure 26. Curve Fit for Long-Spacing Omnidirectional Density, Control Well CW-3, Eccentered Casing

The interpretation of control well CW-3 was improved by comparing logging data with those from control well CW-2. Vertical lines drawn in the density log track in Figure 19 correspond to the side-collimated long-spacing density means for the similar intervals in Figure 16.

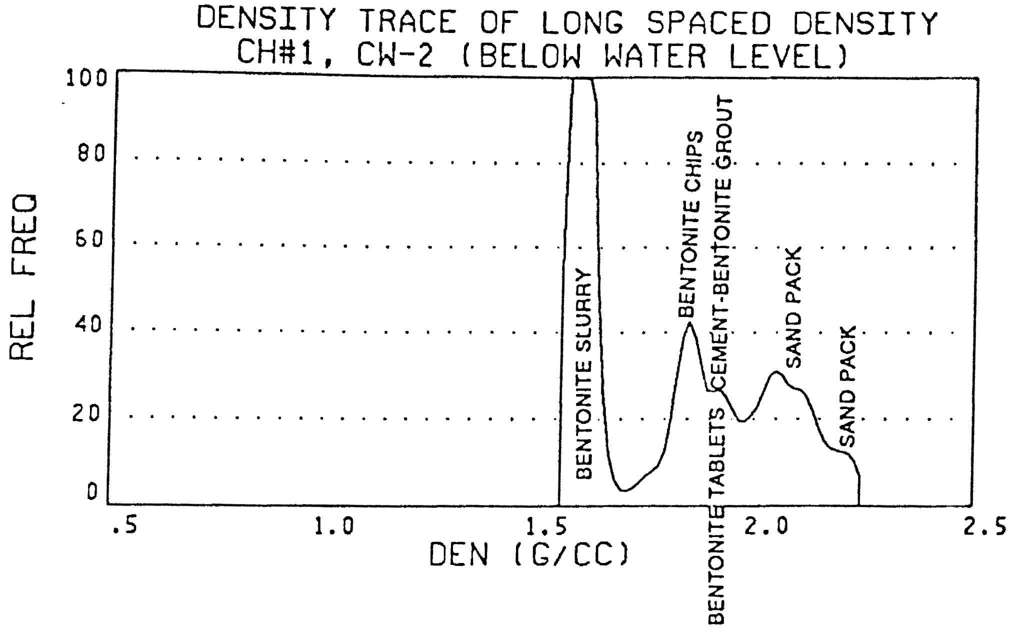
A second inter-well comparison, using the density trace, or smoothed histogram, for the side-collimated long-spacing density logs also facilitated interpretations. Figure 27 illustrates the density trace for wells CW-2 and CW-3. The eccentered casing interval in control well CW-3 stands out as a possible problem area due to its apparent density below 1.5 grams per cubic centimeter.

Logging Methods and Analytical Techniques, Region II. The strategy for evaluating Region of Investigation II, the well casing and screen, was to run every log available and observe the responses. Too little previous work was adequately documented to predict which tools would prove effective and which features of well construction would be detected.

Figure 28 illustrates the logging responses of the following electrical logging methods in PVC screen and casing:

- Induction logging;
- Guard resistivity (focused resistivity), 15-inch, 55-inch, and 120-inch spacing (GL-15 IN, GL-55 IN, GL 120 IN);
- Normal resistivity, 16-inch and 64-inch spacing (EL-16N, EL-64N);
- Differential single point resistance (DSPR);
- Spontaneous potential (SP); and
- Fluid resistivity logging (FRL).

The induction log responds to the stainless steel centralizers attached to the casing, but not to the well screen or casing features. The guard logs respond to the well screen and to other features of the well casing. The normal resistivity logs respond to the well screen, but not to casing features. The two differential single point resistance logging runs respond to the well



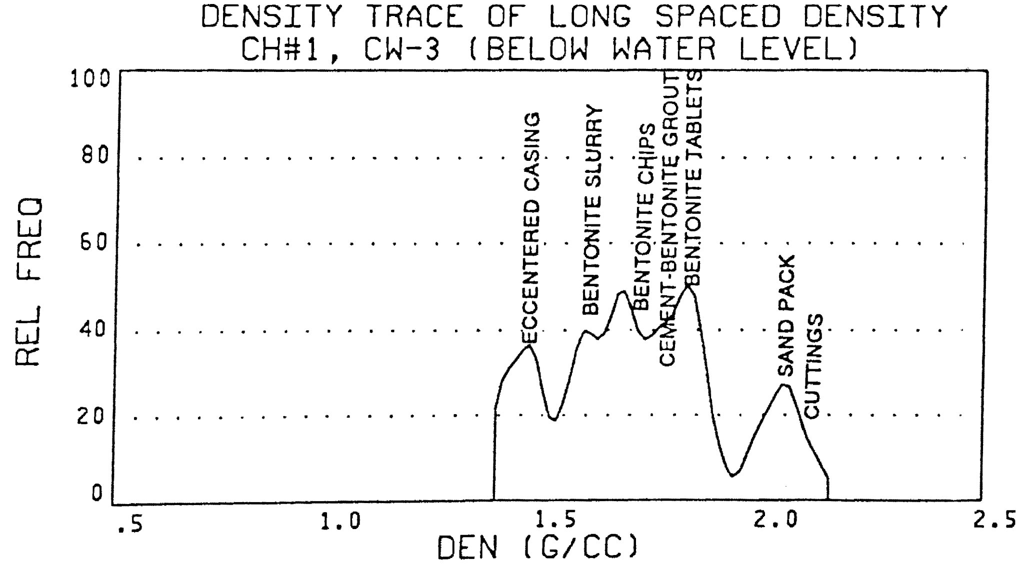


Figure 27. Comparison of Density Traces, Control Wells CW-2 and CW-3

Well Name: OSU/CGC CW-3
File Name: CH1 ELOG
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC
PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

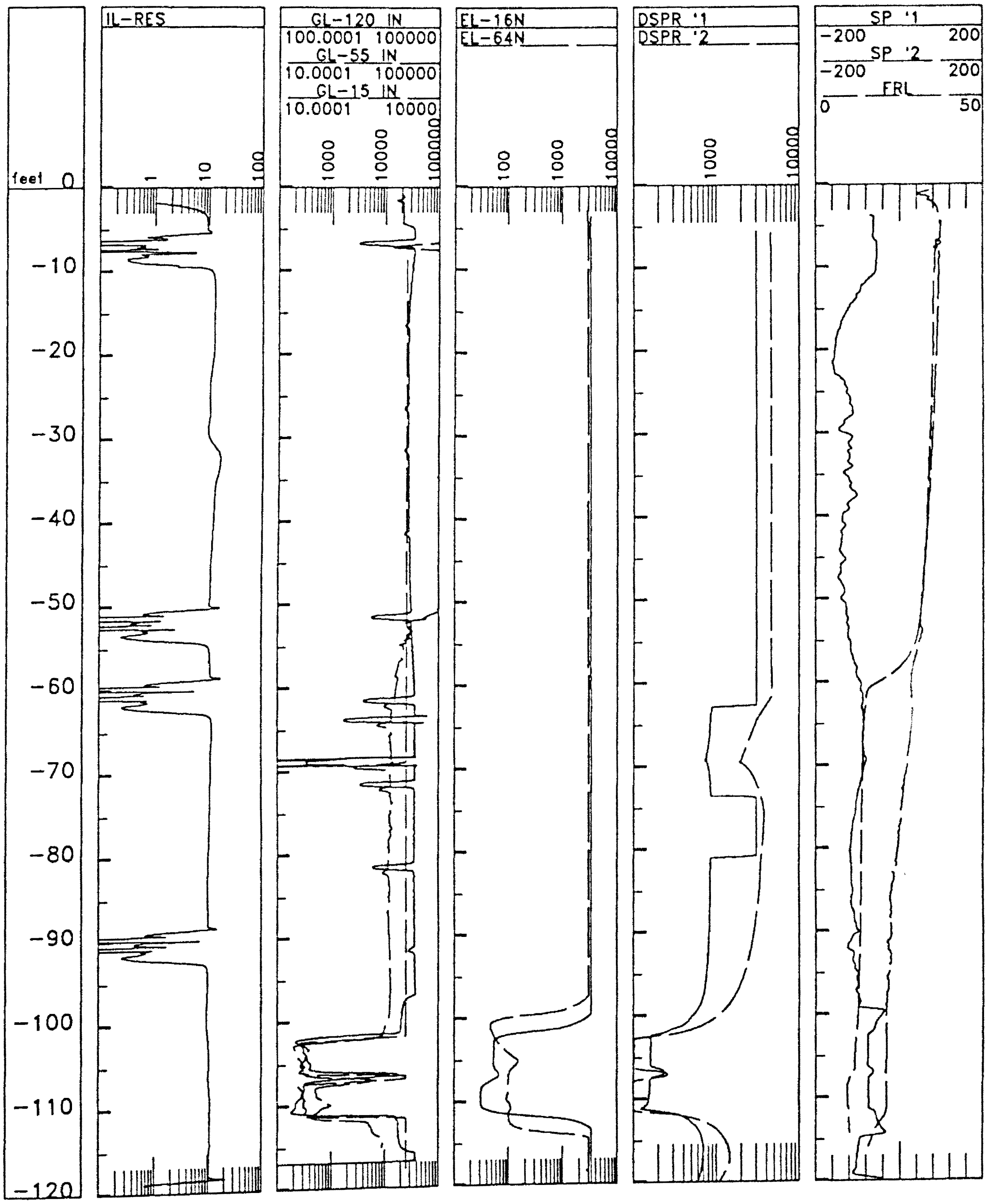


Figure 28. Comparison of Electrical Logging Methods, Control Well CW-3

Well Name: OSU/CGC CW-3
File Name: CH1 GL
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC
PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

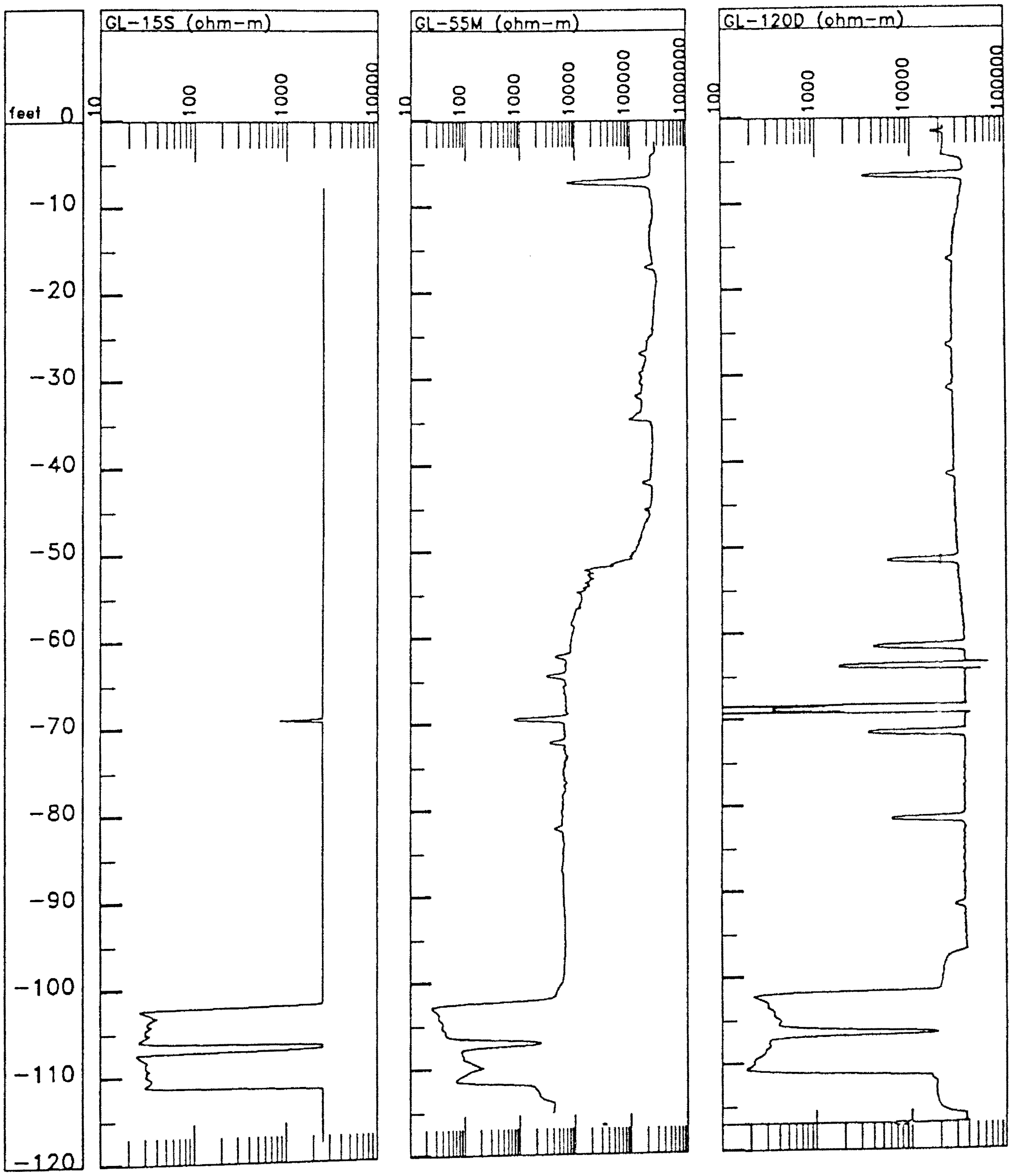


Figure 29. Comparison of Three Guard Logs, Control Well CW-3

screen, and to the holes in the casing, but not with repeatable responses. The two spontaneous potential logs and the fluid resistivity log did not yield easily interpreted results.

Because the guard logs were the most effective electrical logs for characterizing PVC well casing and screen, the three guard logs were compared in detail (Figure 28). The 120-inch or deep guard array (GL-120 IN) produced responses to more features of well construction than the shorter arrays. The deep guard log clearly indicates flush-threaded casing joints and holes (Figure 29) and well screen (Figure 30).

Although the steel centralizers are in the well annulus, they are also considered a part of Region of Investigation II, the casing. Figure 31 illustrates the responses of the induction, high-resolution density, and casing collar locator logs to steel centralizers. Each of these logs exhibits a strong and reproducible response to the steel centralizers.

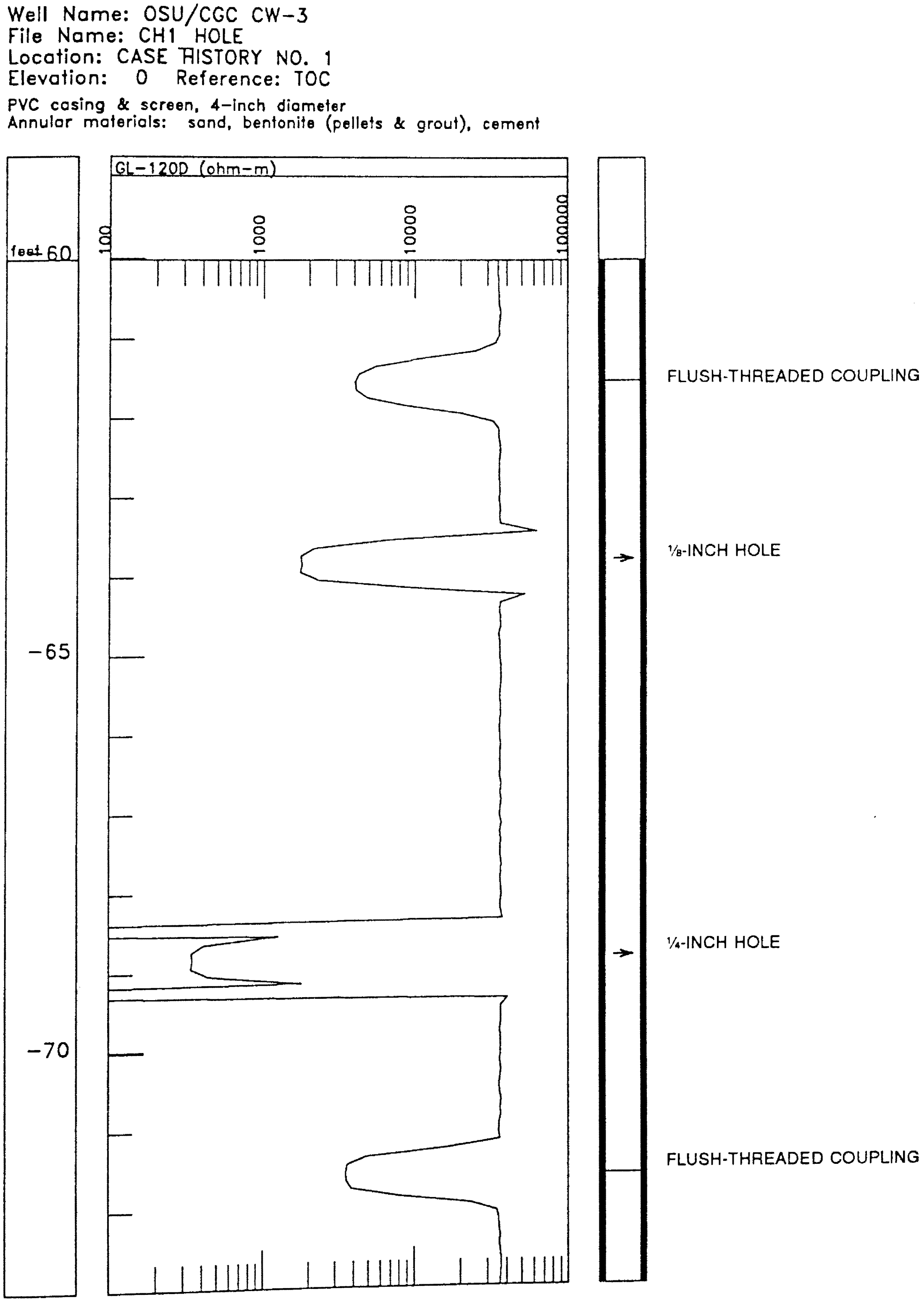


Figure 30. Guard Log (GL-120D) Response to Flush-Threaded Couplings and Holes, Control Well CW-3

Well Name: OSU/CGC CW-3
File Name: CH1_SCRN
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

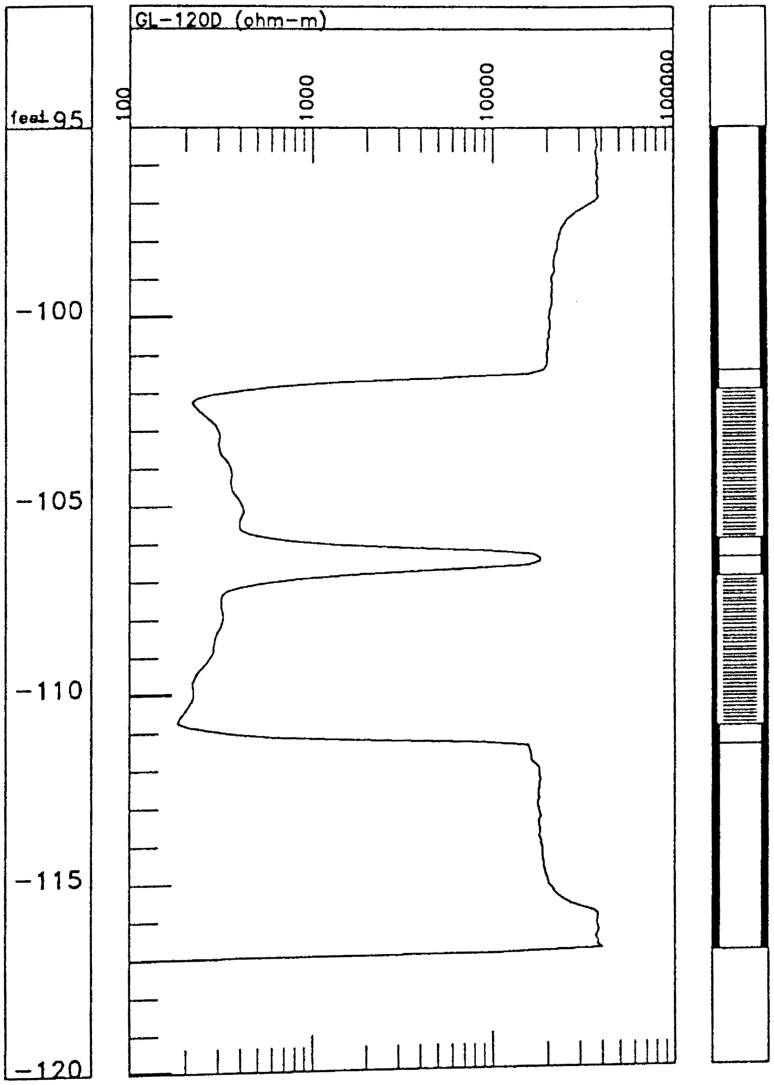


Figure 31. Guard Log (GL-120D) Response to 0.010-Slot PVC Well Screen, Control Well CW-3

Well Name: OSU/CGC CW-3
File Name: CW3 CNTR
Location: CASE HISTORY NO. 1
Elevation: 0 Reference: TOC
PVC casing & screen, 4-inch diameter
Annular materials: sand, bentonite (pellets & grout), cement

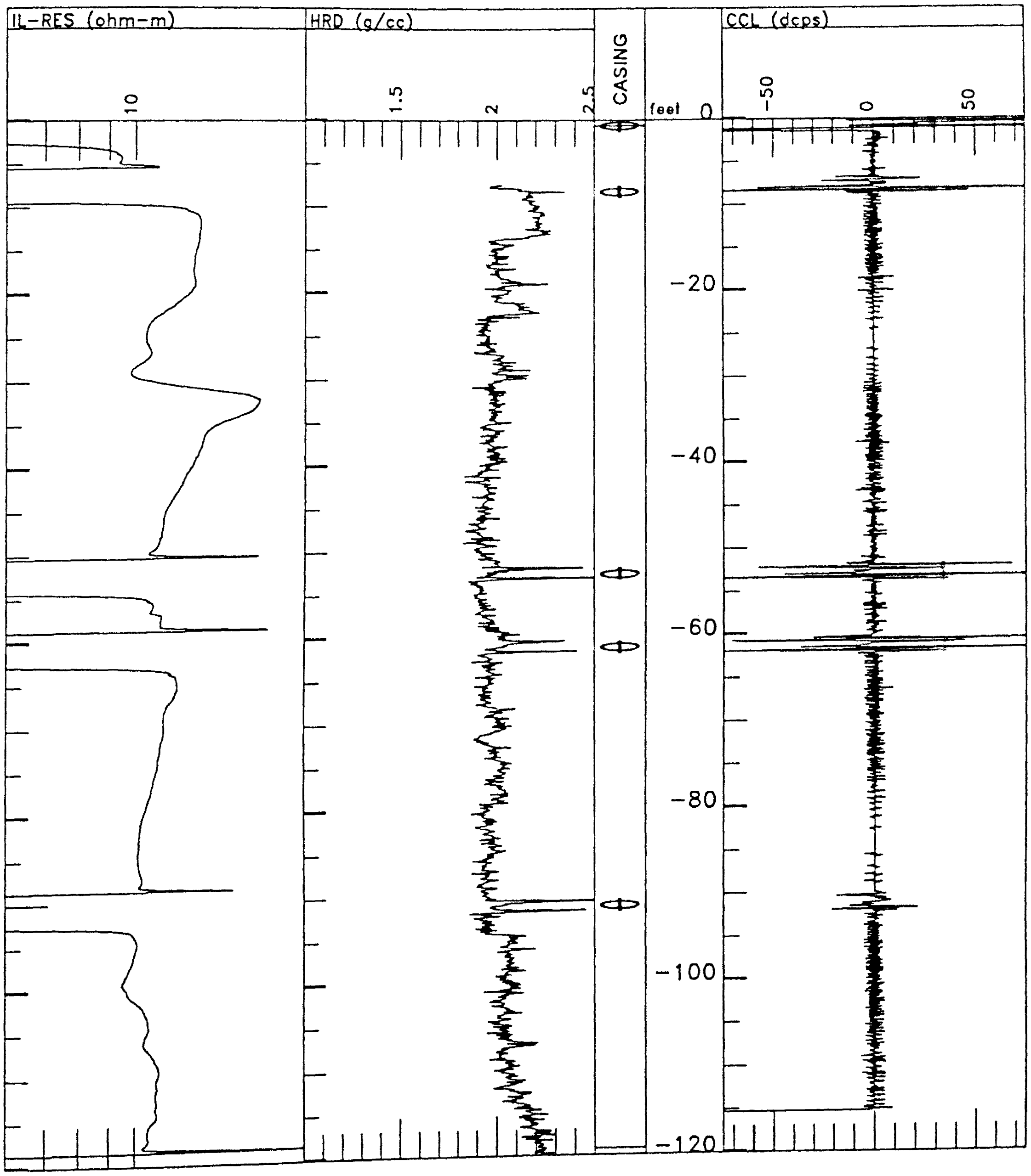


Figure 32. Induction, High-Resolution Density, and Casing Collar Locator Responses to Steel Centralizers, Control Well CW-3

CHAPTER 4

SUMMARY OF DEMONSTRATIVE CASE HISTORIES

Purpose

The experimental control wells described in Chapter 3 constitute the best documented case history developed during this research. Numerous geophysical well logs from other sites were obtained and evaluated to demonstrate the application of the logging and analytical methods developed using the control wells. Examples of geophysical logging responses were selected from the available logs to document the additional case histories.

These case histories illustrate the application of many of the geophysical logging methods and analytical techniques developed at the control well site (Case History No. 1). The case histories presented herein verify the logging methods and analytical approaches developed with the experimental control wells. In addition, the varied hydrogeologic settings and well construction provided opportunities to develop additional analytical techniques. In some instances, the lack of an optimal suite of logs necessitated the development of alternative analytical strategies.

Interpretations are based on the control well results and the observation of log responses to over 35 wells. A preliminary interpretation of each well log was used to select the wells which would form the case histories. New analytical techniques evolved during the interpretation of the many well logs. In addition, the interpretive skills of the log analysts improved during the initial interpretational phase. Therefore, all well logs were reinterpreted, using the experience and insight gained throughout the study.

Case History No. 2

Background

Case History No. 2 is based on geophysical logs for a single groundwater monitoring well, designated MW-1. The initial borehole was drilled to a total reported depth of 200 feet with an 8-inch diameter bit. Shales and sandstones were penetrated.

All logs were run by Century Geophysical Corporation, were obtained in digital format, and were of excellent quality. Open-hole and cased-hole logs were available for analysis.

Pre-Logging Construction Summary

The wellsite geologist provided field notes from the drilling and well construction. The monitoring well was constructed using glued, bell-jointed, 4-inch diameter PVC casing and screen. Two sections of casing were manually slotted with a saw to produce well screen, each section approximately 10 feet in length. According to the as-built diagram, the screens were reportedly placed at depths of approximately 160 to 150 feet and 100 to 90 feet, with a single steel centralizer located at the center of each screen section. The sand filter pack was to have been emplaced from total depth to 80 feet, with ten feet of bentonite pellets above the sand. Cuttings were introduced from the surface by shovel to fill the interval from 70 feet to a depth of three feet below the surface.

Geophysical Well Log Analysis

Well construction and integrity for monitoring well MW-1 was evaluated using open-hole and cased-hole logs. Each region of investigation is evaluated as shown in Figure 33. The assessment of Region of Investigation IV is summarized briefly, and interpretations for Regions III and II are explained in Tables 9 and 10.

Region IV. Lithology was interpreted using open-hole logs including the gamma-ray and caliper logs. A sequence of interbedded claystone, shale, and sandstone is interpreted as

Well Name: MW-1
File Name: CH2 MW1
Location: CASE HISTORY NO. 2
Elevation: 0 Reference: TOC

PVC casing & screen, 4-inch diameter, 2 screened intervals
Annular materials: sand, bentonite pellets (?), cuttings, void space

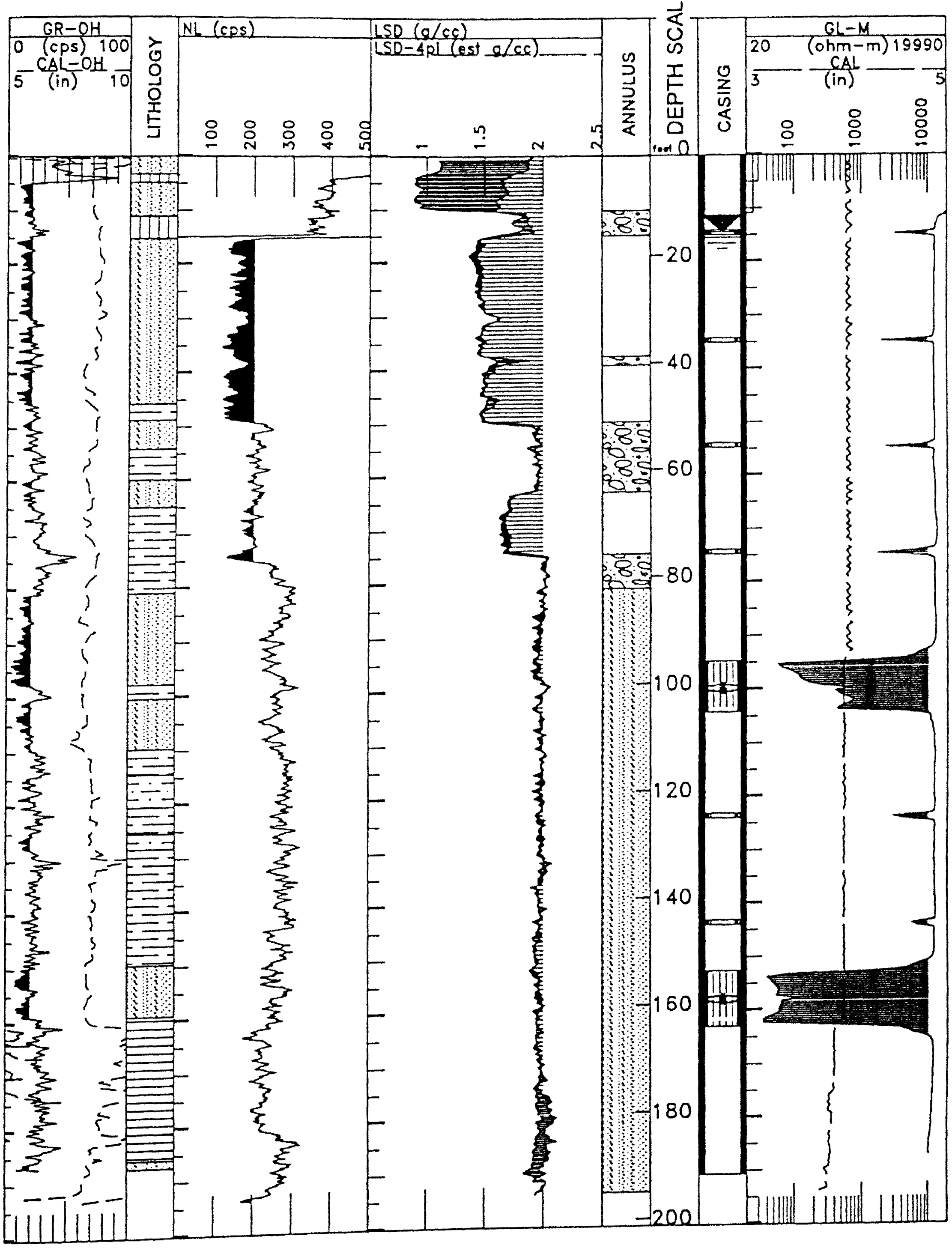
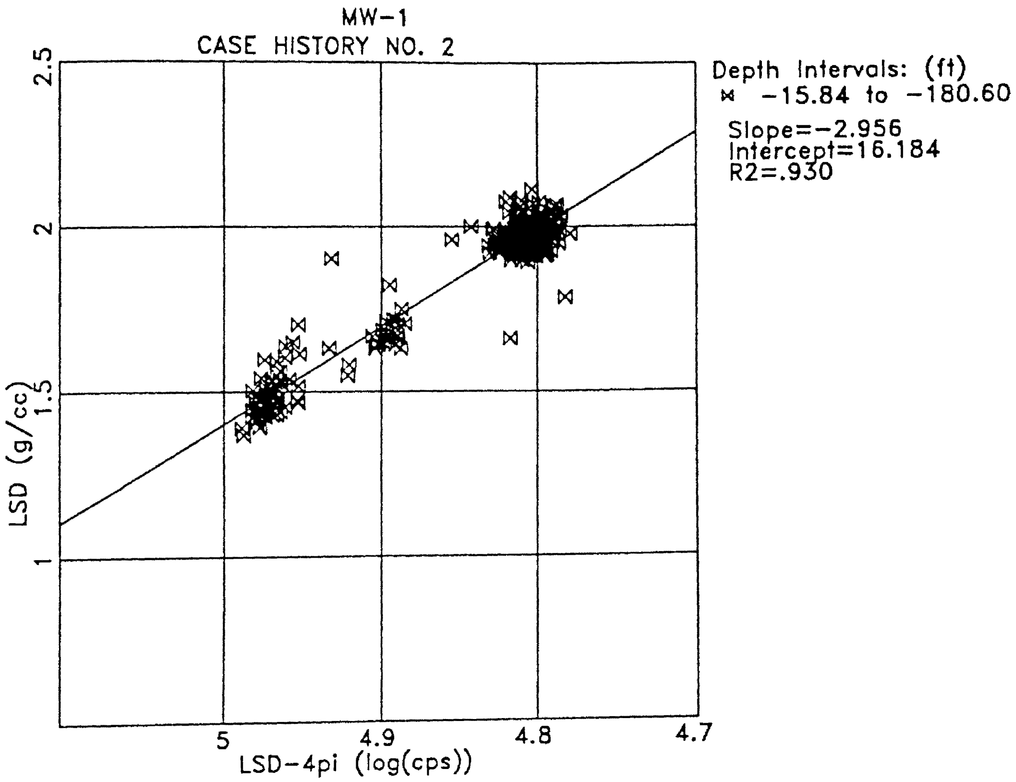


Figure 33. Geophysical Well Logs, Case History No. 2, Monitoring Well MW-1

shown in the graphic column of Figure 33 labelled "LITHOLOGY". This interpretation is consistent with generalized lithologic descriptions provided by the wellsite geologist. Hole enlargement (washout) below 160 feet creates some uncertainty regarding log interpretations below that depth.

Region III. The annular space was interpreted using the neutron log (NL), omnidirectional density (LSD-4pi), and side-collimated density (LSD) logs. The omnidirectional density log was calibrated to units of grams per cubic centimeter using the calibration technique developed in Case History No. 1 (Figure 34). The wellsite geologist described the types of annular materials used. Annular materials shown in the graphic column of Figure 33 labelled "ANNULUS" are explained in Table 9.



CALIBRATION EQUATION

LSD-4pi (est g/cc) = -2.956 [LSD-4pi (log(cps))] + 16.184

Figure 34. Calibration for Long-Spacing Omnidirectional Density, Case History No. 2, Monitoring Well MW-1

TABLE 9

REGION III INTERPRETATION FOR CASE HISTORY NO. 2
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	81.0	drill cuttings and water-filled voids	Apparent densities of 1.46 to 1.68 g/cc (LSD), and decreased neutron log counts indicate water-filled voids. Apparent densities of 1.93-2.0 g/cc (LSD) indicate cuttings. The relatively homogeneous low-density zones are interpreted to represent significant void spaces. Separation of the LSD and LSD-4pi traces above the water level results from the calibration of the LSD-4pi to the LSD response below the water table.
		bentonite pellets	Pellets shown in the as-built drawing are missing. No increase in gamma-ray counts in cased-hole logs as compared to open-hole logs. No high porosity zones indicated by neutron log.
81.0	194.0	sand	Note the separation of the LSD-4pi and LSD logs below 175 feet. The sand pack may be irregularly distributed in that interval, or the casing may not be centered in the borehole. The borehole washouts documented by the open-hole caliper log may have contributed to such heterogeneities. Above 175 feet, the sand pack appears uniform. Apparent density of 1.98 g/cc (LSD).

Region II. The well casing and screen were interpreted using the medium-spaced, or 55" guard log (GL-M) and the single-arm caliper log. The wellsite geologist described the casing, well screen, and centralizers used. Details of the well casing and related construction shown in the graphic column of Figure 33 labelled "CASING" are explained in Table 10.

TABLE 10

REGION II INTERPRETATION FOR CASE HISTORY NO. 2
MONITORING WELL MW-1

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
14.6	94.7	PVC casing	No GL-M response above water level at 14.5 feet. No defects evident (GL-M). Couplings at 14.6, 34.7, 54.4, and 74.4 feet.
94.7	104.3	slotted PVC casing	Low apparent resistivity (GL-M). High-resistivity spike (GL-M) at 99.8 feet may be response to steel centralizer or joint between two five-foot screen sections, or some combination. Unique interpretation not possible without field notes.
104.3	152.6	PVC casing	No defects evident, based on the GL-M. Couplings at 123.5 and 143.5 feet.
152.6	163.0	slotted PVC casing	Slotted interval is evident on GL-M. High-resistivity spike (GL-M) at 157.9 feet may be response to steel centralizer or joint between two five-foot screen sections, or some combination. Unique interpretation not possible without field notes.
163.0	190.0	PVC casing	No couplings or defects evident (GL-M).

The guard log has the characteristic of sometimes producing horns at zone boundaries. The horns or spikes at the upper and lower margins of the slotted intervals may be responses to couplings. However these spikes may be related to tool configuration relative to the thickness of the slotted intervals.

Discussion of Case History No. 2

The depth of the upper screened interval was four feet below the as-built depth and the depth of the lower screened interval was three feet below the as-built depth as reported by the wellsite geologist. The bentonite seal is missing. Significant water-filled voids are evident in the annulus above 80 feet.

The wellsite geologist was interviewed to determine the cause of the differences in field notes and the actual well construction as determined by geophysical well logs. The wellsite geologist stated that the casing had sunk several feet into the borehole. This may have occurred because the casing had not been landed on bedrock or competent backfill or because annular materials had not bonded to the casing adequately to hold the casing in place. Additional casing stickup was added at the surface after the sinking occurred, but was not reflected in the field notes. This explains the discrepancy between the geophysical well log depths and the depths provided in the field notes.

The designed bentonite seal is missing, perhaps due to the lodging of bentonite pellets or chips within the annulus before they reached the desired depth. The method of emplacement for the bentonite seal is not known.

Case History No. 3

Background

Case History No. 3 is an analysis of a published case history (Yearsley, Crowder, and Irons, 1991). Yearsley, Crowder, and Irons used density logs to demonstrate that cross-aquifer flow within the annulus is possible for several example wells at an unspecified site or sites. Yearsley, Crowder, and Irons conducted physical modeling experiments to determine the responses of their specific density tool to various annular materials. One of the examples from that paper, a monitoring well designated (field example) FE-1, is reevaluated here.

Mr. Crowder graciously provided the digital data for FE-1. Because of a client-contractor confidentiality agreement, hydrogeologic background information was limited to limited to the published summary. Yearsley, Crowder, and Irons made interpretations that suggest some knowledge of the site geology. Their determination that the density response indicates the presence of alluvium in several intervals, either due to caving or eccentered casing, was apparently based on a knowledge of the local geology, well installation details, and the results of their modeling experiments. The published interpretations significantly influenced the interpretations made herein.

COLOG, Inc. logging equipment produced analog data downhole which was converted to digital data in the logging unit. Robert Crowder provided all logs in digital format. Dual-spacing, side-collimated density logs and an omnidirectional density log were acquired by COLOG, Inc. using analog tools with analog to digital conversion in the logging unit at the surface. The logs are of excellent quality.

Pre-Logging Construction Summary

Field example FE-1 was constructed of 4-inch diameter PVC casing and screen installed in a nine-inch diameter borehole. The approximate depth of the slotted interval was from 170 feet to 180 feet. Approximately 20 feet of sand pack was installed from total depth to 170 feet. A five-foot interval described as a bentonite slurry seal was reported from 170 feet to 165 feet. The bentonite slurry may have been installed directly above the sand pack, without an intervening interval of bentonite granules, chips, or pellets. The completion design indicates the presence of cement/bentonite grout from 165 feet to the surface.

Geophysical Well Log Analysis, Field Example FE-1

Well construction and integrity for monitoring well FE-1 was evaluated using cased-hole logs. Because of the limited suite of logs, only region of investigation III is evaluated.

Region III. The annular space was interpreted using the omnidirectional density (LSD-4pi), and dual-spacing, side-collimated density logs (LSD and SSD). Two analytical approaches were used to make possible a more systematic analysis than that provided by Yearsley, Crowder, and Irons. The omnidirectional density log was calibrated to the long-spacing density response using the linear regression approach developed for the experimental control wells. The resulting calibrated omnidirectional density was compared to the long-spacing density response to locate radial heterogeneities in the annular space. In addition, the density traces for the long-spacing density log, above and below the water level, were correlated with the reported annular materials.

The correlation between the omnidirectional density response and the long-spacing density response was poor over the entire well, having a goodness-of-fit (R^2) value of 0.669 (Figure 35). The data were then segregated into two sets, data above the water level and data below the water level. The R^2 values were significantly improved after segregating the data as described. The R^2 above the water level was 0.915 (Figure 36). The R^2 below the water level was 0.966 (Figure 37). The omnidirectional density log was calibrated in two stages, using the respective regression coefficients for data above and below the water.

Annular materials are shown in the graphic column of Figure 38 labelled "ANNULUS", and are interpreted in Table 11. The water level is shown in the graphic column of Figure 38 labelled "CASING". The water level within the casing is indicated by a pronounced shift in density log responses towards higher counts per second and lower density.

Discussion of Case History No. 3

The initial cross plot used to calibrate the omnidirectional density log (Figure 35) clearly showed the effect of the water level in the casing (Figure 38). Two distinct log-linear trends are evident due to a shift of the omnidirectional density data at the water level. The use of the omnidirectional density vs. long-spacing, side-collimated density cross plot to segregate data into subsets for additional analysis is a valuable technique.

The omnidirectional density log as presented by Yearsley, Crowder, and Irons (see the omnidirectional density track which has units of counts per second) is difficult to interpret intuitively, and impossible to compare quantitatively with the side-collimated density curves expressed in units of g/cc.

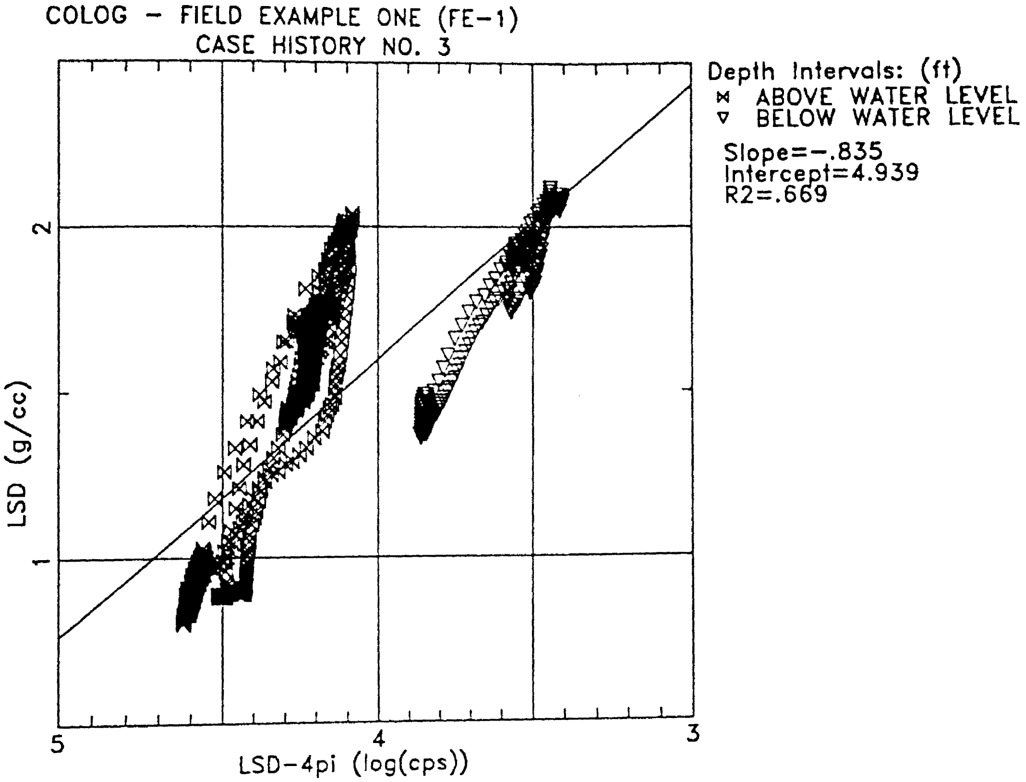
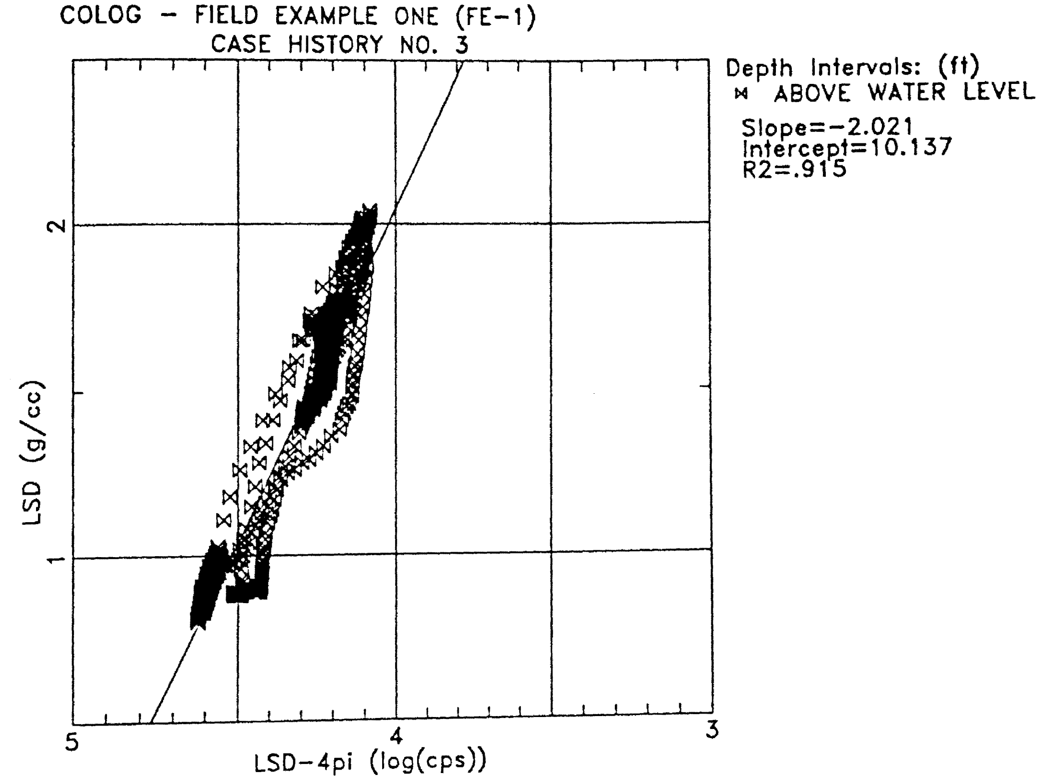


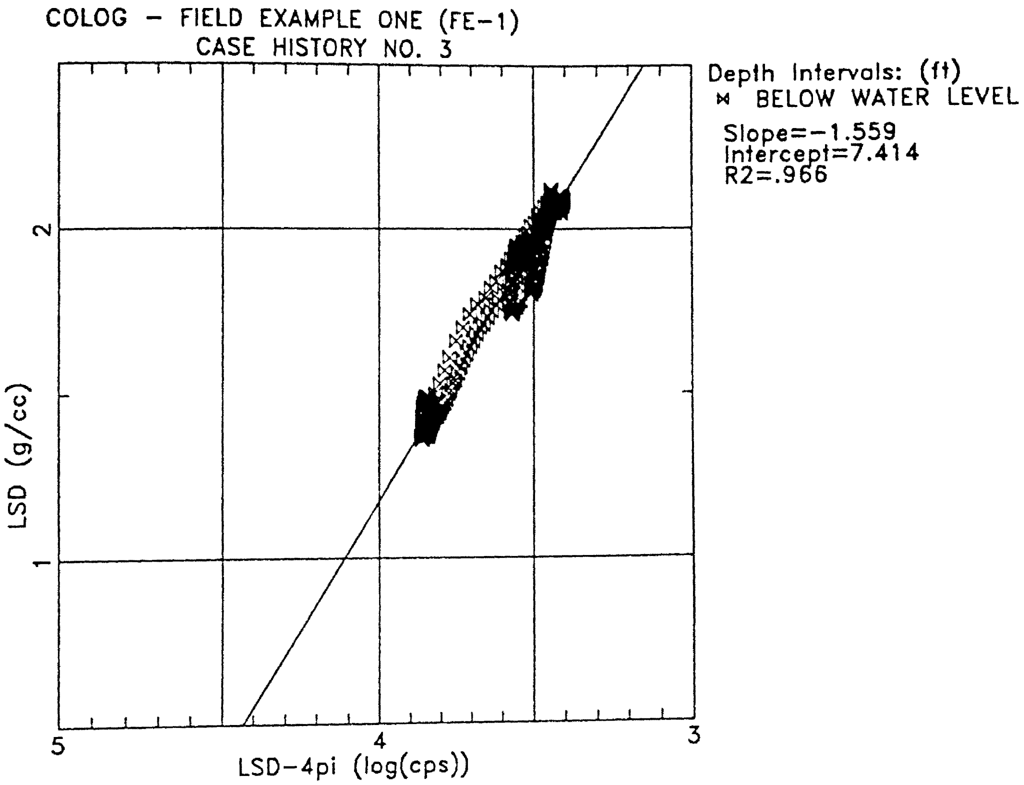
Figure 35. Curve Fit for Long-Spacing Omnidirectional Density, Case History No. 3, Field Example FE-1, All Intervals



CALIBRATION EQUATION

LSD-4pi (est g/cc) = -2.021 [LSD-4pi (log(cps))] + 10.137

Figure 36. Calibration for Long-Spacing Omnidirectional Density, Case History No. 3, Field Example FE-1, Above Water Level



CALIBRATION EQUATION

LSD-4pi (est g/cc) = -1.559 [LSD-4pi (log(cps))] + 7.414

Figure 37. Calibration for Long-Spacing Omnidirectional Density, Case History No. 3, Field Example FE-1, Below Water Level

Well Name: COLOG - FIELD EXAMPLE ONE (FE-1)
File Name: CH3 FE1c
Location: CASE HISTORY NO. 3
Elevation: 0 Reference: Unknown

4-inch PVC casing and screen in 9-inch borehole
After Yearsley, Crowder, and Irons (1991)

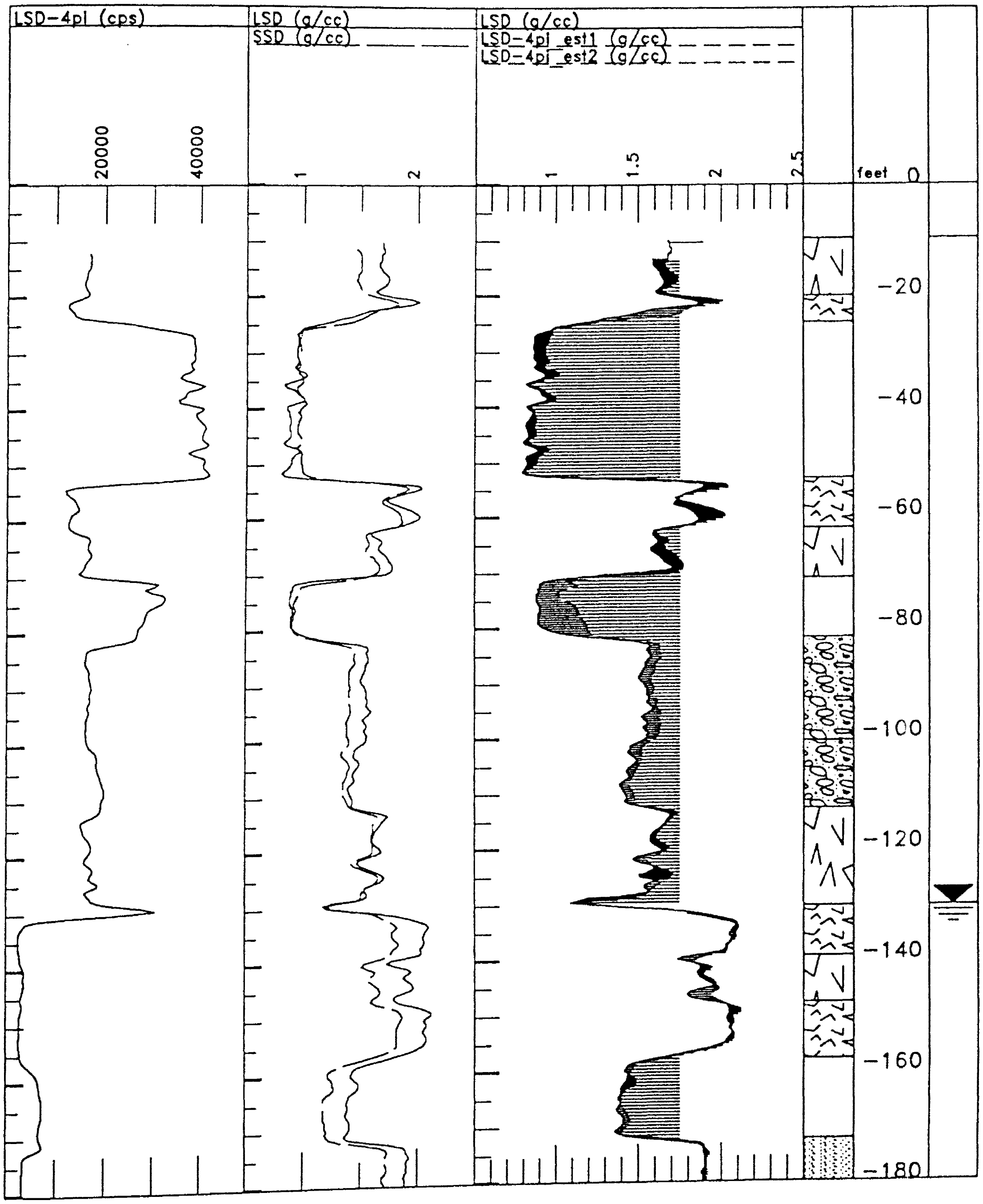


Figure 38. Geophysical Well Logs, Case History No. 3, Field Example FE-1

TABLE 11

REGION III INTERPRETATION FOR CASE HISTORY NO. 3
FIELD EXAMPLE FE-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	10.4		Not logged.
10.4	24.9	poor cement and cement	Poor cement from 10.4'-20.1'; apparent density of 1.69 g/cc (LSD), 1.49 g/cc (SSD). Cement from 20.1'-24.9'; apparent density of 1.87 g/cc (LSD), 1.77 g/cc (SSD).
24.9	53.0	air-filled void	Apparent density of 0.92 g/cc (LSD), 0.98 g/cc (SSD).
53.0	71.1	cement and poor cement	Cement from 53.0'-62.1'; apparent density of 1.87 g/cc (LSD), 1.78 g/cc (SSD). Poor cement from 62.1'-71.1'; apparent density of 1.65 g/cc (LSD), 1.58 g/cc (SSD).
71.1	81.9	air-filled void	Apparent density of 0.92 g/cc (LSD), 0.95 g/cc (SSD).
81.9	112.7	caved alluvium	Apparent density of 1.44-1.53 g/cc (LSD), 1.37-1.39 g/cc (SSD).
112.7	130.3	poor cement	Apparent density of 1.58 g/cc (LSD), 1.54 g/cc (SSD).
130.3	157.9	cement and poor cement	Cement from 130.3'-139.3', 147.9'-157.9'; apparent density of 1.97-2.00 g/cc (LSD), 1.74-1.77 g/cc (SSD). Poor cement from 139.3'-147.9'; apparent density of 1.88 g/cc (LSD), 1.61 g/cc (SSD).
157.9	172.3	water-filled void	Lower density than bentonite grout slurry in Case History No. 1, CW-2; comparable density to water-filled voids in Case History No. 2, MW-1; Apparent density of 1.42 g/cc (LSD), 1.22 g/cc (SSD)
172.3	180.0	sand pack	The sand pack appears uniformly distributed based on the similarity of the LSD and LSD-4pi logs.

The calibration of the omnidirectional density log trace to g/cc enables the interpreter to make intuitive interpretations, and makes possible a quantitative comparison of the omnidirectional density and long-spacing, side-collimated density log traces. Thus, radial heterogeneity in the annular space is indicated by separation of the omnidirectional density and long-spacing, side-collimated density curves. Significant log separation is believed to represent a mixture of materials in the annular space which have different densities. Uniform annular materials and uniform void space both exhibit relatively little separation between the omnidirectional density and long-spacing, side-collimated density log traces.

For well FE-1, two intervals exhibit a greater separation of omnidirectional density and long-spacing, side-collimated density log traces than do other zones. These zones are interpreted by Yearsley, Crowder, and Irons to contain alluvium (112.7 to 81.9 feet) and void space (81.9 to 71.1 feet). Therefore the present interpretation supports this portion of the published interpretation.

In order to analyze the density data in more detail, several density traces (similar to smoothed histograms) were plotted. The density trace for the total well (Figure 39) proved difficult to interpret, because as many as six peaks are suggested. When the density data from above and below the water level are segregated, the respective density traces become more decipherable (Figure 40). It becomes much easier to assign annular materials to their respective peaks on the density trace, when data from above and below the water level are considered separately.

The density traces representing annular materials below and above the water level are very similar. Each has an isolated peak at the low end of the density (g/cc) range and a cluster of peaks in the higher density range. This similarity raised the possibility that the interval interpreted as bentonite slurry by Yearsley, Crowder, and Irons may be water-filled void space.

For comparison, monitoring wells which were similarly constructed of four-inch diameter PVC were selected from other case histories. Density traces were plotted for materials below the water level for control well CW-2, Case History No. 1, and for monitoring well MW-1, Case History No. 2. Figure 41 compares the density trace for control well CW-2 with the density trace for field example FE-1. Figure 42 compares the density trace for monitoring well MW-1 with the density trace for field example FE-1.

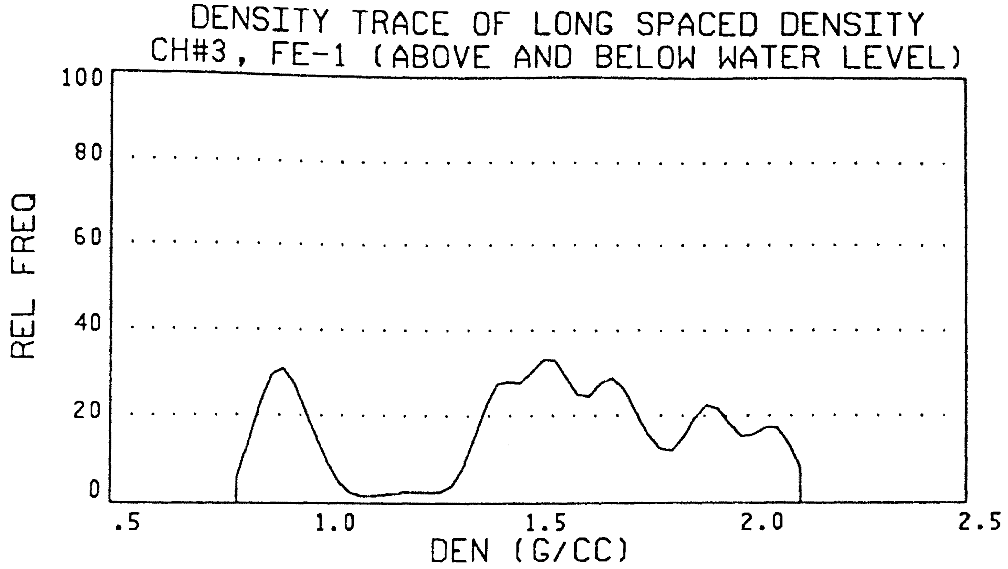
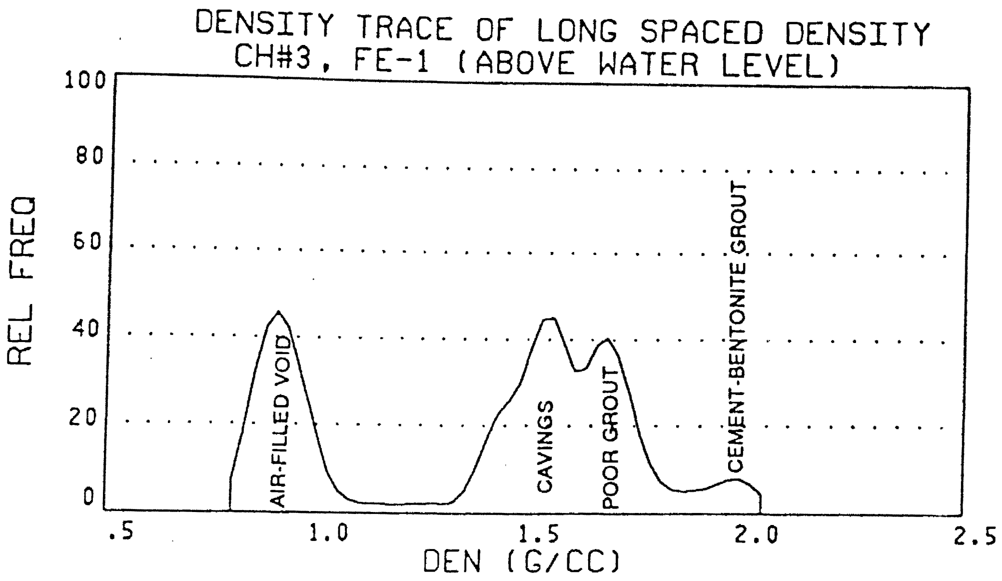


Figure 39. Density Trace, Long-Spacing Density, Case History No. 3, Field Example FE-1, All Intervals



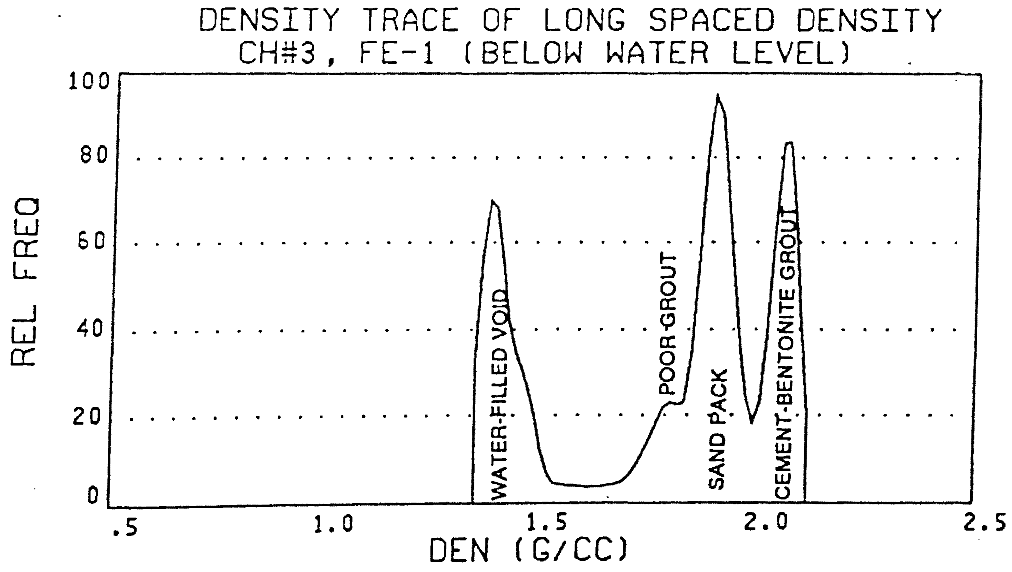


Figure 40. Comparison of Density Traces, Long-Spacing Density, Case History No. 3, Field Example FE-1, Above and Below Water Level

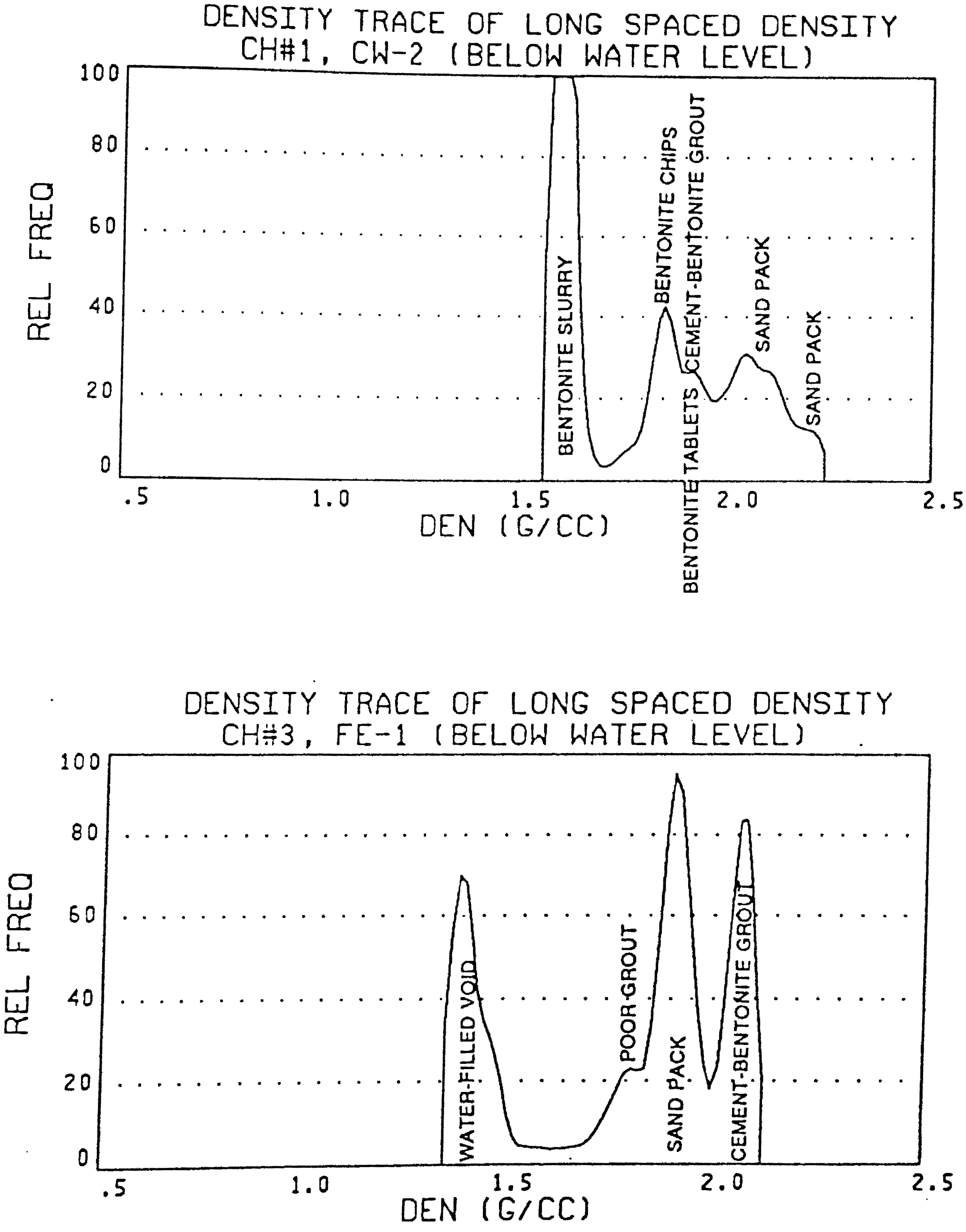
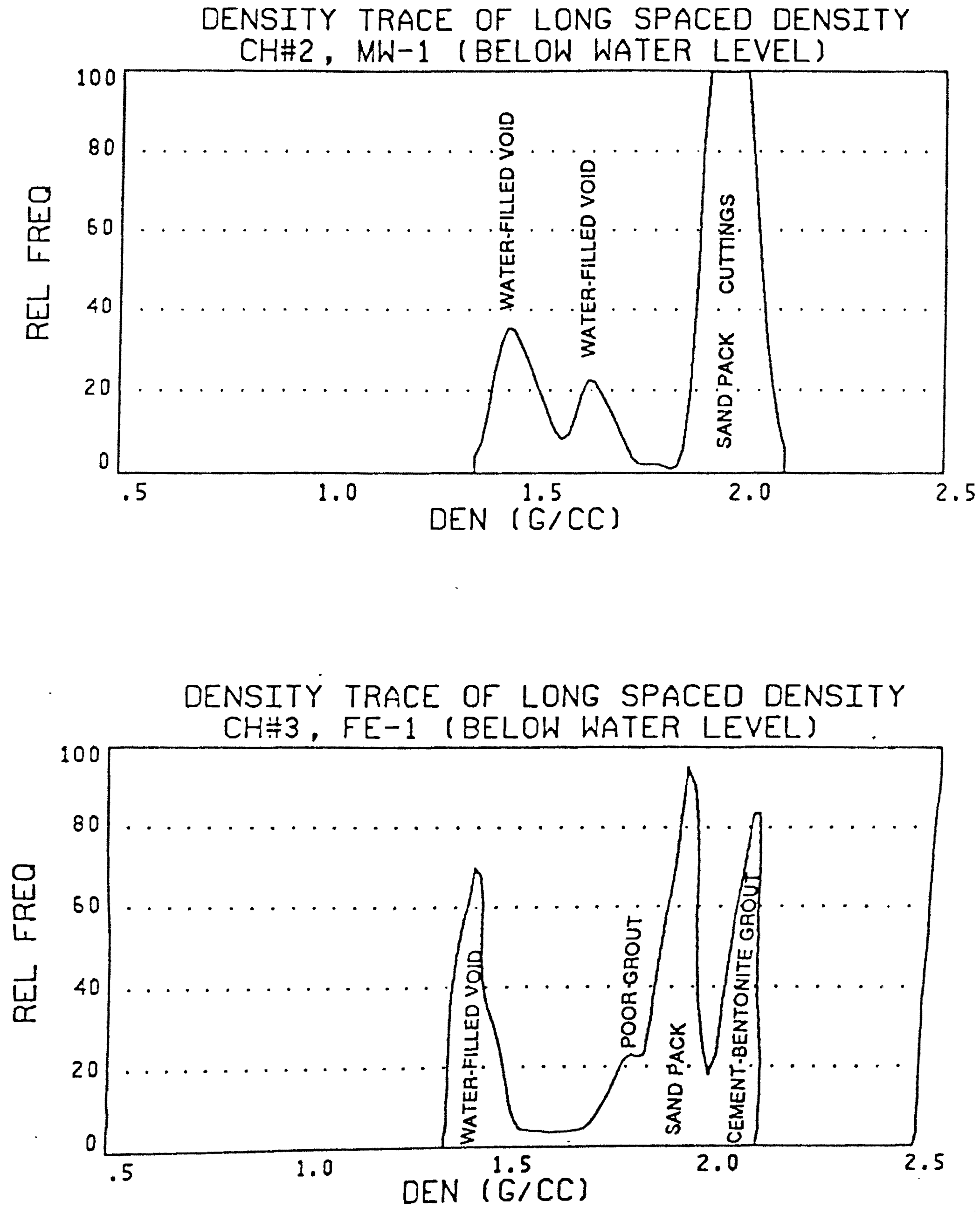


Figure 41. Comparison of Density Traces, Long-Spacing Density, Case History No. 1, Control Well CW-2, and Case History No. 3, Field Example FE-1



DENSITY TRACE OF LONG SPACED DENSITY
CH#2, MW-1 (BELOW WATER LEVEL)

DENSITY TRACE OF LONG SPACED DENSITY
CH#3, FE-1 (BELOW WATER LEVEL)

Figure 42. Comparison of Density Traces, Long-Spacing Density, Case History No. 2, Monitoring Well MW-1, and Case History No. 3, Field Example FE-1

Because the boreholes in which the three wells were installed vary in diameter, it is possible that the long-spacing density logs could be differentially influenced by the respective formations. Control well CW-1 was drilled with a 8.5-inch bit. Monitoring well MW-1 was drilled with an eight-inch bit. Well FE-1 was drilled with a nine-inch bit.

The zone in FE-1 in which the bentonite slurry seal was reportedly installed has an apparent density of 1.42 g/cc (LSD), an apparent density less than that of the bentonite slurry seals in control well CW-2 (1.57-1.62 g/cc, LSD). Figure 41 compares the density traces for FE-1 and CW-2. The possible bentonite slurry seal zone in well FE-1 has an apparent density slightly less than the water-filled voids in monitoring well MW-1. The water-filled voids in MW-1 have apparent densities of 1.45-1.60 g/cc, probably depending upon the proportions of solids and cuttings present. Figure 42 compares the density traces for FE-1 and MW-1.

This reinterpretation of the data is less subjective than the original interpretation by Yearsley, Crowder, and Irons as a result of the classification of annular materials using the density trace method. This graphical analysis method represents an increased level of effort which is justified when interpretations of annular materials using the normal density log presentation prove difficult.

Case History No. 4

Background

Case History No. 4 results from the acquisition of logs from seven wells at a location which is confidential. Two of the wells from the site of Case History No. 4 were selected to illustrate log responses to PTFE casing and screen. Fluoropolymers such as PTFE are sometimes used for monitoring well casing and screen which may be subject to chemical attack. Case History No. 4 is the only case history developed here which provides examples of log responses to PTFE casing and screen.

Century Geophysical Corporation logging equipment produced digital data downhole. The log quality was excellent, but only the gamma-ray (GR), neutron (NL), and omnidirectional density (LSD-4pi) logs were available for interpretation. The two-inch casing diameter restricted the types of tools which could be used. In addition, electric logs were not available to evaluate Region of Investigation II.

Well construction data for both wells were provided by the wellsite geologist. These data were used in conjunction with geophysical well log data to complete the casing interpretations.

Pre-Logging Construction Summary

The monitoring wells designated MW-1 and MW-2 were installed in boreholes 7.25 inches in diameter. For each well, the reported depth of the borehole was the same as the reported depth of the casing string. The wells were constructed using schedule 80, two-inch diameter, flush-threaded well screen and casing. A one foot end cap or well footer was placed at the base of the casing string, with a steel centralizer attached at the center of the well footer. Above the well footer, a ten-foot section of 0.020-inch slotted PTFE well screen was reportedly installed. According to the wellsite geologist, PTFE casing extends from immediately above the well screen to approximately ten feet above the water level. A steel centralizer was attached to the PTFE casing, reportedly one foot above the top of the well screen. PVC casing was installed from the top of the PTFE casing to the surface. It is not known whether the casing string was suspended at the surface or whether the weight of the casing string was on the PTFE section when annular materials were emplaced.

Geophysical Well Log Analysis, Monitoring Well MW-1

Three logs were available to evaluate monitoring well MW-1, a gamma-ray log (GR), a neutron log (NL), and an omnidirectional density log (LSD-4pi). The location of the upper steel centralizer is not shown at the reported depth, but is speculatively located as described below.

Region IV. The GR log was used to interpret sandstone and shale lithologies as illustrated in the column labelled "LITHOLOGY", Figure 43. Sample descriptions were unavailable, but geologic maps of the general area indicate that sandstone and shale are the predominant lithologies.

Region III. The neutron and omnidirectional density logs were used to interpret annular materials indicated in the graphic column labelled "ANNULUS", Figure 43. The log interpretations for Region III are described in Table 12.

Well Name: MW-1
File Name: CH4 MW1
Location: CASE HISTORY NO. 4
Elevation: 0 Reference: GL
PVC & PTFE casing, PTFE screen, schedule 80, 2-inch
Annular materials: sand, bentonite pellets, cement/bentonite

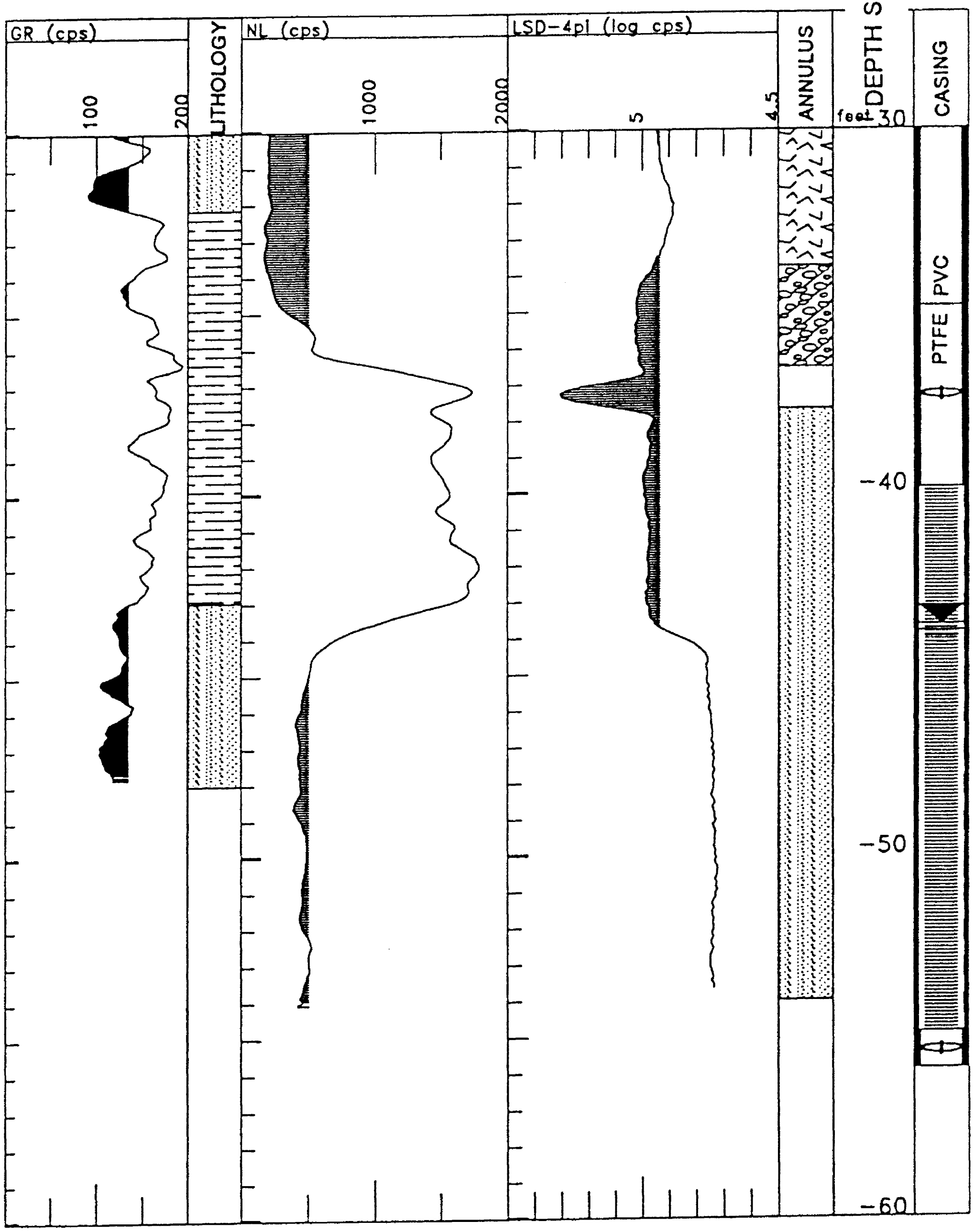


Figure 43. Geophysical Well Logs, Case History No. 4, Monitoring Well MW-1

TABLE 12

REGION III INTERPRETATION FOR CASE HISTORY NO. 4
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
30.0	33.8	cement	Highest density (lowest cps, LSD-4pi) in annulus.
33.8	36.6	bentonite pellets	Lower density (higher cps, LSD-4pi) than overlying cement. Higher water content than underlying sand pack (NL).
36.6	37.7	air-filled void	Lowest apparent density (highest cps, LSD-4pi) in well. Low neutron adsorption (high cps).
37.7	54.0	sand pack	The sand pack appears uniformly distributed based on the consistent LSD-4pi and NL responses. The water level causes a shift in the LSD-4pi and NL logs at 43.7 feet.
54.0	56.0		Not logged. Total depth estimated from logged top of PTFE casing and casing measurements by the wellsite geologist.

Region II. The neutron and omnidirectional density logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 43. The depth of the lower centralizer, well footer, and screened interval are inferred from the reported casing lengths and the interpreted top of the PTFE casing section. The interpretations for Region II are described in Table 13.

The log responses do not directly indicate the metal centralizer which is attached to the PTFE casing above the well screen. However, the centralizer is inferred to be the cause of the void space shown, because it may have caused the bentonite pellets to bridge off at that depth.

TABLE 13

REGION II INTERPRETATION FOR CASE HISTORY NO. 4 MONITORING WELL MW-1

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
30.0	34.9	PVC casing	No electric logs to determine condition. NL counts are less than in PTFE casing (higher thermal neutron capture cross section of PVC).
34.9	39.9	PTFE casing	Interval of five feet based on field measurements. Centralizer not directly detected, but reported in field notes and possibly cause of void space as indicated in Region III evaluation.
39.9	54.9	slotted PTFE	Top of slotted interval is not evident on geophysical logs. Field notes and measurements used to estimate location of slots beginning five feet below PTFE casing.
54.9	55.9	PTFE well footer	Logs not deep enough to interpret. One-foot footer with centralizer reported in field notes.

Geophysical Well Log Analysis, Monitoring Well MW-2

The same three logs which were available for monitoring well MW-1 were also available for MW-2, a gamma-ray log (GR), a neutron log (NL), and a omnidirectional density log (LSD-4pi). The location of the upper steel centralizer is not shown at the reported depth, but is speculatively located as described below.

Region IV. The gamma-ray (GR) log was used to interpret sandstone and shale lithologies as illustrated in the column labelled "LITHOLOGY", Figure 44. Sample descriptions were unavailable, but geologic maps of the general area indicate that sandstone and shale are the predominant lithologies.

Well Name: MW-2
File Name: CH4 MW2
Location: CASE HISTORY NO. 4
Elevation: 0 Reference: TOC
PVC & PTFE casing, PTFE screen, schedule 80, 2-inch
Annular materials: sand, bentonite pellets, cement/bentonite grout

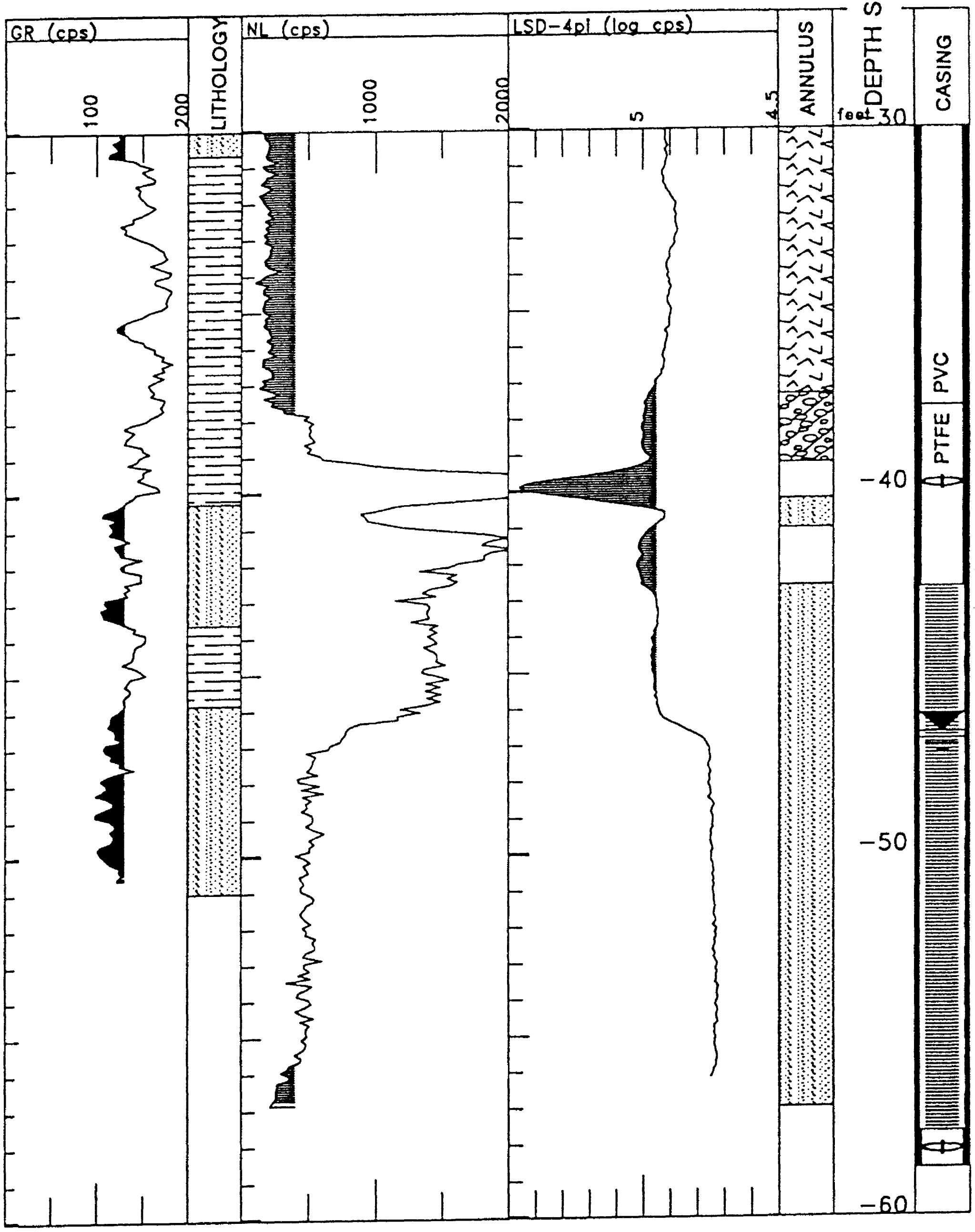


Figure 44. Geophysical Well Logs, Case History No. 4, Monitoring Well MW-2

Region III. The neutron (NL) and omnidirectional density (LSD-4pi) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 44, and described in Table 14.

The log responses do not directly indicate the metal centralizer which is attached to the PTFE casing above the well screen. However, the centralizer is inferred to be the cause of the void space shown, because it may have caused the bentonite pellets to bridge off at that depth.

TABLE 14

REGION III INTERPRETATION FOR CASE HISTORY NO. 4
MONITORING WELL MW-2

DEPTH (FEET)		MATERIAL	COMMENTS
TOP	BOTTOM		
30.0	37.3	cement	Highest density (lowest cps, LSD-4pi) in annulus.
37.3	39.2	bentonite pellets	Lower density (higher cps, LSD-4pi) than overlying cement. Higher water content than underlying sand pack (NL).
39.2	40.6	air-filled void	Lowest apparent density (highest cps, LSD-4pi) in well. Low neutron adsorption (high cps).
40.6	41.3	sand pack	Apparent density (LSD-4pi) similar to sand pack, but NL response similar to bentonite. May contain cavings or bentonite in addition to sand.
41.3	42.6	air-filled void	Lowest apparent density (highest cps, LSD-4pi) in well. Low neutron adsorption (high cps).
42.6	54.0	sand pack	The sand pack appears uniformly distributed based on the consistent LSD-4pi and NL responses. The water level causes a shift in the LSD-4pi and NL logs at 46.7 feet.
54.0	58.7		Not logged. Total depth estimated from logged top of PTFE casing and casing measurements by the wellsite geologist.

Region II. The neutron (NL) and omnidirectional density (LSD-4pi) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 44. The interpretations are described in Table 15. The depth of the lower centralizer, well footer, and screened interval are inferred from the reported casing lengths and the interpreted top of the PTFE casing section.

The neutron log (NL) shift to lower counts per second above a depth of 37.7 feet is believed to reflect the increased thermal neutron capture cross section of the PVC as compared to the PTFE casing.

The log responses do not directly indicate the metal centralizer which is attached to the PTFE casing above the well screen. However, the centralizer is inferred to be the cause of the void space shown, because it may have caused the bentonite pellets to bridge off at that depth.

TABLE 15

REGION II INTERPRETATION FOR CASE HISTORY NO. 4
MONITORING WELL MW-2

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
30.0	37.7	PVC casing	No electric logs to determine condition. NL counts are less than in PTFE casing (higher thermal neutron capture cross section of PVC).
37.7	42.7	PTFE casing	Interval of five feet based on field measurements. Centralizer not directly detected, but reported in field notes and possibly cause of void space as indicated in Region III evaluation.
42.7	57.7	slotted PTFE	Top of slotted interval is not evident on geophysical logs. Field notes and measurements used to estimate location of slots beginning five feet below PTFE casing.
57.7	58.7	PTFE well footer	Logs not deep enough to interpret. One-foot footer with centralizer reported in field notes.

Discussion of Case History No. 4

The distinction between the PVC and PTFE casing is the unique feature of this case history. The high thermal neutron capture cross section of the chlorine in the PVC casing resulted in a marked contrast between PVC and PTFE on the neutron log (NL) trace. The interpretations of void spaces or channeling are made with confidence, but the size of the voids are unknown. Other interpretations are inferred, using as-built information provided by the wellsite geologist.

Case History No. 5

Background

Case History No. 5 results from geophysical well logging conducted at a confidential location. One of the wells from the site of Case History No. 5 was selected to illustrate log responses to air-filled void space in two-inch diameter steel casing. In addition, Case History No. 5 is the only case history developed during this research which provides examples of log responses in two-inch diameter steel casing and screen.

Century Geophysical Corporation logging equipment produced digital data downhole. The log quality was excellent, but only the gamma-ray (GR), neutron (NL), and dual-spacing omnidirectional density logs (LSD-4pi, SSD-4pi) were available for interpretation. The two-inch casing diameter restricted the types of tools which could be used. In addition, the electric logs were not of use in the steel casing.

Drilling cuttings and well construction data for monitoring well MW-1 were provided by the wellsite geologist. These data were used in conjunction with geophysical well log data to develop interpretations.

Pre-Logging Construction Summary

Monitoring well MW-1 was installed in a borehole 10.25 inches in diameter using a hollow-stem auger. The wells were constructed using two-inch diameter, flush-threaded, stainless steel well screen and casing. A two-foot sediment trap was reported at the base of the casing string. Above the well footer is a ten-foot section of 0.020-slotted well screen.

Geophysical Well Log Analysis, Monitoring Well MW-1

Well construction and integrity for monitoring well MW-1 was evaluated using cased-hole logs. All logs were run by Century Geophysical Corporation, were obtained in digital format, and were of excellent quality. Each region of investigation is evaluated as shown in

Figure 45. This case history was unique in that a qualitative density log calibration was performed to using only two calibration points, one of which was not well suited to the site-specific conditions.

Density Tool Calibration. Omnidirectional density tools are not generally calibrated, although work is reportedly under way in Australia to develop a mudcake-compensated omnidirectional density tool (Hallenburg, 1993). For undetermined reasons, the omnidirectional density tool was calibrated in a water tank and in an aluminum calibration block prior to the logging at Case History No. 5. The log header on the field print for monitoring well MW-1 included the water tank and aluminum block calibration data. This afforded an opportunity to perform an approximate calibration of both the long- and short-spacing omnidirectional density logs (LSD-4pi, SSD-4pi) to units of grams per cubic centimeter.

The calibration was inadequate for several reasons. First, only two points were used for the calibration, whereas at least three points are recommended (Hallenburg, 1993). In addition, the aluminum block was designed for side-collimated tools. The diameter of the water-filled borehole in the aluminum block is 5.125 inches, which is not significant for the side-collimated tool, but is critical to the omnidirectional tool calibration. The dissimilarity of the 5.125-inch diameter aluminum block and the two-inch diameter steel casing also contributes to the error in this calibration.

The density response curve is linear over most of the range of densities, when density is plotted versus the logarithm of counts per second. The response curve may be slightly curved near the low-density and high-density extremes. The two calibration points were the water calibration tank and the aluminum calibration block described above. The water tank calibration used the value of 1.106 g/cc for the density of water. The aluminum calibration block has a density of 2.612 g/cc, although this value is too high for the omnidirectional tool calibration because of the influence of water in the 5.125-inch diameter hole. Both water and aluminum densities are the apparent densities which would be measured prior to correcting for Z/A.

Well Name: MW-1
File Name: CH5 MW1
Location: CASE HISTORY NO. 5
Elevation: 0 Reference: GL

Stainless steel casing & screen, 2-inch diameter
Annular materials: sand, bentonite pellets, Volclay, cement w/12% bentonite

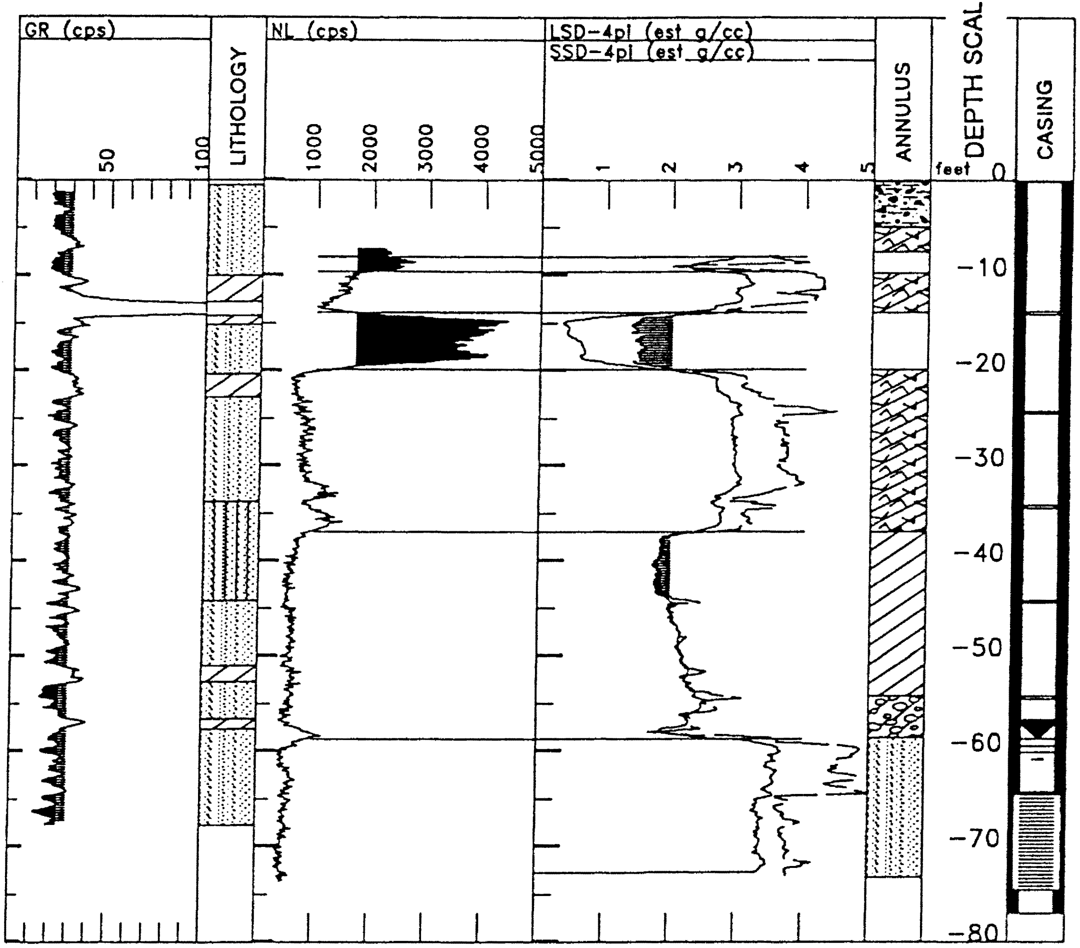


Figure 45. Geophysical Well Logs, Case History No. 5, Monitoring Well MW-1

The omnidirectional density channel recorded 45,224 cps in a water tank and 10,311 cps in an aluminum block. The SSD-4pi channel recorded 163,186 cps in a water tank and 127,865 cps in an aluminum block. Assuming a log-linear relationship between counts per second and grams per cubic centimeter, the equations used to calibrate the density logs were:

- LSD-4pi (est g/cc) = $-2.34555 \log_{10}$ LSD-4pi (cps) + 12.02538; and
- SSD-4pi (est g/cc) = $-14.21667 \log_{10}$ SSD-4pi (cps) + 75.21298.

Region IV. The gamma-ray (GR) log was used to interpret lithology as illustrated in the column labelled "LITHOLOGY", Figure 45. The gamma-ray anomaly at a depth of approximately 13 feet may represent naturally-occurring secondary mineralization in an organic-rich clay. A less likely interpretation of the anomaly is a zone of naturally-occurring secondary mineralization at a perched water table. Cuttings descriptions indicate that sand and clay are the predominant lithologies.

Region III. The neutron log (NL) and long- and short-spacing density logs (LSD-4pi, SSD-4pi) were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 45. Annular materials shown in the graphic column of Figure 45 labelled "ANNULUS" are explained in Table 16.

TABLE 16

REGION III INTERPRETATION FOR CASE HISTORY NO. 5
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	8.0		Not logged.
8.0	9.7	channels or voids	Low apparent density and high air-filled porosity (NL).
9.7	13.9	cement with 12% bentonite	Higher apparent density (LSD-4pi, SSD-4pi) than bentonite pellets, comparable or slightly lower density than sand pack.
13.9	19.9	channels or voids	Low apparent density and high air-filled porosity (NL).
19.9	36.9	cement with 12% bentonite	Higher apparent density (LSD-4pi, SSD-4pi) than bentonite pellets, comparable or slightly lower density than sand pack.
36.9	54.2	bentonite grout slurry	Lower apparent density (LSD-4pi, SSD-4pi) than bentonite pellets.
54.2	58.6	bentonite pellets	Lower density (LSD-4pi, SSD-4pi) than sand, higher density than bentonite slurry grout. Interpretation is complicated by coincident water level, and therefore tentative.
58.6	73.2	sand	The sand pack appears uniformly distributed based on the similarity of the long- and short-spacing density logs (LSD-4pi, SSD-4pi). The water level at 58.8' causes a shift in the density logs toward lower density.
73.2	77.1		Not logged.

Region II. The calibrated long- and short-spacing omnidirectional density logs (LSD-4pi, SSD-4pi) were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 45. Interpretations for Region II are described in Table 17. The depth of the well footer is inferred from the reported casing lengths and the interpreted top of the screened interval.

TABLE 17

REGION II INTERPRETATION FOR CASE HISTORY NO. 5
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	8.0		Not logged.
8.0	64.6	2" stainless steel casing	Couplings at 13.8', 24.2', 34.2', 44.2', 54.2', and 64.3' (top of 0.3' coupling) produce sharp high-density spikes on short-spacing density log (SSD-4pi). Density logs offset towards lower density at 58.8' water level.
64.6	73.0	2" stainless steel screen	Both density logs indicate lower density adjacent to well screen.
73.0	76.6		Not logged.

Discussion of Case History No. 5

The calibration of the long-spacing density (LSD-4pi) and short-spacing density (SSD-4pi) logs produces a log in density units, which are more easily understood. Flaws in the calibration method for the omnidirectional density logs and in the normal calibration method for the side-collimated density logs are discussed in Chapter 6.

The density log response to the bentonite slurry grout interval suggests a mechanism for the formation of voids in the annular space. Density stratification apparently occurred in the bentonite slurry grout due to the settling of solids. This would have created a low-density zone near the top of the interval. After emplacement, the relatively dense cement-bentonite grout could have settled into the interval containing low-density bentonite slurry grout, creating a void space within the cement grout interval.

The casing collar locator and the high-resolution density logging tools were too large to run in two-inch diameter casing. Even so, the casing couplings produced high-density spikes on the omnidirectional, short-spacing density trace (SSD-4pi). The spikes are spaced at ten-foot intervals. Because stainless steel casing is often supplied in ten-foot lengths, the uniform ten-foot spacing between density spikes supports this interpretation.

Case History No. 6

Background

Case History No. 6 is based on four wells which were logged to determine well construction and evaluate well integrity. The location of the wells and many details regarding this case history are confidential. Based on the observed well construction and the records of wells drilled in the area, three of the wells are believed to have been former water supply wells which were installed during the 1940's. The fourth well appeared to have been an observation well or a comparatively low-yield water supply well, and is believed to have been installed in 1968.

Century Geophysical Corporation logging equipment produced digital data downhole. The log quality was excellent. The gamma-ray (GR), neutron (NL), dual-spacing, side-collimated density (LSD, SSD), high-resolution density (HRD), casing collar locator (CCL), and caliper (CAL) logs were run with three logging tools. All logging tools were calibrated prior to initiating logging. At each well, a repeat run was made over the total well depth for the dual-spacing density tool.

The gamma-ray (GR) log is the only log which could have been used to interpret lithology. The site of Case History No. 6 is underlain by a complex sequence of gravel, sand, silt, clay, and caliche. No lithologic descriptions were available. Therefore, no lithology is interpreted for the wells in Case History No. 6. A two-component system such as sand/silt and clay could have been interpreted with only the gamma-ray log.

Pre-Logging Construction Summary

The operator of the wells provided few details of well construction, but made several general statements regarding the wells. The wells were said to have been constructed in the mid-1950's. The surface casing was described as 10-inch to 12-inch diameter steel pipe. The operator stated that the water table was approximately 120 feet below ground level. The information provided by the operator proved reasonably accurate for three of the wells, but was not correct for well WS-4.

Well completion records filed with a state agency indicated that the wells were installed in the 1940's (WS-1, WS-2, and WS-3), and in the 1960's (WS-4). Visual inspection of well WS-4 prior to logging revealed a well casing much smaller in diameter (about six inches) than the approximately 12-inch diameter well casings for WS-1, WS-2, and WS-3.

Geophysical Well Log Analysis, Water Supply Well WS-2

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided. However, alternate interpretations are possible, especially for Region II.

Region III. The neutron (NL) and side-collimated, dual-spacing density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 46. Interpretations for Region III are described in Table 18.

Well Name: WS-2
File Name: WS2
Location: CASE HISTORY NO. 6
Elevation: 0 Reference: TOC
Steel Casing

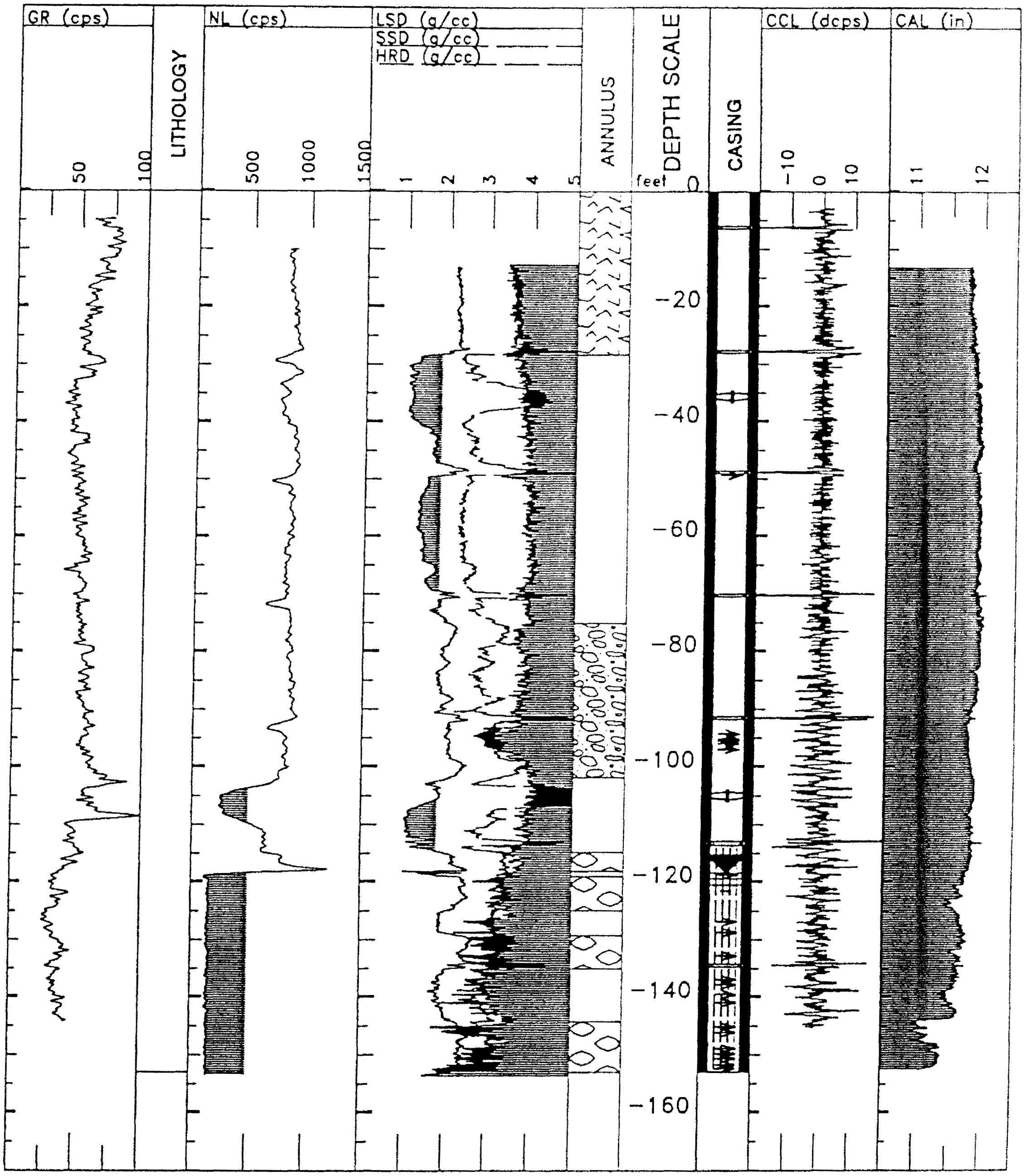


Figure 46. Geophysical Well Logs, Case History No. 6, Water Supply Well WS-2

TABLE 18

REGION III INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-2

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	28.4	cement	Highest apparent density (LSD, SSD) above water level. SSD averages 3.58 g/cc. Surface conductor could contribute to the comparatively high density measurement.
28.4	75.2	air-filled void	Lowest apparent density (LSD, SSD). SSD averages 2.52 g/cc and 2.41 g/cc respectively, in two zones. Some cavings possibly accumulated above casing couplings as indicated by higher densities.
75.2	101.9	possible drill cuttings or cavings	Lower apparent density (LSD, SSD) than possible gravel pack. SSD averages 3.02 g/cc.
101.9	114.9	air-filled void	Low apparent density (LSD, SSD). SSD averages 2.98 g/cc and LSD averages 1.11 g/cc.
114.9	153.0	possible pea gravel or sand pack with water-filled voids	High apparent density (LSD, SSD). LSD averages 2.42-2.53 g/cc below water level. SSD averages 3.35 g/cc below water level. Lower density zones of 1.87-1.89 g/cc (LSD) represent water-filled voids. The low-density spike (LSD) at 118.8' is interpreted as a void space and not a tool artifact due to guard log interference at the water level. Any such artifacts would be expected to occur approximately three to five feet below the water level.

Region II. The high-resolution density (HRD), short-spacing density (SSD), casing collar locator (CCL), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 46. Interpretations for Region II are describe in Table 19. Locations of slotted intervals are speculative.

TABLE 19

REGION II INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-2

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
0.0	113.6	steel casing	I.D. = 11.88" (s = ±0.06") (CAL). Possible surface conductor from surface to 28.4' (SSD). Most casing joints approximately 21' in length. Tops of threaded couplings at 6.0', 27.6', 48.6', 70.0', 91.4', 113.0' indicated by increased density (SSD) and CCL. Increased density (SSD) and slightly reduced neutron response (NL) at 35.7' and 105.1' interpreted as centralizers. Low apparent densities (HRD) from 94.3'-97.0' may indicate corrosion, perforations, or cracks.
113.6	153.0	field- or torch-slotted casing	I.D. = 11.58" (s = ±0.22") (CAL). Comparatively low HRD density without correspondingly low LSD and SSD densities interpreted as slotted pipe with low percentage open area. Neutron counts increase above water level at 118.4'. The top of a threaded coupling is indicated at 113.0'. Low apparent densities (HRD) and caliper variations (CAL) indicate scaling and corrosion from 118.8' to 152.4' as indicated by perforation symbols in Figure 46, but CCL does not confirm.

Geophysical Well Log Analysis, Water Supply Well WS-3

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided. However, alternate interpretations are possible, especially for Region II.

Region III. The neutron (NL) and side-collimated, dual-spacing density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 47, and described in Table 20.

Well Name: WS-3
File Name: WS3
Location: CASE HISTORY NO. 6
Elevation: 0 Reference: TOC
Steel casing

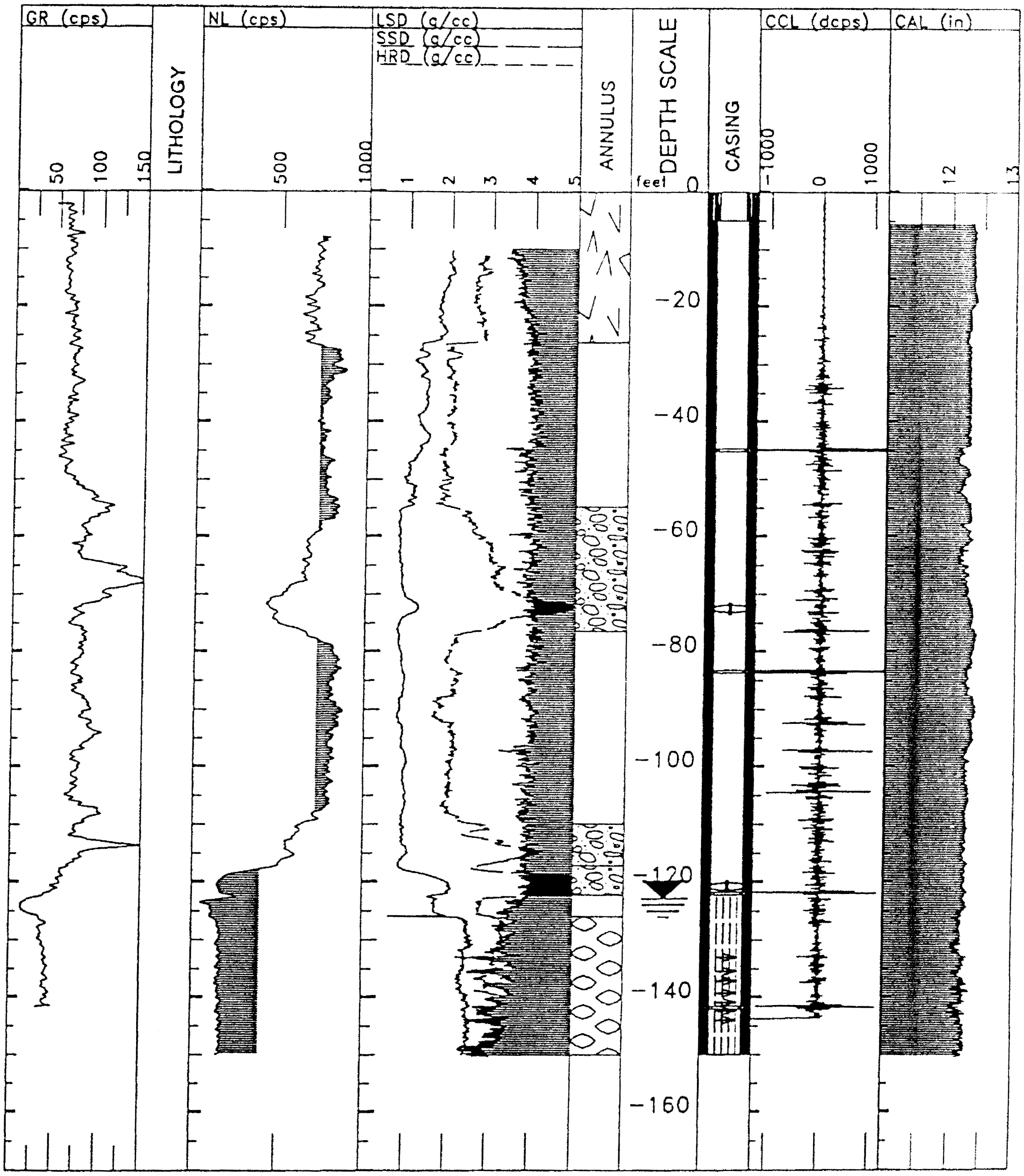


Figure 47. Geophysical Well Logs, Case History No. 6, Water Supply Well WS-3

TABLE 20

REGION III INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-3

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	26.2	poor cement	Highest apparent density (LSD, SSD) above water level. SSD averages 2.70 g/cc.
26.2	54.8	air-filled void	Low apparent density (LSD, SSD). SSD averages 1.99 g/cc.
54.8	76.5	possible drill cuttings or cavings with channels or voids	Lower apparent density (LSD, SSD) than possible gravel pack. SSD averages 2.27 g/cc. Comparatively low LSD density suggests channeling and/or voids.
76.5	109.9	air-filled void	Low apparent density (LSD, SSD). SSD averages 2.03 g/cc.
109.9	122.2	possible drill cuttings or cavings with channels or voids	Lower apparent density (LSD, SSD) than possible gravel pack. SSD averages 3.28 g/cc. Comparatively low LSD density suggests channeling and/or voids.
122.2	126.0	water-filled void	Low apparent density (LSD, SSD). SSD averages 2.85 g/cc. Water level at 123.0 (NL).
126.0	153.0	possible pea gravel or sand pack	High apparent density (LSD, SSD). SSD averages 3.18 g/cc.

Region II. The high-resolution density (HRD), short-spacing density (SSD), casing collar locator (CCL), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 47. Interpretations for Region II are described in Table 21. Locations of slotted intervals are speculative.

TABLE 21

REGION II INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-3

DEPTH (FEET)		MATERIAL	COMMENTS
BOTTOM	TOP		
0.0	113.6	steel casing	I.D. = 12.27" (s = ±0.06") (CAL). Most casing joints approximately 39' in length. Tops of welded couplings at 44.7', 83.2', 121.7' indicated by CCL and absence of density (SSD) response. Increased density (SSD) and slightly reduced neutron response (NL) at 72.5' and 120.8' interpreted as centralizers.
113.6	153.0	field- or torch-slotted casing	I.D. = 12.20" (s = ±0.06") (CAL). Comparatively low HRD density without correspondingly low LSD and SSD densities interpreted as slotted pipe with low percentage open area. Neutron counts increase above water level at 118.4'. The low-density spike (LSD) at 125.9' is interpreted as a tool artifact due to guard log interference at the water level. The top of a welded coupling is indicated at 113.0' (CCL). Low apparent densities (HRD) suggest rugosity and corrosion from 118.8' to 152.4' as indicated by perforation symbols in Figure 47, but CCL does not confirm.

Geophysical Well Log Analysis, Water Supply Well WS-4

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided. However, alternate interpretations are possible, especially for Region II.

Region III. The neutron (NL) and side-collimated, dual-spacing density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 48. Interpretations for Region III are described in Table 22.

Well Name: WS-4
File Name: WS4
Location: CASE HISTORY NO. 6
Elevation: 0 Reference: TOC
Steel casing

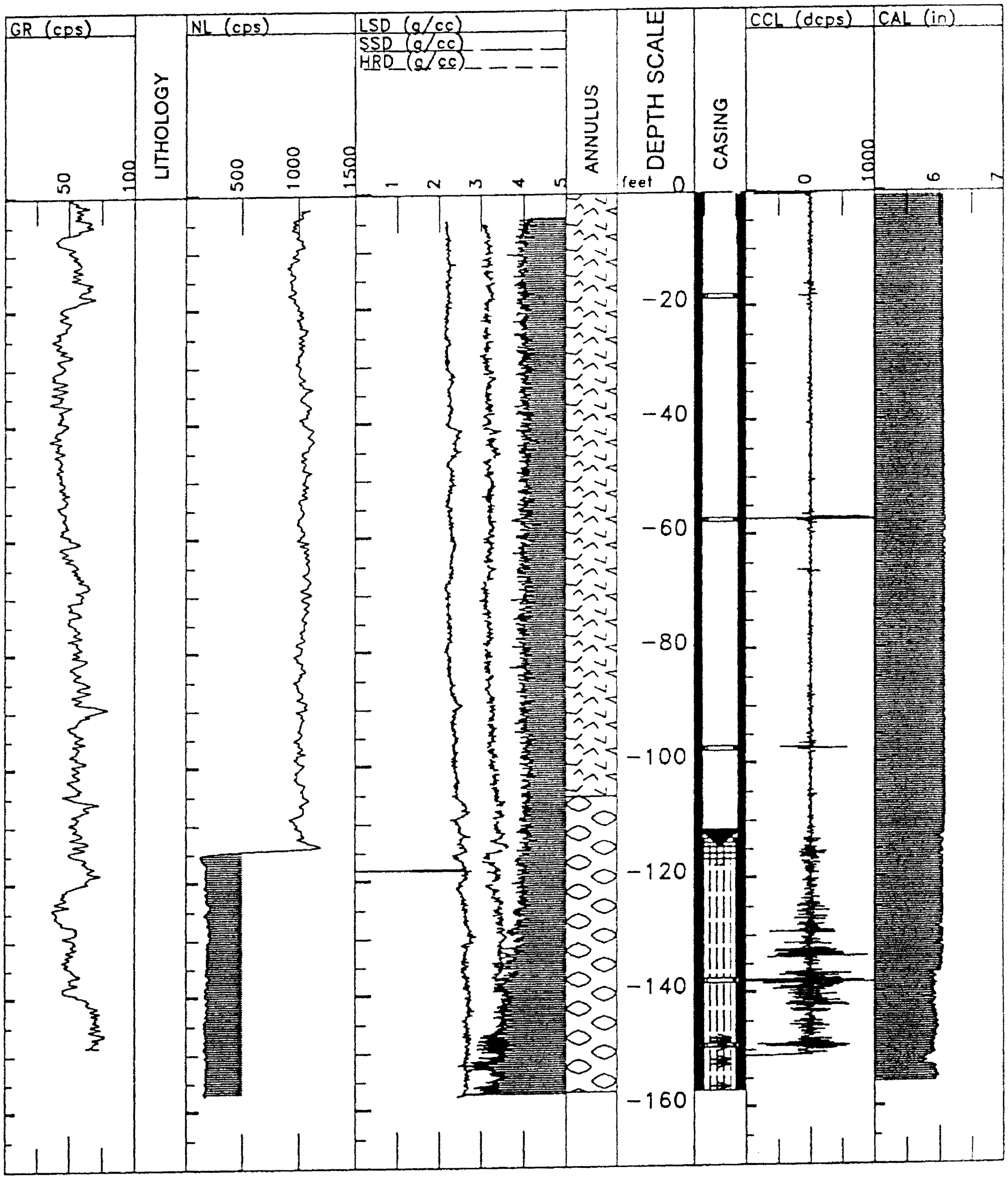


Figure 48. Geophysical Well Logs, Case History No. 6, Water Supply Well WS-4

TABLE 22

REGION III INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-4

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	105.4	cement	High apparent density (LSD, SSD). SSD averages 3.21 g/cc. Uniform density.
105.4	157.0	possible pea gravel or sand pack	Higher apparent density than cement grout (LSD, SSD). SSD averages 3.45 g/cc.

<u>Region II.</u> The high-resolution density (HRD), short-spacing density (SSD), casing collar locator (CCL), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 48. Interpretations of Region II are described in Table 23. Locations of slotted intervals are speculative.

TABLE 23

REGION II INTERPRETATION FOR CASE HISTORY NO. 6
WATER SUPPLY WELL WS-4

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
0.0	113.6	11.88" ID steel casing	I.D. = 6.06" (s = ±0.01") (CAL). Most casing joints approximately 39' in length. Tops of welded couplings at 17.9', 57.0', 97.0', 113.0' indicated by CCL and absence of density (SSD) response.
113.6	153.0	field- or torch-slotted casing	Comparatively low HRD density without correspondingly low LSD and SSD densities, and increased CCL response frequency interpreted as slotted pipe with low percentage open area. Neutron counts increase above water level at 114.5'. The low-density spike (LSD) at 118.1' is interpreted as a tool artifact due to guard log interference at the water level. Tops of welded couplings indicated at 137.5', 148.8' (CCL). Low apparent densities (HRD) indicate rugosity and/or corrosion from 147.9' to 156.3' as indicated in Figure 48.

Discussion of Case History No. 6

With the exception of the caliper log measurements, the interpretations presented in Case History No. 6 are mostly qualitative. Even so, many details of well construction were determined with confidence, including casing and screen diameter, the locations and types of casing couplings, the locations of voids in the annular space, and the water level. The interpretations of centralizers, corrosion, scaling, pitting, and torch-cut slots were determined with less certainty, but were valuable indications of potential problems and probable well construction.

The combined responses of the short-spacing density log (SSD) and the casing collar locator log (CCL) permitted the distinction between casing joints which had box couplings and those which were apparently welded, because no couplings were indicated by the short-spacing density response. Both welded joints and box or threaded couplings were detected by the casing collar locator log.

The casing collar locator log and the high-resolution density log (HRD) appeared to indicate intervals of corrosion, pitting, and scaling of casing and slotted pipe. Apparent density (HRD) decreased in such intervals. The casing collar locator (CCL) log amplitude increased in many of these zones.

Slotted intervals were difficult to detect because of the small percentage of open area in field- or torch-slotted casing. Case History No. 5 demonstrates that manufactured well screen produces a density contrast detected by both the long- and short-spacing density logs. No such contrasts were noted in Case History No. 6. However, the water levels and indicators of corrosion (HRD, CCL) proved strong evidence that slotted intervals were present. Although the interpretations are tenuous, Case History No. 6 establishes a probable response suite for field- or torch-slotted steel casing.

In addition, the case history illustrates the importance of digital data acquisition. At least one of the casing collar locator logs would not have been interpreted correctly had an analog logging unit been used. Figure 49 shows the casing collar locator logs for all four wells logged, with the horizontal scales initially selected in the field. Note that the casing collar locator log for well WS-2 provides no useful information, and that the log responses for wells WS-3 and WS-4 are subdued.

Digital data permitted the amplitudes of log responses to be increased to yield useful information (see Figure 50). For well WS-2, a scale increase of two orders of magnitude was required to produce useful information. Less drastic scale increases for wells WS-3 and WS-4 made the logs more easily interpreted. Background noise was increased in the same proportion as the meaningful signals, but did not require filtering.

An anomalous response was noted, apparently due to electronic interference within the Century Geophysical Corporation tool model 9035, the dual-spacing, side-collimated density tool. When the guard log module of the tool is pulled out of water, a signal is believed to be

Well Name: FOUR WATER SUPPLY WELLS
File Name: CCL 4MW2
Location: CASE HISTORY NO. 6
Elevation: 0 Reference: TOC
Steel casing

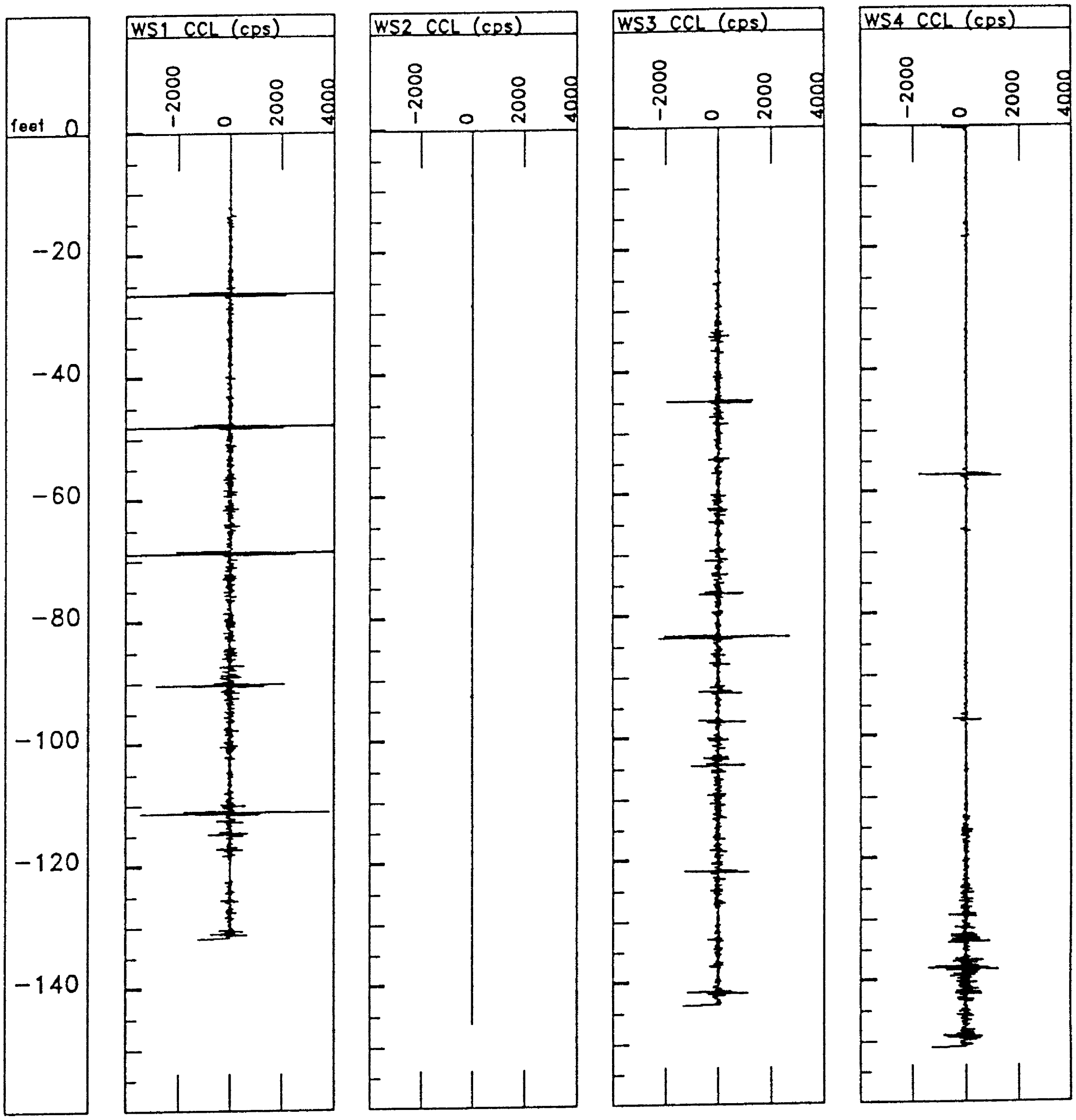


Figure 49. Comparison of Four Casing Collar Locator Logs, Case History No. 6
Field-Selected Log Scales

Well Name: FOUR WATER SUPPLY WELLS
File Name: CCL 4MWS
Location: CASE HISTORY NO. 6
Elevation: 0 Reference: TOC
Steel casing

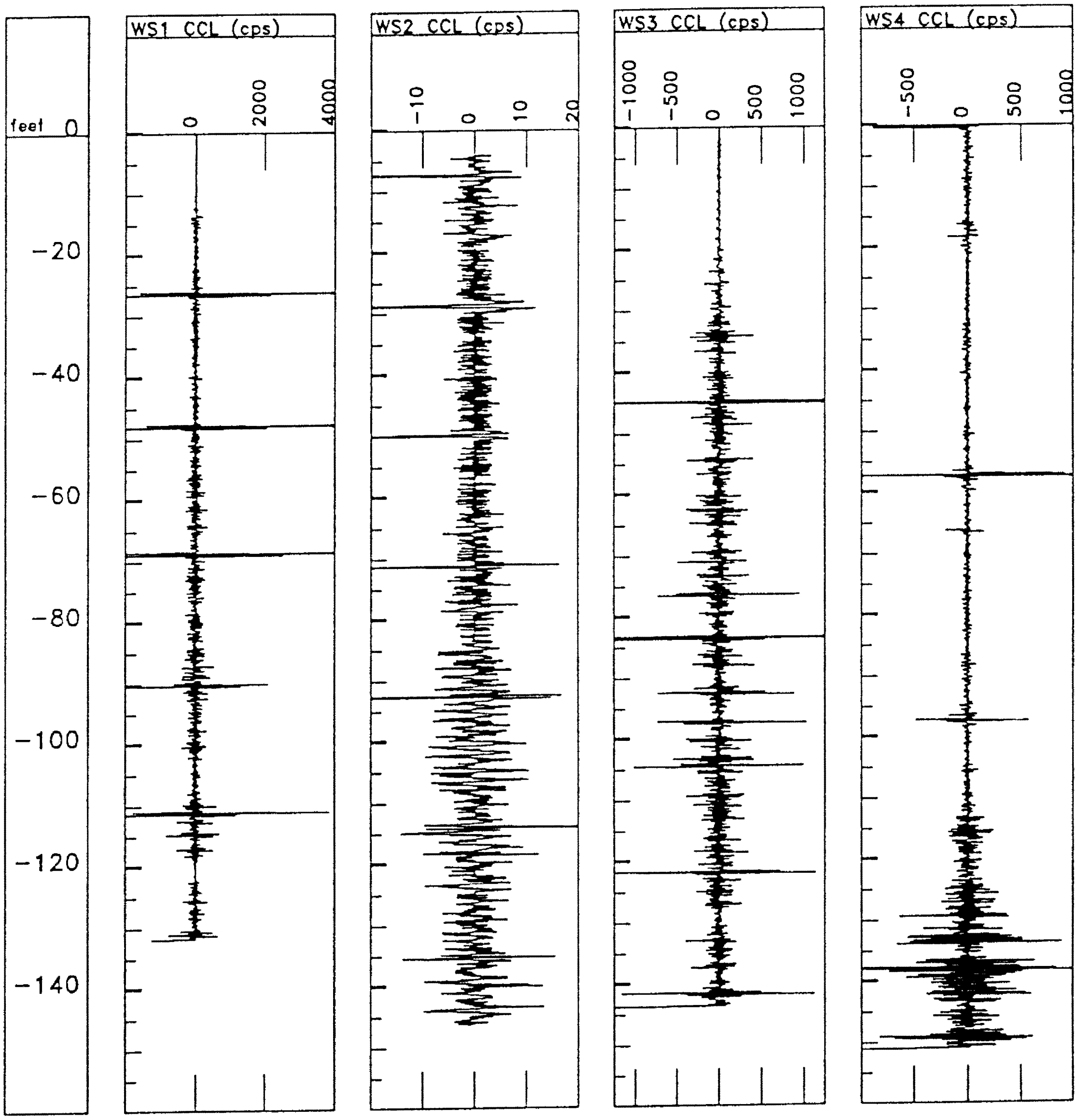


Figure 50. Comparison of Four Casing Collar Locator Logs, Case History No. 6
Modified Log Scales

emitted which causes a response in the long-spacing density log circuit. These long-spacing density peaks are described as artifacts in Tables 20 and 22. The peaks occur at an apparent depth of three to five feet below the water level, approximately the distance between the measure points for the guard log module and the long-spacing density log.

Case History No. 7

Background

Case History No. 7 is based on twelve wells which were logged to determine well construction and evaluate well integrity. The location of the wells and many details regarding this case history are confidential. Intervals were selected from three of these wells to illustrate log responses to well construction features which are not documented in the previous case histories.

Century Geophysical Corporation logging equipment produced digital data downhole. The log quality was excellent. The gamma-ray (GR), neutron (NL), dual-spacing, side-collimated density (LSD, SSD), high-resolution density (HRD), and caliper (CAL) logs were run in the three examples documented here. The casing collar locator log (CCL) was run in two of the three wells described.

The gamma-ray (GR) log is the only log which was used to interpret lithology. The site of Case History No. 7 is underlain by a complex sequence of gravel, sand, silt, clay, and caliche, similar to Case History No. 6. Although no lithologic descriptions were available, Region of Investigation IV is interpreted assuming a two-component system of sand/silt and clay. Therefore, these lithologic interpretations are speculative, but could be considerably refined with the availability of sample descriptions. Region of Investigation IV is not discussed for Case History No. 7 because of the speculative nature of the interpretations.

Pre-Logging Construction Summary

The operator of the wells provided generalized summaries of well construction which contained few details. The monitoring wells were installed during the 1970's and 1980's using various methods including mud rotary and air rotary with a casing driver. The drillers reportedly experienced problems with the well installations due to borehole instability.

Monitoring wells MW-6, MW-7, and MW-8 are constructed of stainless steel and PVC materials. The well screen and 20 feet of riser pipe above the screen are stainless steel. PVC casing is used from the stainless riser to the surface. Casing and screen diameters range from about 3.75 to 5.5 inches.

Geophysical Well Log Analysis, Monitoring Well MW-6

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided, but alternate interpretations are possible.

Region III. The neutron (NL) and dual-spacing, side-collimated density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 51 and described in Table 24.

Well Name: MW-6
File Name: CH7 MW6
Location: CASE HISTORY NO. 7
Elevation: 0 Reference: TOC

PVC and steel casing, steel screen: 4-inch diameter
bit size 9.875-inch

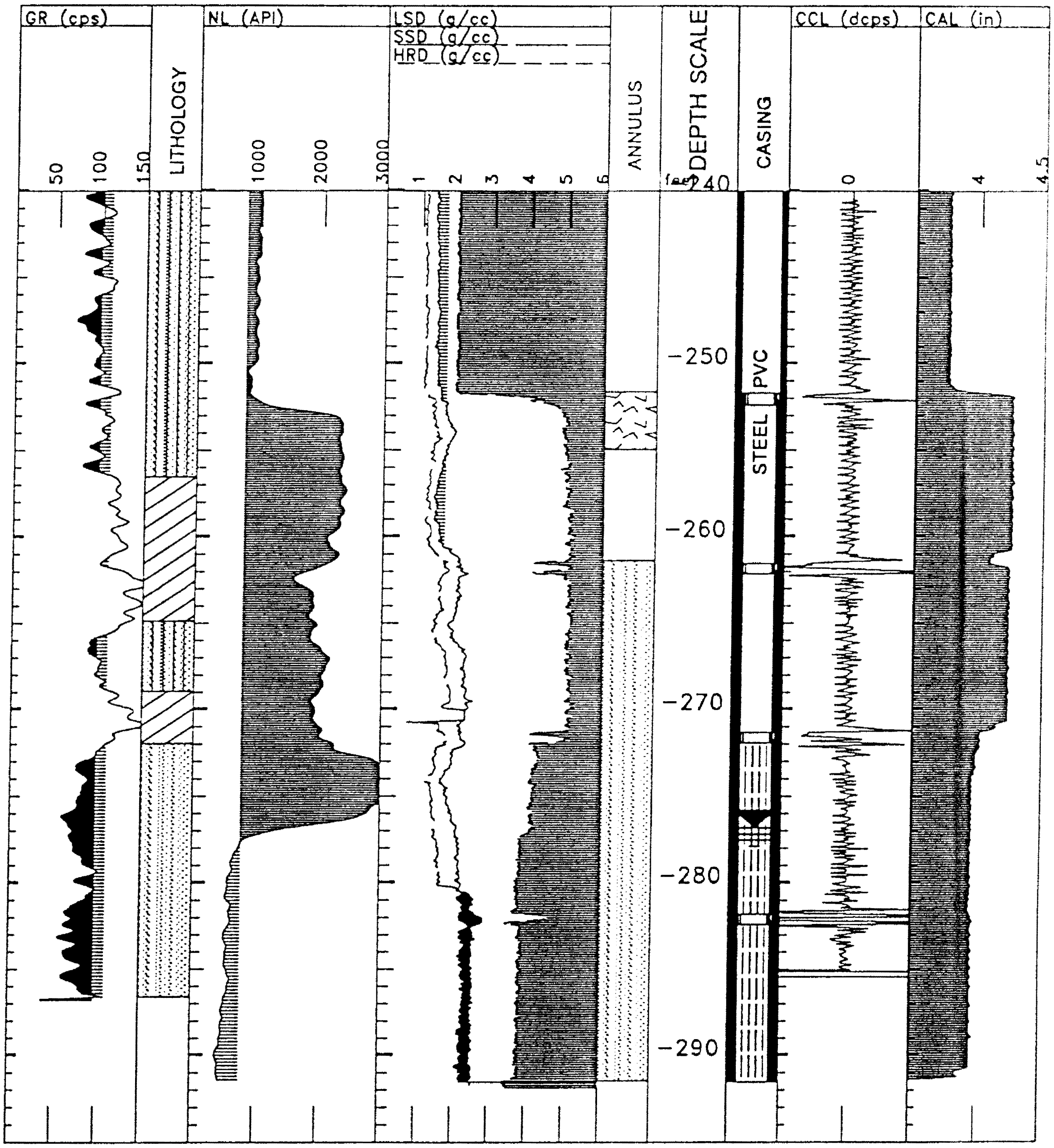


Figure 51. Geophysical Well Logs, Case History No. 7, Monitoring Well MW-6

TABLE 24

REGION III INTERPRETATION FOR CASE HISTORY NO. 7 MONITORING WELL MW-6

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
240.0	251.6	air-filled void	Low apparent density (LSD, SSD). SSD averages 1.12 g/cc.
251.6	255.0	cement (fair to poor)	Mid-range apparent density (LSD, SSD). SSD averages 1.38 g/cc.
255.0	261.4	air-filled void	Low apparent density (LSD, SSD). SSD averages 1.30 g/cc.
261.4	291.5	possible sand pack	High apparent density (LSD, SSD). SSD averages 1.67 above water level through stainless steel riser, 1.50 g/cc above water level through stainless steel screen, 2.56 g/cc through stainless steel screen below water level. Water levels at 276.9' (NL) and at 280.2' (SSD) on two logging dates.

Region II. The high-resolution density (HRD), short-spacing density (SSD), casing collar locator (CCL), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 51, and described in Table 25. Locations of slotted intervals are speculative.

TABLE 25

REGION II INTERPRETATION FOR CASE HISTORY NO. 7
MONITORING WELL MW-6

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
240.0	251.7	PVC casing	I.D. = 3.76" (s = ±0.005") (CAL). Lengths of casing joints not determined (no electrical logs were run). Apparent density (HRD) 1.98 g/cc. PVC indicated by low neutron (NL) counts.
251.72	271.4	steel casing or riser	I.D. = 4.24" (s = ±0.005") (CAL). High apparent density (HRD), 5.01 g/cc. Two ten-foot joints. Couplings indicated by HRD and casing collar locator (CCL).
271.4	291.6	steel screen	I.D. = 3.96" (s = ±0.007") (CAL). Lower apparent density (HRD) than steel casing, 4.02 g/cc above water level, 3.81 g/cc below water level. Water levels at 276.9' (NL) and at 280.2' (SSD) on two logging dates.

Geophysical Well Log Analysis, Monitoring Well MW-7

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided, but alternate interpretations are possible.

Region III. The neutron (NL) and dual-spacing, side-collimated density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 52, and described in Table 26.

Well Name: MW-7
File Name: CH7 MW7
Location: CASE HISTORY NO. 7
Elevation: 0 Reference: TOC
PVC & steel casing, slotted steel casing: 4-inch diameter
Bit size: 9.875-inch

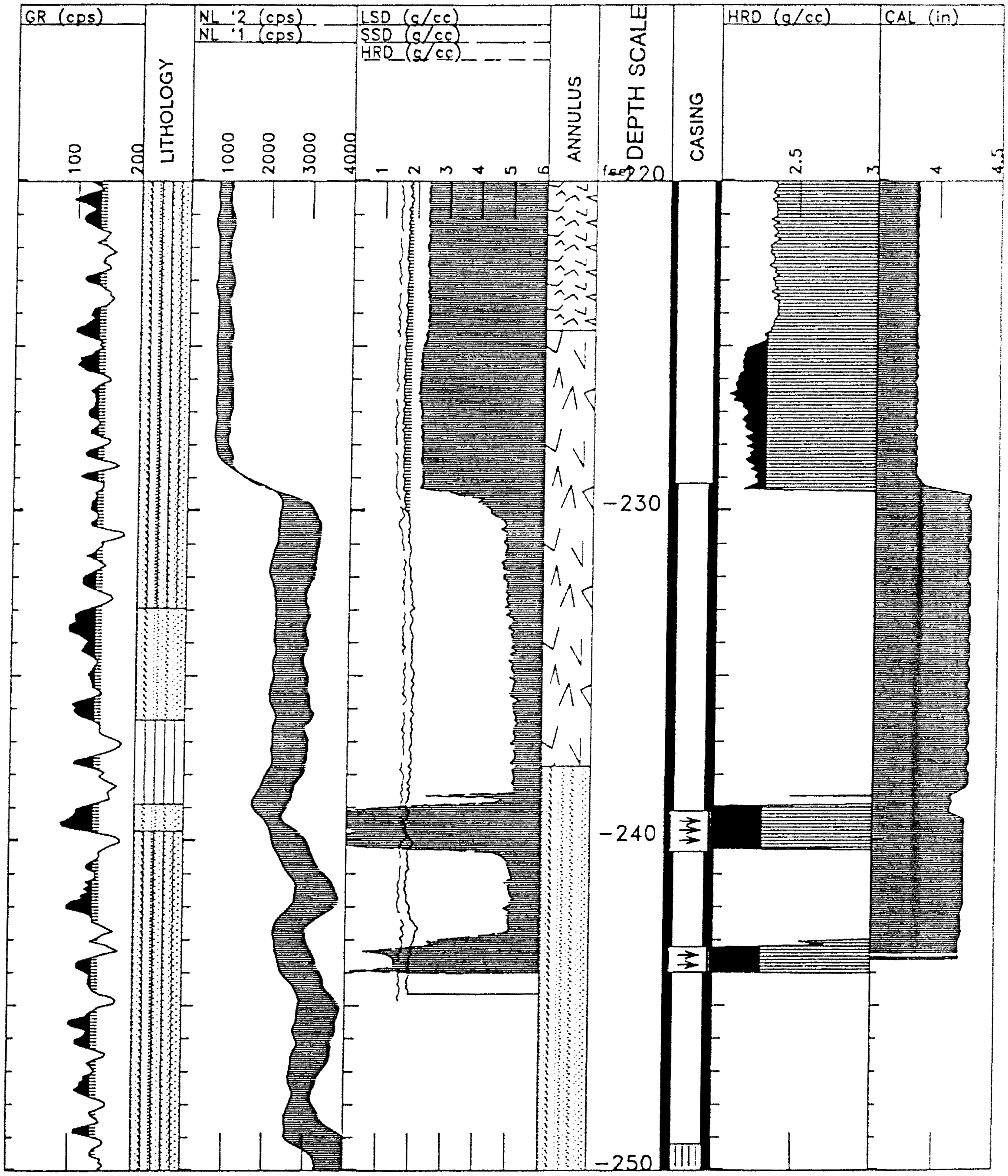


Figure 52. Geophysical Well Logs, Case History No. 7, Monitoring Well MW-7

TABLE 26

REGION III INTERPRETATION FOR CASE HISTORY NO. 7
MONITORING WELL MW-7

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
220.0	224.5	cement	Mid-range apparent density (LSD, SSD). SSD averages 1.52 g/cc, HRD averages 2.34 g/cc.
224.5	237.8	lower-density cement	Mid-range apparent density (LSD, SSD). SSD averages 1.48 g/cc, HRD averages 2.16 g/cc through PVC. SSD averages 1.71 g/cc through steel.
237.8	250.0	possible sand pack	Mid-range apparent density (LSD, SSD). SSD averages 1.67 g/cc. Neutron (NL) counts greater than overlying (possible) bentonite.

Region II. The high-resolution density (HRD), short-spacing, side-collimated density (SSD), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 52, and described in Table 27. Locations of slotted intervals are speculative.

TABLE 27

REGION II INTERPRETATION FOR CASE HISTORY NO. 7 MONITORING WELL MW-7

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
220.0	229.2	PVC casing	I.D. = 3.82" (s = ±0.005") (CAL). Lengths of casing joints not determined (no electrical logs were run). Apparent density (HRD) 2.16-2.34 g/cc. PVC indicated by low neutron (NL) counts.
229.2	239.1	steel casing or riser	I.D. = 4.27" (s = ±0.007") (CAL). High apparent density (HRD), 4.99 g/cc.
239.1	240.3	possible severely-corroded coupling or parted casing	I.D. = 4.13" (CAL). Low apparent density (HRD), 0.04 g/cc. Tool could have been jarred by coupling to cause anomalous response.
240.3	243.2	steel casing or riser	I.D. = 4.24" (s = ±0.009") (CAL). High apparent density (HRD), 5.00 g/cc.
243.2	244.0	possible severely-corroded or parted casing	No caliper (CAL) log. Low apparent density (HRD), 1.54 g/cc. Tool could have been jarred by coupling to cause anomalous response.
244.2	250.0	steel casing or riser	No caliper (CAL) or density (LSD, SSD, HRD) logs. Characterization is speculative.

Geophysical Well Log Analysis, Monitoring Well MW-8

Region of Investigation III (the annulus) and Region of Investigation II (the casing and screen) were evaluated. Interpretations of well construction and possible defects have not been confirmed by alternate testing methods. The most plausible explanations for observed log responses are provided, but alternate interpretations are possible.

Region III. The neutron (NL) and side-collimated, dual-spacing density (LSD, SSD) logs were used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 53, and described in Table 28.

Well Name: MW-8
File Name: CH7_MW8
Location: CASE HISTORY NO. 7
Elevation: 0 Reference: TOC

Steel casing and wire wrap (.010-in. slots) screen, 5-inch diameter
Bit size: 10.25-inch

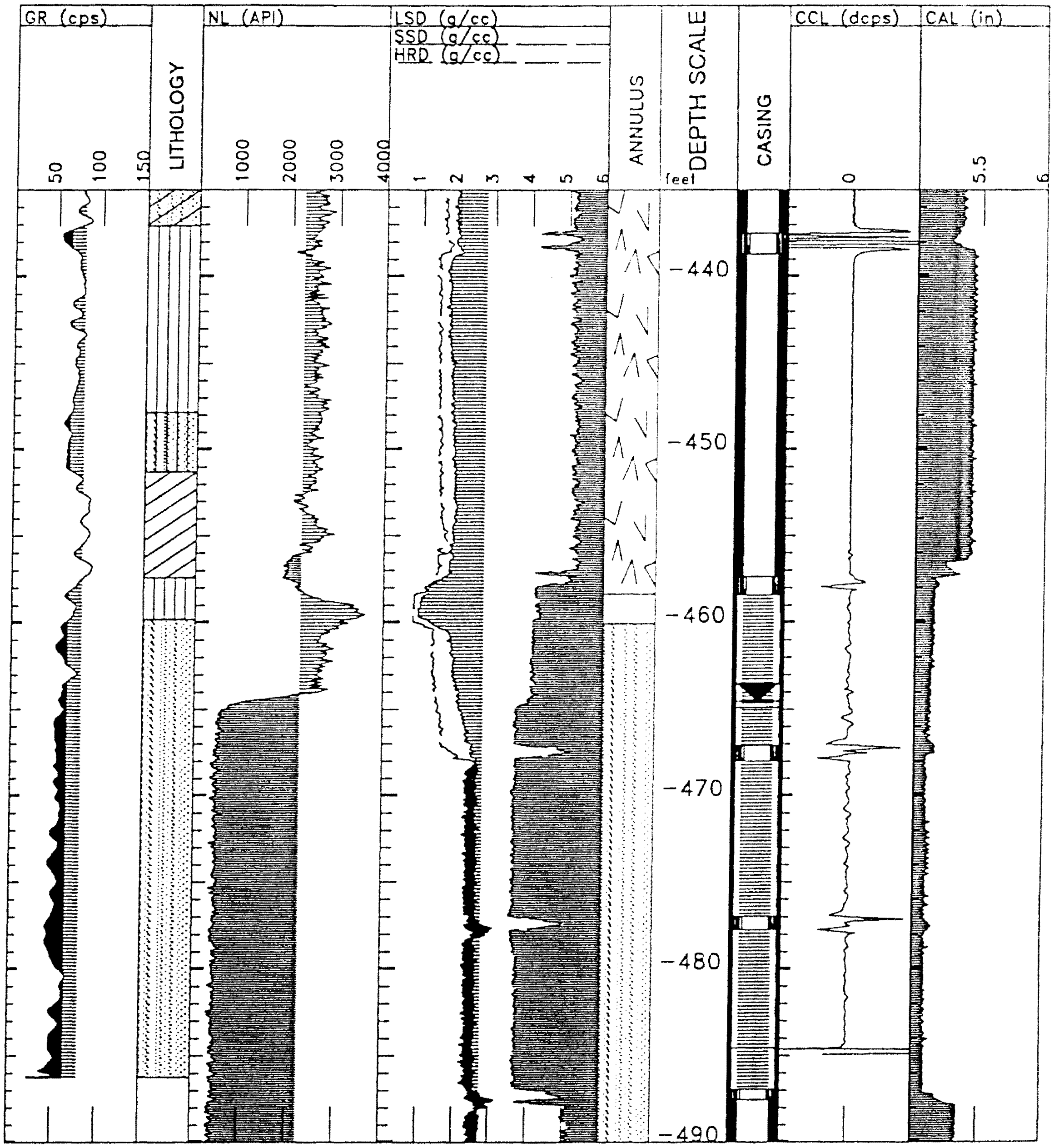


Figure 53. Geophysical Well Logs, Case History No. 7, Monitoring Well MW-8

TABLE 28

REGION III INTERPRETATION FOR CASE HISTORY NO. 7
MONITORING WELL MW-8

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
435.0	458.4	possible poor cement	Low apparent density (LSD, SSD) for cement. SSD averages 1.54 g/cc. Uniform density.
458.4	460.1	air-filled void	Low apparent density (LSD, SSD). SSD averages 0.84 g/cc. Uniform density.
460.1	490.0	possible pea gravel or sand pack	Higher apparent density than cement grout (LSD, SSD). SSD averages 3.45 g/cc.

Region II. The high-resolution density (HRD), short-spacing, side-collimated density (SSD), casing collar locator (CCL), and caliper (CAL) logs were used to interpret casing materials as indicated in the graphic column labelled "CASING", Figure 53, and described in Table 29. Locations of slotted intervals are speculative.

TABLE 29

REGION II INTERPRETATION FOR CASE HISTORY NO. 7
MONITORING WELL MW-8

DEPTH (FEET)			
BOTTOM	TOP	MATERIAL	COMMENTS
435.0	457.4	steel riser or casing	I.D. = 5.43" (s = ±0.01") (CAL). Most casing joints approximately 20' in length. Apparent density (HRD) 5.17 g/cc. PVC indicated by low neutron (NL) counts.
457.4	487.0	steel screen	I.D. = 5.13" (s = ±0.02") first 10' joint (CAL). I.D. = 5.09" (s = ±0.01") second, third 10' joints (CAL). Lower apparent density (HRD) than steel casing, 4.22 g/cc above water level, 3.60-3.67 g/cc below water level. Water levels at 464.5' (NL) and at 467.9' (SSD) on two logging dates. Tops of threaded couplings indicated at 467.1', 477.0' (HRD, CCL).
487.0	490.0	steel casing (footer)	I.D. = 5.34" (s = ±0.01") (CAL). High apparent density (HRD), 5.09 g/cc.

Discussion of Case History No. 7

With the exception of the caliper log measurements, the interpretations presented in Case History No. 7 are mostly qualitative. Even so, many details of well construction were determined with confidence, including casing and screen diameter the distinction between PVC and steel casing, the determination that couplings were threaded, the location of well screen, the locations of voids in the annular space, and the water levels.

In monitoring well MW-7, the high-resolution density log (HRD) indicated two intervals of extremely low apparent density. One interpretation of the low density zones is a split or parted casing. An alternative interpretation is that the logging tool may have been deflected at the coupling which the caliper log detects at approximately 239 feet. The tool may have been jarred when the top of the tool passed the coupling, explaining the lower density anomaly, and again when the base of the tool passed the coupling, explaining the upper density anomaly. No repeat run was available to confirm the tool response. Such quality control measures might have resolved this question. A small diameter borehole camera or acoustic televiewer would resolve this dilemma.

The well screen was very apparent on the high-resolution density log. This suggests a high percentage of open area, or a manufactured well screen. The short- and long-spacing density logs did not distinguish between the steel casing and screen as well as they did in Case History No. 5. The same dual-spacing density tool model was used in both case histories. The different responses may relate to well screen diameter, percent open area, or both.

Case History No. 8

Background

Two wells at the site of Case History No. 8 were logged to determine well construction and evaluate well integrity. The well location and many details regarding this case history are confidential. One of the two wells was selected to document log responses to the formation and to well construction which are not documented in the previous case histories.

Century Geophysical Corporation logging equipment produced digital data downhole. The gamma-ray (GR), induction (IL), neutron (NL), omnidirectional density (LSD-4pi), differential single-point resistance (DSPR), and spontaneous potential (SP) logs were run in the well. The quality of most logs was excellent. However, the differential single-point resistance log malfunctioned or would not function in the well environment, and the spontaneous potential log could not be interpreted with certainty. These latter two logs were not included in the log analysis.

Pre-Logging Construction Summary

The wellsite geologist provided generalized summaries of the monitoring wells. Monitoring well MW-1 was constructed of two-inch diameter, schedule 80 PVC casing and

0.020-slot PVC well screen. Two, ten-foot well screens were reported to have been installed at depth intervals from 90 to 80 feet and from 70 to 60 feet.

In ascending sequence, the annular materials reported were sand pack, bentonite pellets, bentonite grout slurry, and cement.

Geophysical Well Log Analysis, Monitoring Well MW-1

Region of Investigation IV (the formation) and Region of Investigation III (the annulus) were evaluated. Region of Investigation II (the casing and screen) are shown as reported by the wellsite geologist.

Region IV. The gamma-ray (GR), induction (IL), and neutron (NL) logs, in combination with lithologies reported by the wellsite geologist, were used to interpret lithology as indicated in the graphic column labelled "LITHOLOGY", Figure 54, and described in Table 30.

Well Name: MW-1
File Name: CH8 1AA
Location: CASE HISTORY NO. 8
Elevation: 0 Reference: GL

2-inch sch-80 PVC casing & 20-slot screen
depths of well construction materials are corrected

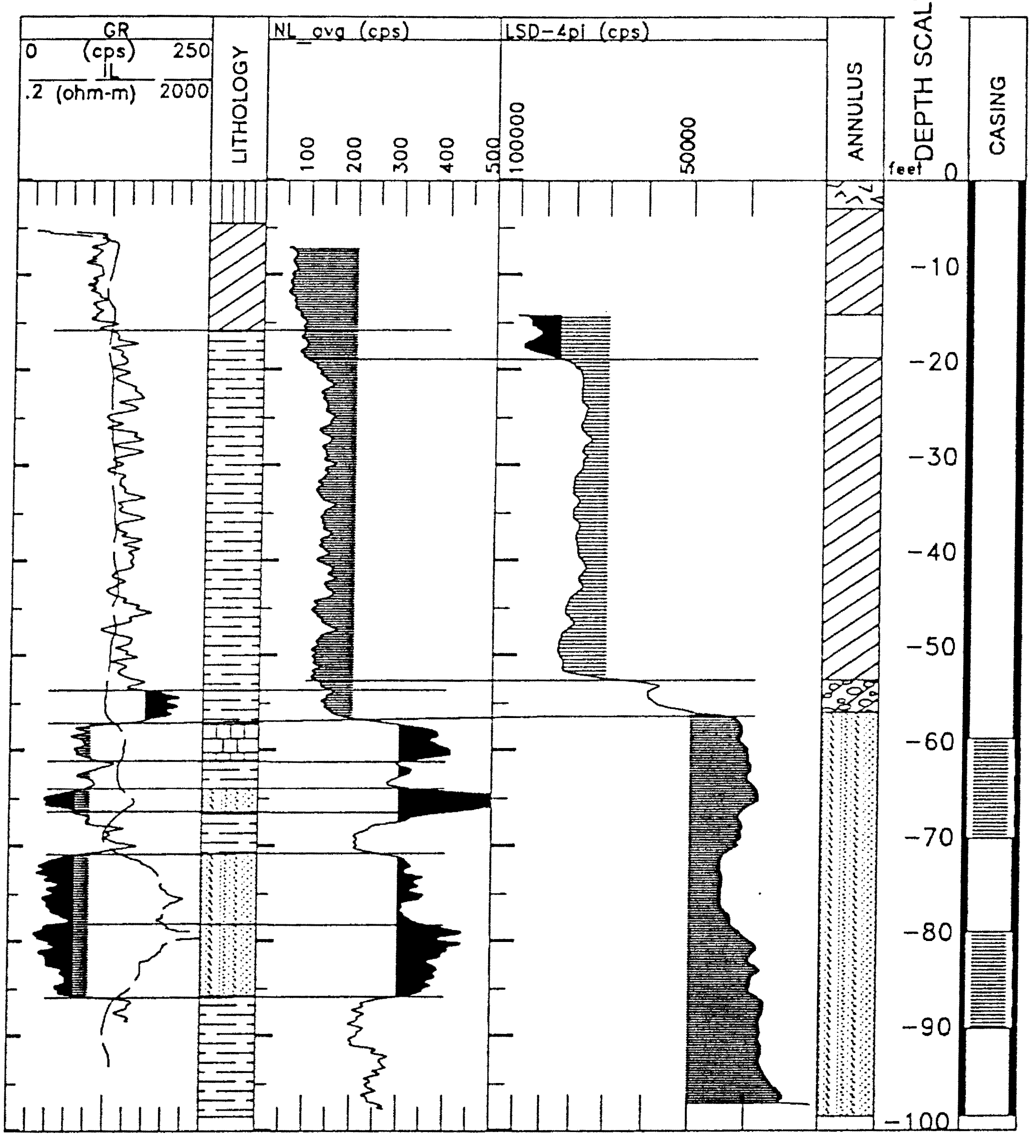


Figure 54. Geophysical Well Logs, Case History No. 8, Monitoring Well MW-1

TABLE 30

REGION IV INTERPRETATION FOR CASE HISTORY NO. 8
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	4.5	silt	Wellsite geologist's description; not logged.
4.5	16.0	clay	High natural radioactivity (GR), low apparent resistivity (IL), higher apparent porosity than shale (NL).
16.0	57.2	shale	High natural radioactivity (GR), low apparent resistivity (IL), high apparent porosity (NL).
57.2	61.0	shaly limestone	Low natural radioactivity (GR), high apparent resistivity (IL), lower apparent porosity than shales (NL). Wellsite geologist described limestone in this interval.
61.0	63.9	shale, with sandy or silty streak	High natural radioactivity (GR), low apparent resistivity (IL), high apparent porosity (NL).
63.9	66.6	sandstone	Low natural radioactivity (GR), high apparent resistivity (IL), lower apparent porosity than shales (NL).
66.6	70.7	shale	High natural radioactivity (GR), low apparent resistivity (IL), high apparent porosity (NL).
70.7	85.8	sandstone	Low natural radioactivity (GR), high apparent resistivity (IL), lower apparent porosity than shales (NL).
85.8	98.5	shale	High natural radioactivity (GR), low apparent resistivity (IL), high apparent porosity (NL).

Region III. The omnidirectional density (LSD-4pi) log was used to interpret annular materials as indicated in the graphic column labelled "ANNULUS", Figure 54, and described in Table 31. The gamma-ray (GR) log confirmed the location of bentonite pellets as indicated by the omnidirectional density log.

TABLE 31

REGION III INTERPRETATION FOR CASE HISTORY NO. 8
MONITORING WELL MW-1

DEPTH (FEET)			
TOP	BOTTOM	MATERIAL	COMMENTS
0.0	14.2		not logged with density tool
14.2	18.8	possible water-filled void	Lower apparent density than bentonite grout slurry (LSD-4pi).
18.8	52.6	bentonite grout slurry	Lower apparent density than bentonite pellets (LSD-4pi).
52.6	56.0	bentonite pellets	Lower apparent density than sand (LSD-4pi). Gamma-ray anomaly, high counts per second.
56.0	98.5	sand pack	High apparent density (LSD-4pi).

Region II. The differential single-point resistance log malfunctioned or would not function in the well environment and was not interpreted. The spontaneous potential log could not be interpreted with certainty. The graphic column labelled "CASING" shows the casing and screen intervals reported by the wellsite geologist.

Discussion of Case History No. 8

Case History No. 8 provides two examples of log responses which are not as clearly illustrated elsewhere in this study. The lithology interpretation and the neutron log response are unique to this Case History.

The varied lithology, the availability of both the gamma-ray and induction logs, and the availability of sample descriptions result in the best example of lithologic interpretation in this study. In addition, the neutron log (NL) correlates very well with the gamma-ray log and thus responds mostly to lithologic changes. In the other case histories, the neutron log responds more strongly to the annular materials. This example of neutron log response illustrates that the neutron log response should not be attributed to any region of investigation or combination of regions without careful examination of the well-specific data.

The induction log (IL) shows that the interval which exhibits high gamma-ray counts does not correspond to a lithologic change, but results from the presence of bentonite pellets in the annular space. The combined induction log and gamma-ray log are used in much the same way as the open-hole and cased-hole gamma-ray logs to detect bentonite pellets.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Results

Each of the stated objectives of this study were accomplished. These objectives are:

- to verify the feasibility of using geophysical well logging to assess groundwater monitoring well construction and integrity;
- to identify the types of geophysical well logging tools which are effective in groundwater monitoring well environments, and which are cost effective and readily available to industry;
- to identify and develop analytical methods which are effective for geophysical well logs acquired in groundwater monitoring wells, and which are cost effective;
- to identify and develop well logging strategies and analytical methods to address specific problems of groundwater monitoring well construction and integrity; and
- to develop case histories which demonstrate the logging strategies and analytical methods developed during this research.

Methods were developed to identify details of well construction and common problems with well integrity. Quantitative and qualitative methods were developed. Features which were evaluated include:

- inside diameter of casing and screen;
- casing joints;
- screened or slotted intervals;
- holes or cracks in the casing;
- casing centralizers;

- eccentered casing;
- voids and channels in the annular space between the casing and borehole; and
- filter (sand) pack and grout materials in the annular space.

Feasibility Determination

Both the literature review and the preliminary assessment of Case History No. 2 demonstrated the feasibility of using geophysical well logging to assess well construction and integrity. The literature review identified several logging methods which had a high probability of success for achieving the objectives of this research. The several nuclear logging methods, gamma-ray, neutron, and density logging, had been utilized in (cased) oil and gas wells for many years (Hughes, 1943; Ahmed, 1977; Neill, 1977; Neal and Carroll, 1985; Sollee, 1985). These methods have been applied to groundwater monitoring wells in recent years, but additional work was required to more clearly demonstrate or improve the published applications, and to develop additional applications and analytical methods. Morzenti (1989) demonstrated that electrical methods (the single-point resistance log) respond to PVC casing joints and PVC well screen under some conditions, but the examples were not published and the log responses were not consistent.

Well logs from Case History No. 2 were available for preliminary evaluation during the feasibility study. These logs provided additional evidence that this study was feasible.

Identification of Logging Tools

Geophysical well logging tools were identified which are effective in groundwater monitoring well environments, and which are cost effective and readily available to industry. Most of the tools studied are not designed for environmental logging and could be improved for this purpose with some reconfiguration.

Identification and Development of Analytical Methods

Traditional analytical methods for well log analysis were considered and experimented with. Methods which utilize several logs to characterize a zone include cross-plotting and principal components analysis. Such methods would be especially useful for characterizing the annular space. Because the nuclear methods which respond to annular materials have different volumes of investigation, these traditional methods were determined to be impractical.

A systematic approach to cased-hole well log analysis was developed which employed several simple methods. A well log presentation format, a calibration method, and a graphical method for data distribution analysis were shown to be effective. These methods require only basic data analysis skills, but require digital well log data and data-processing software. These methods are described in detail in Chapter 1, are demonstrated in many of the case histories, and are briefly recapitulated below.

A logical and consistent well log presentation format was developed based on Smolen's (1987) concept of Regions of Investigation. Geophysical well logs are displayed adjacent to graphics columns where interpretations of those logs are shown. The logs and graphics columns are displayed according to the regions of investigation of the respective tools. From left to right, the logs and graphical interpretations represent Region IV or the formation, then Region III or the annular space, and finally Region II or the well casing and screen. This systematic and logical approach facilitates well log analysis and the explanation of interpretations.

The curve-fitting method most commonly available with computer software, linear regression, proved effective as a calibration tool for density logs. Several variations of this curve-fitting method were useful for analyzing heterogeneity in the annular space and for transforming omnidirectional density data from counts per second to the more readily interpreted grams per cubic centimeter.

A fundamental approach to data analysis, the frequency distribution (the density trace was used here), proved very effective in assigning annular materials of varying density to modal peaks on the density trace.

Specific Problems

A stated objective of this study was to identify and develop logging and analytical methods for evaluating specific features of well construction and well defects. These features are located in Regions of Investigation III and II.

Inside Diameter of Casing and Screen. Mechanical caliper logs were used to physically measure the inside diameter of well casing and screen. A three-arm caliper tool was used in the four-inch diameter wells of Case History No. 1. This tool provided a measurement of the averaged diameter of the well casing (or screen). Other caliper logs used are produced by the decentralizing arm of the side-collimated density tools. No small-diameter caliper tools were available to log two-inch diameter wells. The mechanical caliper logs are equally effective in PVC and steel casing.

The three-arm caliper used in Case History No. 1 mechanically averages the extensions of the three independent arms. The single caliper arm which decentralizes the side-collimated density tools is not as accurate as the three-arm caliper for measuring hole volume. However, the single-arm caliper is as precise as the three-arm caliper, provided that changes in diameter occur around the complete circumference of the hole or casing.

In addition to measuring hole diameter, the caliper log facilitates the identification of screened intervals, especially in steel casing where electrical methods are ineffective. The caliper log can detect rugosity, which may indicate corrosion, pitting, and scaling of casing or screen. In extreme situations, reduced hole diameter as measured by the caliper log may indicate the beginning of casing collapse.

Casing Joints. Casing joints or couplings were detected in both PVC and steel casing, where inside diameter was four inches or greater. Electrical logging methods were used to detect joints in PVC casing. The electrical logging methods used are not applicable above the water level. Casing collar locator, density, and caliper logs were used to detect casing couplings in steel casing.

Long-spacing guard logs (focused electric logs) consistently detect joints in PVC casing. Differential single-point resistance logs do not consistently detect joints in PVC casing. Other electrical methods do not consistently detect joints in PVC casing. Case History No. 1 demonstrated the effectiveness of the 10-foot spacing guard log in detecting flush-threaded joints in four-inch diameter PVC casing. Case History No. 2 demonstrated the effectiveness of the 55-inch spacing guard log in detecting bell-joints in four-inch diameter PVC casing. The tools which incorporate a guard log and which were employed during this study were too large to use in two-inch diameter wells.

The casing collar locator log consistently located steel casing couplings and butt-welded seams in steel casing (Case History Nos. 5, 6, and 7). The high-resolution density log consistently detected steel casing couplings, but not butt welds (Case History No. 4). The combined responses of these two logs could therefore distinguish between casing couplings and butt welds because of the increased steel thickness at casing couplings. The short-spacing density log detected steel casing couplings in instances where the couplings were very thick. The caliper log detected some casing couplings.

Screened or Slotted Intervals. Manufactured well screen in both PVC and steel casing was consistently detected. Field-slotted PVC casing was readily detected. Field- or torch-slotted steel casing was detected, but some interpretations are questionable. Electrical logging methods were used to detect manufactured PVC well screen and field-slotted PVC casing. Well screen and slots are generally below the water level. Therefore, electrical logging methods is generally applicable for PVC well screen and slotted intervals. Casing collar locator, density, and caliper logs were used to detect manufactured and field- or torch-slotted steel well screen.

The several guard logs, the normal resistivity logs, and the differential single-point resistance log consistently detect manufactured PVC well screen and field-slotted PVC casing (Case History No. 1). The spontaneous potential (SP) log performed poorly and inconsistently in detecting PVC well screen and slotted casing.

Manufactured steel well screen was readily detected with the casing collar locator and density logs (Case History Nos. 5 and 7). Field- or torch-slotted casing was tentatively detected with the casing collar locator, high-resolution density, and caliper logs.

Holes or Cracks in the Casing. Holes in PVC casing and holes, splits, pitting, and scaling in steel casing were detected, where inside diameter was four inches or greater. Electrical logging methods were used to detect holes or cracks in PVC casing (Case History No. 1). However, the electrical logging methods used for PVC casing inspection are not applicable above the water level. Density and casing collar locator logging were used to detect casing couplings in steel casing (Case History Nos. 6 and 7).

Casing Centralizers. Steel or metallic centralizers attached to PVC and steel casing were detected. Centralizers attached to steel casing were probably detected because of their massive character.

Steel centralizers attached to PVC casing were readily detected by the casing collar locator, the high-resolution density, and the induction electric logs (Case History No. 1). Steel centralizers attached to PVC well screen were tentatively detected by the 55-inch spacing guard log. The casing collar locator log responded strongly at each band of the centralizer. The high-resolution density log also showed a high-density spike at each band of the centralizer. The induction electric log responded to the centralizers attached to PVC casing, exhibiting low-resistivity through the entire interval, and showing a very low-resistivity spike at each of the two bands attaching the centralizer.

exhibiting low-resistivity through the entire interval, and showing a very low-resistivity spike at each of the two bands attaching the centralizer.

Steel centralizers attached to steel casing were tentatively detected (Case History No. 6). These centralizers are believed to consist of massive bands of steel, welded to the outside of the casing. The short-spacing, and to a lesser degree the long-spacing, density logs exhibited a high-density response to these centralizers (Case History No. 6).

Annular Materials. Annular materials were characterized using density, neutron, and gamma-ray logging through PVC, PTFE, and steel casing. The density log determined the relative densities of annular materials. The neutron log was used to estimate the relative water-filled or air-filled void space within the annulus. The gamma-ray log was used as in indicator of bentonite pellets, chips, or tablets.

Density log interpretation was facilitated with the analytical techniques described in Chapter 1. The use of the frequency distribution plot, referred to as the density trace, graphically displayed the relative densities of annular materials. When these relative densities are compared to the actual relative densities of the same annular materials, the resulting interpretations have a more rational basis.

The side-collimated density logs detected void space through PVC casing in Case History Nos. 1, 2, and 3. The omnidirectional density logs detected void space through PVC or PTFE casing in Case History Nos. 1, 2, 3, 4, and 8. The calibrated omnidirectional density log in combination with the side-collimated density log has the greatest effectiveness as demonstrated in Control Well No. 3, Case History No. 1, where small-scale channeling was identified.

The side-collimated density logs detected void space through steel casing in Case History Nos. 6 and 7. The omnidirectional density logs, calibrated to water and an aluminum block, detected void space through steel casing in Case History No. 5.

The frequency distribution plot or density trace plot was used to display the relative densities of annular materials including void space. When used in combination with a list of bulk densities for the annular materials used, the density trace peak which corresponded to void space was generally significantly lower in grams per cubic centimeter than the peaks representing other annular materials. The density trace analysis was effective only after the data from above the water level were segregated from the data below the water level in a well.

Several additional analytical techniques facilitated the interpretation of annular materials. The comparison of open-hole with completed cased-hole logs, and the comparison of cased-hole open annulus logs with completed cased-hole logs were techniques which were very effective for the gamma-ray logs, and generally effective for the neutron logs. The comparison of similarly constructed wells at the same site was useful, for example the comparison of control wells CW-2 and CW-3 at the site of Case History No. 1.

Voids and Channels. Voids and/or channels constitute one of the distinct entities which occur in the annular space, but are considered as a special case, separate from other annular materials. Voids and channels were identified using density logging through PVC, PTFE, and steel casing. The neutron log was used to determine whether the fluid filling a void was air-filled or water-filled, and was effective through PVC, PTFE, and steel casing. Analytical techniques enhanced the ability to distinguish between void space and low-density annular materials.

The side-collimated density logs detected void space through PVC casing in Case History Nos. 1, 2, and 3. The omnidirectional density logs detected void space through PVC or PTFE casing in Case History Nos. 1, 2, 3, 4, and 8. The calibrated omnidirectional density log in combination with the side-collimated density log has the greatest effectiveness as demonstrated in Control Well No. 3, Case History No. 1, where small-scale channeling was identified.

The side-collimated density logs detected void space through steel casing in Case History Nos. 6 and 7. The omnidirectional density logs, calibrated to water and an aluminum block, detected void space through steel casing in Case History No. 5.

The neutron log distinguished between air-filled and water-filled voids, and through PVC, PTFE, and steel casing, in Case History Nos. 1, 2, 4, 5, 6, and 7. In Case History No. 8, the neutron log response was dominated by its response to the formation.

Two analytical techniques significantly facilitated the identification of voids and channels. The use of frequency distribution plots, called density trace plots, facilitated the interpretation of density logs. Zones where the annular space consists of homogeneous annular materials or a complete lack of annular materials (void space) were readily identified (Case History Nos. 2, 3, 5, 6). Mixtures of annular materials and voids were characterized by their heterogeneity, as indicated by the separation of long- and short-spacing density logs, or the separation of the calibrated omnidirectional density log and a comparable spacing side-collimated density log (Case History No. 1). A measure of this heterogeneity is the best fit of the regression performed during log calibration. Zones which were classified as homogeneous had an R^2 of 0.9 or greater.

The frequency distribution plot or density trace plot was used to display the relative densities of annular materials including void space. When used in combination with a list of bulk densities for the annular materials used, the peak on the density trace which corresponded to void space was generally significantly separated from other annular materials, toward the low-density extreme. Density trace analysis was successful only after segregating the data above the water level from the data below the water level in a well.

The comparison of more than one type or spacing of density tool made it possible to locate heterogeneities in the annular space, which were interpreted as mixtures of annular materials and/or voids, or eccentered casing. The distinction between channeling and eccentered casing requires the consideration of other information such as well construction, formation lithology, and expected density of annular materials

Eccentered Casing. Heterogeneities in the annular space should indicate potential channeling or eccentered casing as described above. The comparison of more than one type or spacing of density tool identified heterogeneities in the annular space. Case History No. 1, control well CW-3 contained an intentionally eccentered section of casing (Figure 11). An omnidirectional density log was calibrated to the side-collimated log having a similar source to detector spacing. The calibrated omnidirectional density log trace was displayed in the same log track with the corresponding side-collimated density log trace (Figure 19). The separation between these two density log traces was shaded to accentuate the differences. The largest shaded area in control well CW-3 occurred adjacent to the eccentered section of casing.

Water Level. A manually operated, electronic, water level indicator or interface probe is generally used to determine the water level in wells gauged for environmental or groundwater investigations. The water level as determined in this study, refers to the water level within the casing. As previously noted, water is required for operation of electrical logging methods such as single-point resistance and guard logs. The discussions in this chapter on the characterization of annular materials and on the identification of voids and channels recapitulated the observed influence of the water level on the neutron and omnidirectional density log responses. It has been shown that the water level influences certain electrical and nuclear logs. Conversely, these same logs can be used as water level indicators.

A note of caution is warranted regarding the determination of water level, using either neutron, density, or resistivity logs. The water level determined during logging is not a static water level. The portion of a logging tool below the measure point for a specific log will displace water within a borehole or casing. This displacement will be more pronounced in wells where the tolerance between the casing and tool is small, because a greater proportion of the volume of the casing is occupied by the tool.

Secondly, the water level within the casing may not be the same as the water level(s) in the formation. Both of these phenomena may have affected log responses and water level determinations in the case histories described.

Conclusions

Borehole geophysics is an effective method for characterizing the details of well construction for all types of monitoring wells studied. Common defects which could compromise well integrity were identified in steel, PVC, and PTFE casing or screen materials. An additional benefit of logging for well construction and integrity is the production of logs which evaluate the formation.

The experimental control wells (Case History No. 1) document with certainty the log responses to the common features of well construction and to many defects for PVC monitoring wells. Table 32 indicates the applicability of nine logging methods for the regions of investigation and for specific types of well construction.

The systematic approach to well log analysis developed herein facilitates log interpretation and the presentation of results. The analytical methods employed provide a more objective and comprehensive approach to monitoring well assessment than any approach which has been published previously.

The logging methods used had several restrictions. Electrical logs used for PVC casing inspection are not applicable above the water level. Density, casing collar locator, and caliper logs used to evaluate field- or torch-slotted steel casing were interpreted with considerable subjectivity. The additional use of an acoustic televiewer or downhole camera would address these limitations.

Another significant restriction was imposed by logging tool diameter. Many of the more effective logging tools are too large in diameter to use in two-inch diameter monitoring wells, for example the dual-spacing, side-collimated density tool and the dual-spacing thermal neutron tool (because of its 10-foot guard log array).

Most of the wells which were evaluated had identifiable defects. Many of the wells had defects which have the potential to compromise the well integrity or otherwise cause data from the well to misrepresent the zone of interest. The determination of the significance of a well defect requires additional information. Site geology and the distribution of any contaminants

TABLE 32

APPLICABILITY OF SELECTED LOGGING METHODS FOR SPECIFIED MONITORING WELL ENVIRONMENTS

LOGGING METHOD	REGION INVESTIGATED				FLUID		TUBULAR MATERIALS			
							PVC, PTFE		STEEL	
							INSIDE DIAMETER			
	I	II	III	IV	AIR	H_2O	2"	≥4"	2"	≥4"
GAMMA RAY										
free swinging				1	✓	✓	✓	✓	✓	✓
decentralized				1	✓	✓		✓		✓
DENSITY										
free swinging & omnidirectional (4π)										
single spaced, 15"		2	1		✓	✓	✓	✓	✓	✓
dual spaced, 9.8" & 18.9"		2	1		✓	✓	✓	✓	✓	✓
decentralized & side collimated										
single spaced, 1.75"		1	2		✓	✓		✓		✓
single spaced, 8"		2	1		✓	✓		✓		✓
dual spaced, 5.9" & 12.2"		2	1		✓	✓		✓		✓
NEUTRON (THERMAL)										
free swinging & omnidirectional (4π)										
single spaced, 14"			2	1	✓	✓	✓	✓	✓	✓
single spaced, 16.75"			2	1	✓	✓		✓		✓
dual spaced, 10.8" & 24.5"			2	1	✓	✓		✓		✓
DIFFERENTIAL SINGLE POINT RESISTANCE	1	2				✓	✓	✓		
free swinging & omnidirectional										
NORMAL RESISTIVITY										
free swinging, 16"-64"	1	2				✓		✓		
GUARD LOG										
decentralized, 15"	1	2				✓		✓		
decentralized, 55"	1	2				✓		✓		
decentralized, 120"	1	2				✓		✓		
INDUCTION LOG										
free swinging			2	1	✓	✓	✓	✓		
CASING COLLAR LOCATOR										
free swinging	1	1	2		✓	✓		✓		✓
CALIPER										
decentralized, one-arm, 8" or 14" arm	1				✓	✓		✓		✓
centralized, three-arm	1				✓	✓	✓	✓	✓	✓

REGIONS OF INVESTIGATION

I INSIDE CASING OR SCREEN
II CASING OR SCREEN WALL
III ANNULUS BETWEEN PIPE AND FORMATION
IV FORMATION

ADDITIONAL NOTATIONS

1 PRIMARY AREA OF INVESTIGATION
2 SECONDARY OR INCIDENTAL AREA OF INVESTIGATION
✓ INDICATES METHOD IS APPLICABLE

are factors which will determine the potential of well defects to cause cross-aquifer contamination, to invalidate aquifer test data, or to cause water samples to be unrepresentative of the zone of interest. Significant aspects of site geology include structure, stratigraphy, and the hydrogeology of the aquifer system.

Logging services available to the mineral and groundwater industries are cost effective for evaluating well construction and integrity. The cost of evaluating a well with the geophysical logging methods used in this study is low in comparison to the indirect costs which may be incurred as a result of defective wells. These indirect costs could result from invalidated samples and tests, cross-contamination of aquifers, and other problems which are a consequence of poor well design or construction.

The logging methods which evaluate Region of Investigation IV, the formation, afford an opportunity to perform stratigraphic analysis at a level of detail which is uncommon at environmental sites. Intervals from which samples can not be recovered can be evaluated. For example, where the aquifer consists of thick, saturated, unconsolidated sands and gravels, complete remediation systems are commonly installed with little or no stratigraphic analysis. As a result, aquifer tests at such sites often show boundary effects for which a cause can not be identified, and recovery wells are commonly placed in areas where they are ineffective. Cased-hole logging can result in significant improvements in remediation design, by better defining subsurface conditions. The resulting project cost savings can exceed logging costs many times over. For example, one inoperative recovery well can cost tens-of-thousands of dollars. This equals the cost of an extensive logging project.

CHAPTER 6

GUIDELINES AND RECOMMENDATIONS

One of the principal objectives of this research was to develop guidelines for geophysical well logging to verify well construction and integrity. A decision matrix was proposed to facilitate the selection of logging methods. A recommended approach to planning and developing a well logging strategy is outlined with a decision matrix for logging method selection.

This research also identified problem areas which can be addressed with future research. These problem areas include a need for calibration methods and models for cased-hole logging in typical groundwater monitoring wells and water supply wells, a need for logging tools which are designed for the purpose of assessing groundwater monitoring well construction and integrity, and a need to reduce the Federal and State regulations which impede the use of radioactive sources for geophysical well logging in groundwater studies.

A Systematic Approach to the Selection of Logging Methods

Preliminary Research

Prior to selecting specific logging methods and logging tools for a project, several types of information should be acquired if possible. The probable effectiveness of a proposed logging effort increases as background information is made more detailed and complete. The tasks required to produce the desired background information are described below.

Summarize Well Construction Details. Only a few logging tools are typically transported to a job site for logging. If the log analyst knows in advance the details of well construction such as the depth to water, casing materials, casing diameter(s), and suspected well defects, the logging strategy will be improved and the optimal suite of logs can be obtained.

Determine Accessibility of Well(s). Restricted access to a well can preclude logging, especially if not anticipated. A well is generally considered inaccessible if pumps, piping, or other appurtenances are in the well casing. Buildings or sheds built over a well and the location of building doors and openings should be considered. If a logging truck cannot back up to a well casing and extend its boom over the well casing for logging, a sheave block can be mounted on the well casing or suspended from rafters or a tripod to permit the lowering of logging tools into the well. If a sheave block is used, the space between the sheave and the logging truck must be unobstructed so that the cable can move freely. The geophysical well logging contractor can advise the worker with regard to the maximum practical distance between the well and logging truck.

Consider Regulatory Constraints. Geophysical well logging is regulated by Federal and State agencies when radioactive sources are used. Such regulations often restrict the types of well logging which may be performed within a fresh-water zone or make well logging prohibitively expensive through licensing fees. Prior to designing a logging program, the worker should review any regulations which pertain to geophysical well logging.

The Nuclear Regulatory Commission (NRC) requires licensing for geophysical well logging when radioactive materials are used, pursuant to 10 CFR Part 39. When a radioactive source is used for well logging, the NRC requires its licensees to enter into a written agreement with the employing well owner or operator prior to initiating logging (Code of Federal Regulations, 10 CFR 39.15(a)). This agreement must identify who will be responsible for recovering or attempting to recover a radioactive source should it become lodged in a well or borehole. Geophysical well logging contractors require the employing well owner or operator to be responsible, unless incompetence or negligence is involved on the part of the logging engineer. This requirement is unacceptable to some potential users of geophysical well logging, especially if they are unfamiliar with the business practices common to the petroleum and mineral industries.

According to NRC Information Notice No. 90-15, dated March 7, 1990, 29 states have entered into agreements with the NRC which make each Agreement State Radiation Control Director responsible for compliance with 10 CFR Part 39. Some of these states have established prohibitively expensive licensing fees for geophysical well logging with radioactive sources. For example, well construction was possibly defective at a Tennessee site and potential cross-aquifer contamination was a concern. However, cased-hole well logging to investigate well integrity and stratigraphy was ruled out due to a State of Tennessee licensing fee of $4,000 for well loggers. State officials provided no encouragement that a short-term waiver of fees could be negotiated, even in the interest of public health and safety.

Several states restrict geophysical well logging through potential aquifers. For example, the State of Kansas prohibits all nuclear logging in water wells and groundwater monitoring wells. As a result, it was impossible to utilize geophysical well logging at a contaminated site in Kansas to characterize an aquifer where samples of unconsolidated alluvium could not be recovered.

The applicable licensing fees and legality of any proposed use of logging tools which have a radioactive source should be confirmed as a part of project planning. In some states, well intentioned regulators are removing a valuable technology from the environmental investigator's toolkit through fees and restrictions.

Identify Potential Contaminants. Any suspected groundwater contamination may affect the logging strategy and will determine precautions against cross-contamination of wells. The logging strategy may be affected if contaminants could damage logging equipment due to corrosivity or other properties. In addition, if free-phase contaminants are present in the formation or in the well casing, certain log responses may be affected, depending on the contaminant. It may be possible to identify free-phase contaminants outside the casing in the same manner that bypassed oil and gas can be identified, especially with neutron logging.

Consider Decontamination Procedures. The method and location of decontamination for logging equipment must be preplanned if contaminants are potentially present. Logging tools and cable will be wetted by any groundwater which they contact, and must be decontaminated before the first logging run at a site and, if groundwater contamination is present, after each logging run.

Most logging contractors have not standardized equipment and procedures for logging tool decontamination. Equipment designed for decontaminating cable for well sampling equipment may be ideal for this application. For example, Art's Manufacturing & Supply, American Falls, Idaho, manufactures an electric boom system for groundwater sampling which is very similar in configuration to a logging unit with a boom. A decontamination box is mounted on the boom, where the cable is sprayed with 195° water at a pressure of approximately 1000 psi as it moves through the box. Equally effective methods should be developed for geophysical well logging equipment for water supply well and groundwater monitoring well logging.

The ease of decontamination of all logging equipment which may cause cross-contamination should be considered. Four-conductor logging cable which uses Kevlar® strands for strength and which is polyethylene-coated is more easily decontaminated than the braided wire-wrapped cable. Polyethylene-coated cable is recommended for environmental logging when available. Manufacturers of geophysical well-logging tools should consider manufacturing disposable, synthetic, prophylactic covers for logging tools to facilitate decontamination.

Identify Logging Objectives. In order to select the appropriate logging methods, the purpose of the logging project must be well defined. The procedure which is described here requires specific and clearly stated objectives.

Select Logging Methods and Equipment

After the preliminary research has been conducted, logging methods can be selected to achieve the stated objectives of the logging program. The concept of "regions of investigation" which guided this research, can be used to categorize logging objectives and to facilitate the selection of appropriate logging methods.

Select Logging Methods. A series of decision matrices have been developed for the selection of logging methods. Each matrix flows from left to right. The first matrix (Figure 33) is used to select the Figure which illustrates the appropriate matrix for each region of investigation.

One decision matrix is provided for each of the four regions of investigation (Figures 34 through 37). The first step to work through each matrix is to select a specific logging objective and follow that path. Where necessary, the anticipated casing material is selected. Finally, the matrix flows to a box containing the logging method or methods which may be applicable. The qualitative terms good, fair, and poor are used to indicate the performance evaluation for each logging method as applied to the specified objective. In addition, examples of selected applications of logging methods which are documented by the case histories are cross referenced.

Select Logging Tools. Where more than one logging method can be used to achieve an objective, prioritize the several logging methods for that objective, using the qualifiers provided in the decision matrices. Obtain logging tool specifications from all potential geophysical well logging contractors. Review the tool dimensions and the logging methods incorporated into each tool.

Eliminate all tools which are not at least ½-inch smaller in diameter than the minimum inside diameter of the wells to be logged. Select one or more logging tools based on:

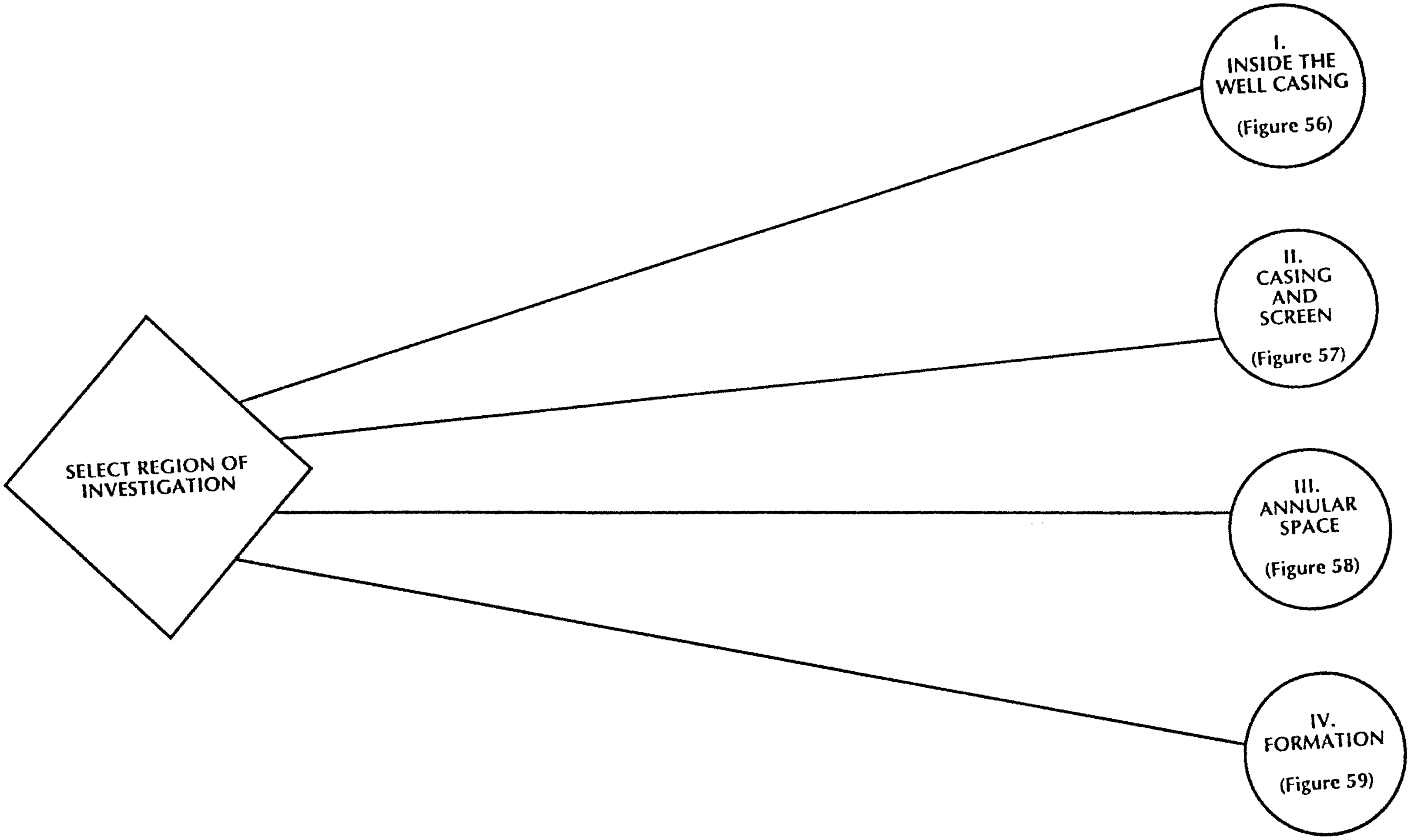


Figure 55. Decision Matrix for Selecting Region of Investigation

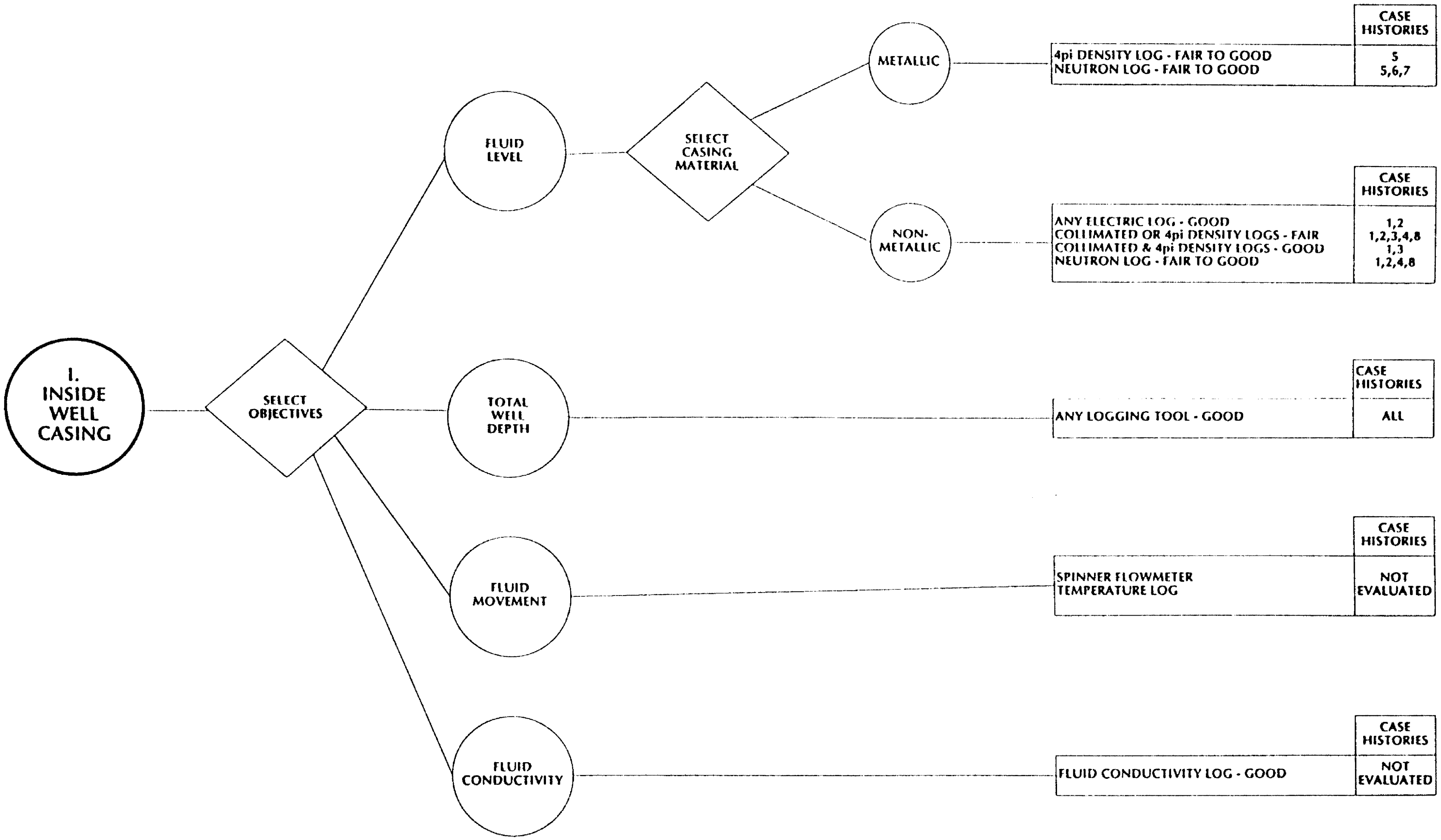


Figure 56. Decision Matrix for Logging Method Selection, Region of Investigation I

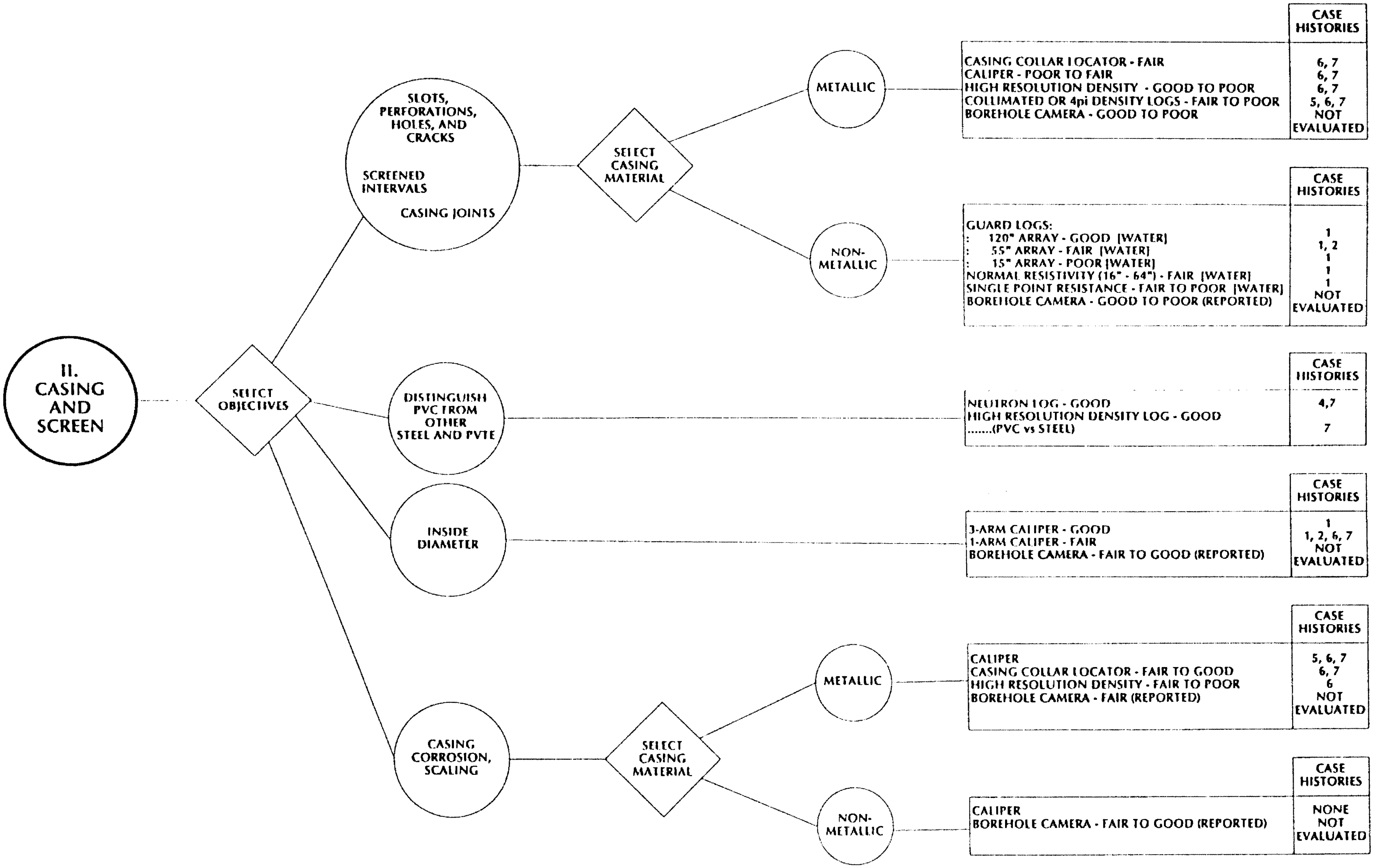


Figure 57. Decision Matrix for Logging Method Selection, Region of Investigation II

[WATER]: LOGGING METHOD REQUIRES WATER

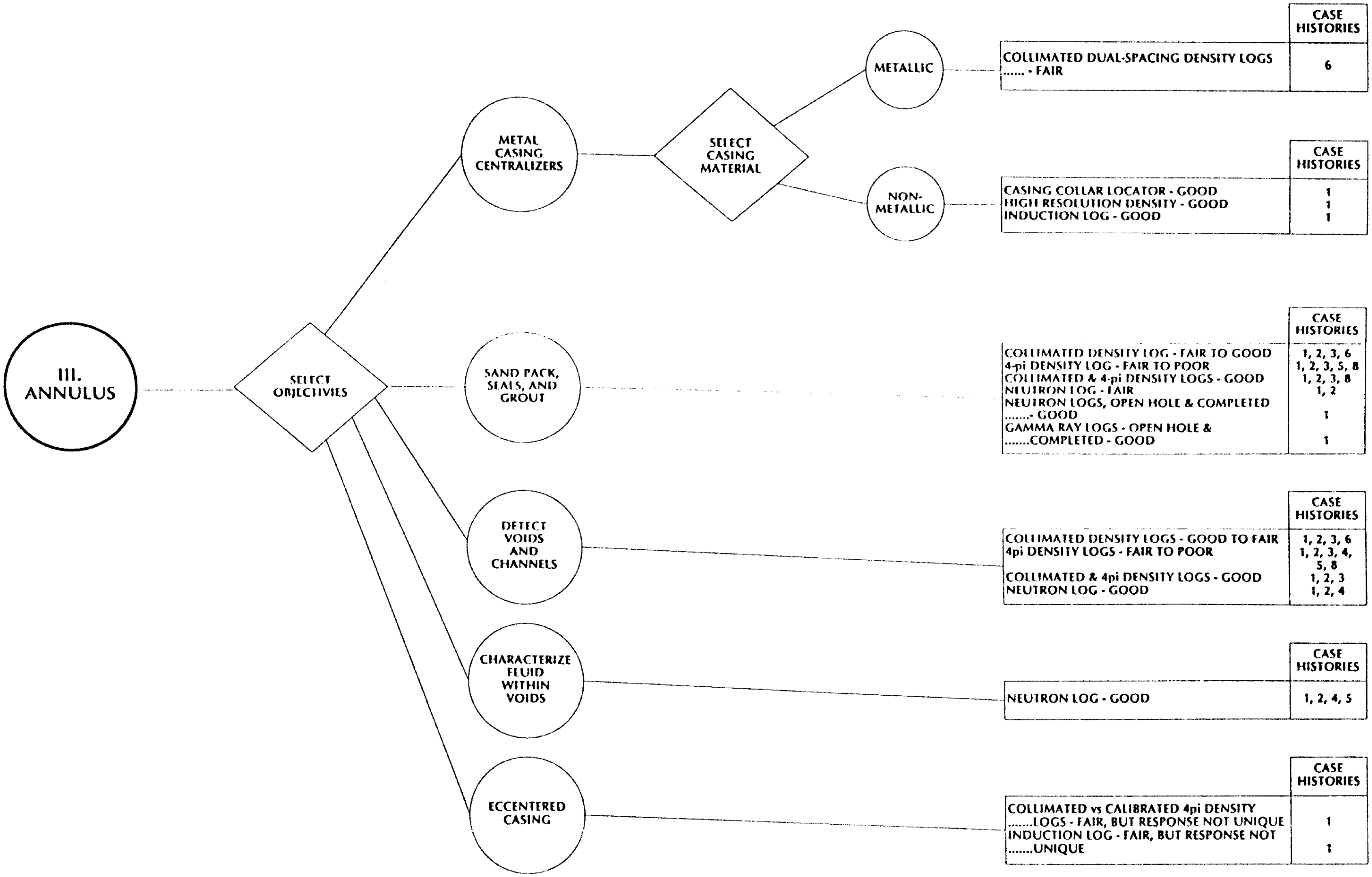


Figure 58. Decision Matrix for Logging Method Selection, Region of Investigation III

(WATER): LOGGING METHOD REQUIRES WATER

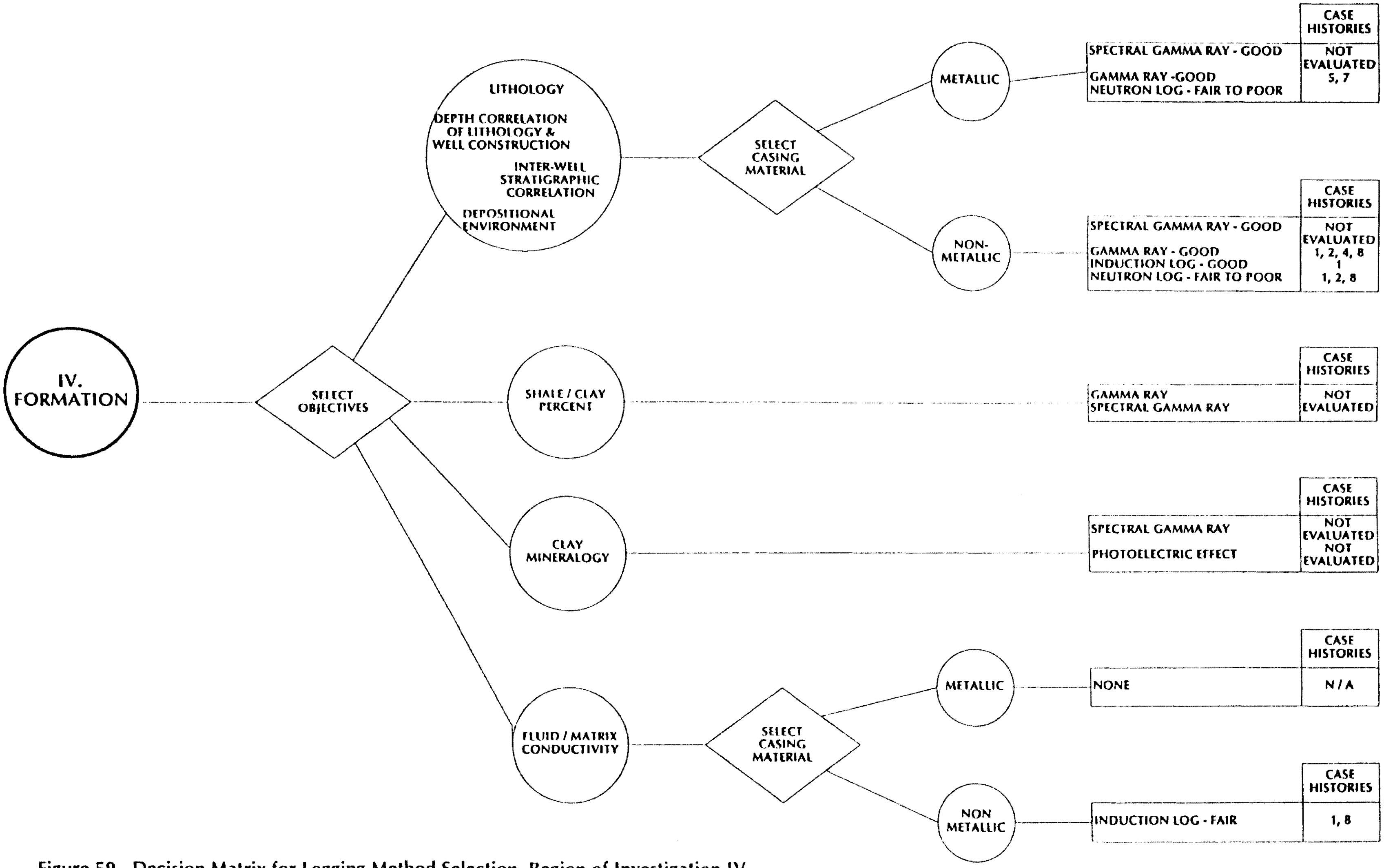


Figure 59. Decision Matrix for Logging Method Selection, Region of Investigation IV

[WATER] : LOGGING METHOD REQUIRES WATER

- selecting the most effective logging methods for each stated objective using the qualitative evaluations for each objective and method (Figures 33 through 37); and,
- minimizing cost by using the smallest number of tools which will address all stated objectives.

Recommendations for Future Research and Development

As a result of this project, a number of ideas have evolved which might improve the ability to evaluate monitoring well and water supply well construction and integrity. Specific recommendations are made for future research, and/or for geophysical technology development.

The responses of the single-point resistance log and the several guard logs to holes, joints, and slots in PVC casing and well screen should be evaluated in fluids having known and varied conductivities. Variations in fluid conductivity are believed to explain many of the variations in response amplitude for these electric logs when used to evaluate Region II.

Research should be conducted to develop calibration and/or analytical methods which would permit a more quantitative evaluation of the annular space. The experimental control wells (Case History No. 1) could be maintained and used as a calibration facility. For example, the omnidirectional response in control well CW-1 could be calibrated to a side-collimated density log for control well CW-2, using specific intervals with the same annular materials in a multipoint calibration equation of an appropriate order.

Two types of logs which were not available for this study have potential use for identifying bentonites used for annular seals, the spectral gamma-ray log and the photoelectric index log. The spectral gamma-ray log passively measures radiation produced by potassium, uranium, and thorium isotopes (see definition and related terms, Appendix A), and has been used for distinguishing between clay minerals. The photoelectric index log measures low energy backscattered gamma rays produced by a density logging tool (see photoelectric absorption and related terms, Appendix A), and has also been used for distinguishing between clay minerals. Both of these logs have the potential for improving the characterization of annular materials, but are not known to be available through mineral logging contractors. The feasibility of using the spectral gamma-ray and the photoelectric index logs for evaluating the annular space should be investigated.

Color information theory should be applied to well log presentations to facilitate data interpretation. Colored log traces and shading are easier to interpret than the black and white log presentations produced for this study.

Logging tools should be manufactured specifically for evaluating monitoring well and water supply well integrity. Such tools would include the optimal suite of logs for evaluating the several regions of investigations in a specified type of well construction.

Finally, all future research will be more readily funded when the methods developed in this study are generally accepted and in widespread use. In order to gain widespread acceptance of these methods, parts or all of certain of the case histories described herein should be published in journals which are read by environmental professionals and hydrogeologists .

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APPENDIX A

GLOSSARY OF TERMS

APPENDIX A

GLOSSARY OF SELECTED TERMS

Note: italics are used by the editor (Ransom) where a definition incorporates technical terms which are also found in (the complete edition) of the SPWLA glossary.

acoustic log: A record of *well-logging* measurement of one or more specific characteristics of *acoustic waves* propagated in and around the liquid-filled wellbore.

(1) The *interval transit time*, usually of the *compressional wave*, is recorded on such logs as the *sonic log*, continuous velocity logs, and the *borehole compensated sonic* and Acoustilogs.

(2) The amplitude of part of the propagated acoustic wave, such as the compressional wave or *shear wave*, is the measurement recorded on other well logs. These are the *amplitude log*, *cement bond log*, and *fracture logs*.

(3) The acoustic wave train of the propagated acoustic wave is displayed in the *amplitude-time* mode on full wave train logs such as *signature logs* or *character logs*; whereas the wave train is shown in the *intensity modulated-time* mode on *variable density logs*, *variable intensity logs*, 3-D velocity Logs, or micro-Seismogram Logs.

(4) Includes logs resulting from the measurements of *travel time* and amplitude of reflected *acoustic* energy. Tools making such measurements are the *borehole televiewer* and *sonar caliper*.

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(5) Also includes logs produced by devices which detect and measure the amplitude of sound waves in the audible frequency range. Audible sound might emanate from liquid or gas movements in the wellbore environment. Tools developed to make such measurements are used in audio or *noise logging* techniques.

acoustic travel time: (1) The total time required for a specific *acoustic wave* to travel from one point to another.

(2) *interval transit time*. The time required for a *compressional wave* (usually) to travel from one point to another separated by a distance of unit length (usually one foot).

activation logging: A well-logging technique in which the *formation* in the near environment of the irradiating tools is irradiated with *neutrons* which transform some nuclei into *radioisotopes*. The specific radioactive *isotopes* which are produced by activation of the nuclei can be detected by their characteristic induced *radioactivity* energy levels and *decay-time* schemes. this provides a means for identifying the elements originally present.

A electrode: The current-emitting *electrode* in the configuration of current and potential-measuring electrodes of a *resistivity*-measuring device.

alpha particle: A particle identical to the helium nucleus which has been ejected from the nucleus of an *atom* as a form of *radiation*. When the alpha particle slows down it picks up two electrons, becoming an atom of helium. The penetrating power of an alpha particle is low; a thin sheet of paper will stop most alpha particles. The readjustment which takes place within the parent nucleus results in gamma *radiation*.

AM spacing: The notation used to refer to the distance between the current electrode (A) and the *potential* measuring electrode (M) of the *normal device*.

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amplitude log: A record of the amplitude of the *compression wave* or *shear wave* portion of the *acoustic wave* propagated through the borehole environment in *acoustic logging*.

AO spacing: The notation refers to the distance between the current electrode (A) and a point (O) midway between the *potential*-measuring electrodes (M and N) of the *lateral device*. On the *reciprocal sonde*, it is the distance between the M electrode and a point (O) midway between the current electrodes (A and B).

API log grid: The API log grid is the standard format used by all logging companies in the petroleum industry. This *log* grid has one *track* on the left side of the *depth column* and two on the right. The tracks are 2.5 inches wide and the depth column is 0.75 inches wide. The tracks may be divided into a linear *scale* or logarithmic scale.

API test pits: *Calibration* pits, located at the API *nuclear log* calibration facility at the University of Houston, used for the calibration or standardization of *gamma-ray logging* responses and *neutron logging* responses into API *units*.

API unit: A unit of counting rate used for scaling *gamma-ray logs* and *neutron logs.*

(1) For gamma-ray curves. The difference in curve *deflection* between zones of low and high *radiation* in the API gamma-ray *calibration* pit is 200 API units. One two-hundredth of this deflection is one API gamma-ray unit.

(2) For neutron curves. The difference between *electrical zero* and the curve deflection opposite a zone of Indiana limestone (19% *porosity*) in the API neutron calibration is 1,000 API units. One one-thousandth of this deflection is one API neutron unit.

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apparent resistivity: *Resistivity* recorded on a resistivity well log which may differ from *true resistivity* because of the influence on the measured response caused by the presence of the *mud* column, *invaded* zone, adjacent *beds*, borehole cavities, etc. These values may need correction prior to use in any computation.

apparent value: The uncorrected value of a *curve* recorded directly on a *log*.

Archie's formulas: Empirical relationships between the *formation resistivity factor* F, *porosity* ϕ, *water saturation* S_w, and resistivities in *clean* granular rocks.

$$F = \frac{1}{\phi^m}$$

$$F = \frac{R_o}{R_w}$$

$$\frac{R_o}{R_t} = S_w^n$$

where m = *porosity exponent*,

R_o = *resistivity* of the *formation* when 100% saturated with *formation water*,

R_w = formation water resistivity,

R_t = *true resistivity* of the formation,

n = *saturation exponent*.

atomic number: The number of *protons* within an atomic *nucleus*, or the number of orbital electrons in a "neutral" *atom*.

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atomic weight: atomic mass. The relative weight of an *atom* on the basis that carbon is 12. For a pure *isotope*, the atomic weight rounded off to the nearest integer equal to the total number of *neutrons* and *protons* in the atomic nucleus.

attenuation: When a form of energy is propagated through a medium, its amplitude is decreased. This decrease is termed attenuation.

background radiation: The *radiation* intensity existing in the environment which is in addition to the specific radiation under consideration. On the surface, this is the ionizing radiation produced by cosmic *irradiation* and naturally occurring trace amounts of radioactive elements. In the subsurface, this is the naturally occurring radiation prior to the introduction of *radioactive tracer* materials or *activation*.

base-line shift: (1) Generally refers to a naturally occurring shift of the base line of any specific *curve*; e.g., the SP curve. Usually the base line referred to is the *shale base line*, but could be the sand base line or other base line.

(2) Sometimes refers to a manual or electrical shift in the curve produced by the logging engineer.

B electrode: A current-return electrode in the current and measure electrode configuration of a *resistivity* measuring device.

beta particle: A high speed disintegration electron (i.e., negatron or positron) spontaneously emitted from an atomic nucleus as a form of *radiation*. Electrons (negative or positive) do not exist in nuclei; they are created at the moment of emission and are accompanied by the transition of a *neutron* into a *proton*, or a proton into a neutron. The *atomic number* of the *nuclide* is changed by a +1 or a -1 with no significant change in *atomic weight*. A beta particle can penetrate only a few millimeters of rock.

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BHT: Bottomhole temperature, usually obtained by *maximum reading thermometers*.

borehole compensated sonic log: A *well log* of the *interval transit time*; i.e., the time required for a *compression wave* to travel one foot in the *formation* (generally in microseconds per foot); the reciprocal of the compressional velocity. The borehole compensated sonic *sonde* carries two sets of *transducers*, one with its *transmitter* above its *receiver* pair and one with its transmitter below. The transmitters are pulsed alternately, and the alternate measurements are averaged. Spurious effects caused by borehole size changes, and sonde tilt, which would affect a measurement with a single set of transducers, are thereby substantially reduced.

borehole effect: The spurious influence on al well-logging measurement due to the influence of the borehole environment; e.g., diameter, shape, *rugosity* of the wall of the borehole, type of borehole fluid, and presence of *mud cake*.

borehole gravimeter: A *gravimeter* designed for use in a borehole and equipped for remote leveling and reading at precisely determined well depths. It can be used to determine *bulk density* deep, laterally within a *formation*.

borehole televiewer: A well-logging system wherein a pulsed, narrow *acoustic (sonar)* beam scans the borehole wall in a tight helix as the *tool* moves up the borehole. A display of the amplitude of the reflected wave on a cathode ray tube (television screen) is photographed yielding a picture of the borehole wall. The picture is a representation of the wellbore wall as if it were split vertically along magnetic north and laid out flat. Physical discontinuities such as fractures, vugs, etc. are detailed on the *log*. The tool may be used for casing inspection, without the magnetic orientation for location of perforations or damage.

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bucking electrodes: bucking-current *electrodes*. Current electrodes on a *laterolog* type *resistivity* measuring system from which bucking current flows in order to confine the *survey* current into a thin, horizontal investigative layer. Serve the same purpose as *guard electrodes* except bucking electrodes are usually rings or point electrodes (e.g., *buttons*).

bulk density: It is the value of the *density* of rock as it occurs in nature. In well logging, it is the density of the rock with the pore volume filled with fluid. Natural density. The equation commonly used to compute *porosity* from *well log* derived bulk density is:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

where ϕ is pore volume filled with a fluid of density ρ_f, ρ_b is the well-log-derived bulk density, and ρ_{ma} is the *density* of the rock framework.

bulk volume water: The quantity of *formation water* present in a unit volume of rock. The product of *water saturation* and *porosity*.

calibration: The process wherein the zero and *sensitivity* of the measuring circuit is adjusted to meaningful units so that the recorded measurements will be accurate with respect to an industry standard.

caliper log: A *well log* which is a record of hole diameter. Hole caliper logging tools sometimes have 1, 2, 3, 4, or 6 arms. Some caliper logging tools use *acoustic* methods of determining hole dimensions.

camera: (1) recorder. An instrument which records traces of light which have been beamed on film by *galvanometers* responsive to logging tool measurements. Some cameras may use laser technology or fiber optics.

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(2) borehole camera. A downhole instrument which photographs the interior of the borehole or casing.

capture cross section: (1) The *nuclear* capture cross section for neutrons is the effective area within which a *neutron* passes in order to be captured by an atomic nucleus. It is a probabilistic value dependent on the nature and energy of the particle as well as the nature of the capturing nucleus. Nuclear capture cross section is often measured in barns
(1 barn = 10^{-24} cm^2).

(2) "Macroscopic capture cross section" Σ is the effective cross-sectional area per unit volume of material for capture of neutrons; hence, it depends on the number of atoms present as well as their nuclear capture cross sections. Thus, the macroscopic capture cross section is the sum of the various weighted capture cross sections. The unit of measure for Σ is cm^2/cm^3 or reciprocal cm (cm^{-1}); Σ is often measured in "capture units" or "sigma units."
A c.u. = $10^{-3}cm^{-1}$.

(3) The rate of absorption of *thermal neutrons* with a velocity v is $v\Sigma$.

(4) of *gamma rays.*

capture gamma ray: A *gamma-ray photon* produced upon the capture of a *thermal neutron* by a neutron absorber such as chlorine. Gamma rays of capture are important in some *neutron logging* methods (n-γ) and in *pulsed neutron* logging methods such as the *Thermal Decay Time Log* or *Neutron Lifetime Log.*

capture unit: c.u., $10^{-3}cm^{-1}$. A unit of measure of macroscopic *capture cross section*. Same as *sigma unit.*

carbon-oxygen log: A log which presents a measure of the relative abundance of carbon to oxygen derived from the detection of *gamma rays* produced from both elements by the *inelastic scattering* of 14-MeV *neutrons*. The gamma rays are measured within energy spectrum windows representing the gamma-ray escape peaks of carbon and oxygen. The ratio of counting rates provides a means of predicting the relative amounts of hydrocarbons and water. The log is an alternate means for detecting hydrocarbons (particularly oil) behind casing in formations not subject to flushing or reinvasion by borehole fluids. The C/O ratio is relatively independent of *formation water salinity* and shaliness. In order to differentiate carbon in hydrocarbon molecules from that in the rock framework (i.e., carbonate solid matter), a Si/Ca ratio is also determined.

The carbon-oxygen log can be put to nearly the same uses as the *pulsed neutron capture logs*, but has proved to be useful under some conditions where pulsed neutron capture logs have shown decreased effectiveness; e.g., in rocks where formation water cannot easily be distinguished from oil because of the lack of sufficient contrast in their neutron *capture cross sections*. Carbon/Oxygen Log is a Dresser Atlas trademark.

casing collar locator: Used to locate casing collars and other features of downhole hardware (e.g., packers, etc) which often serve as reference depths in subsequent completion operations.

(1) a magnetic casing collar locator. Involves a system of two opposed permanent magnets in two similar magnetic circuits which produce characteristic magnetic fields in which flux lines pass through casing or tubing. A deformation of either of the magnetic fields, caused by the gap between casing joints, packers, sometimes holes, etc., is detected by a winding having a core of high permeability. The resulting electromagnetic imbalance, first in one direction

and then in another, is telemetered to the surface where it is recorded, depth correlated, as a feature of the downhole hardware arrangement.

(2) a mechanical collar locator. May involve feelers or fingers which produce *signals* sent to the surface when the feelers cross pipe connections or other irregular features inside casing or tubing.

casing collar log: A record of casing collar responses with depth as measured by a *casing collar locator*. Usually is an integral part of all *well logs* run in the cased borehole. The casing collar log provides a means of depth control for other measurements and responses which cannot in themselves be accurately correlated with the *formation* behind casing.

casing inspection log: Uses a method of relating the effects of eddy currents on a magnetic field to casing wall thickness. The instrument consists of two radial coils — an exciter and a pickup coil. the exciter coil is fed from an AC voltage source at the surface, in turn producing a magnetic field downhole. This field sets up eddy currents in the casing wall. These currents cause the magnetic field to be attenuated and shifted in phase. The resulting magnetic field is detected by the pickup coil and transmitted to the surface. The magnetic field as detected by the pickup coil is then compared with the original field generated by the exciter, coil and the resulting phase shift in the magnetic field that has occurred is recorded. The phase shift can indicate casing wall thickness, splits, and holes.

casing potential profile: Detects corrosion by measuring the electrical *potential* of the casing at various levels to detect current entering or leaving the casing. The amount of cathodic protection needed can be determined and results monitored.

cement evaluation log: CET. A *cased hole* cement evaluation log that displays data processed from ultrasonic *transducers* in such a way that *channels* in the *cement* sheath can be detected. The quality of the cement is given in eight radial segments, and the orientation of a channel can be determined from a recording of the well *deviation* and the *relative bearing* of the first transducer. An acoustic caliper measurement is provided from eight radii measurements. CET is a Schlumberger mark.

cementation factor: The *porosity exponent* (m) in Archie's *formation resistivity factor*-porosity relationship.

cement bond log: Used to determine the presence of cement behind casing and the quality of cement bond to casing or *formation* wall. Usually an *acoustic log.*

The cement bond log is a continuous measurement of the amplitudes of acoustic pulses after they have traveled a length of the casing. The amplitude of a pulse is strong after travelling along unsupported pipe because there is nothing to restrict the vibration of the casing. On the other hand, the vibration of the casing is dampened by the cement sheath in well-cemented pipe, and amplitude is weak. if the formation bond is poor, acoustic energy traveling through the formation is weak; if both the casing and formation are well bonded, only the formation *signal* is strong. The log may consist of (1) an *amplitude log* which represents the amplitude of a portion of the acoustic *wave train*, or (2) a display of the acoustic wave train in the amplitude-time (*wave train*, x-y) mode or the intensity modulated-time (*variable density*, x-z) mode.

centralizer: A device which positions the logging *tool* in the center or near center of the well bore, aligned with the wellbore axis.

chlorine log: A log based on the counting rate of capture *gamma rays* produced by capture of *thermal neutrons* by chlorine in the *formation.* By limiting the count to a certain energy range, the tool is made more sensitive to chlorine and relatively less sensitive to formation porosity. The interpretation of such curves yields a calculated water saturation. the chlorine log's primary application is in cased holes.

collar: (1) A *coupling* device with internal threads used to join two pieces of threaded pipe of the same size.

(2) drill collar. A thick-walled steel pipe used to stabilize the bottom-hole drilling assembly. The drill collars are used to provide the weight required to drill the hole. The collars are usually under compression while the drill pipe is always under tension.

collimated gamma radiation: Gamma *radiation* in which the stream of *photons* is beamed in a single direction.

combination logging tool: A single assembly of logging *tool* components, often joined in tandem, capable of performing more than one general type of logging service with a single trip into the well bore.

compatible scales: The interpretation of *well logs* often requires a direct comparison of one logging response with another, performed at the same time or at a different time In order to facilitate this comparison, the same *grid* type and equal *scale sensitivities* must be used. *Overlay* techniques particularly require the use of compatible scales.

compensated density log: See *compensated formation density log.*

compensated formation density log: A dual-spacing formation *density log*. The compensated *formation* density logging device employs two *detectors* spaced at different distances from the *source*. The detector at the shorter spacing is particularly sensitive to the *density* of material immediately adjacent to the face of the *pad*. The contribution of this material, which includes *mud cake* and *drilling mud* filling minor *borehole* wall irregularities, affects the response of each detector to a different degree. The measurements from both detectors provide a means for making a correction for the influence of drilling mud and mudcake on the measurements. This correction is automatically added to the uncompensated density measurement from the detector at the longer spacing. Through the use of appropriate instrumentation, the parameters recorded are: a corrected or compensated value of *bulk density*, a measure of the correction, $\Delta\rho$, used in making the compensation, and a *caliper curve*. With the unwanted borehole effects removed, the measurement is recorded directly in terms of *bulk density* on a linear *scale*.

compensated log: A *well log* made with a tool designed to correct for unwanted effects associated with the borehole. The *compensated density log* uses the *signal* from a secondary *detector* to correct for the effect of the *mud cake* and small irregularities in the borehole wall. The *borehole compensated sonic log* uses a special arrangement of the *transducers* to correct for irregularities in borehole size and *sonde* tilt.

compensated neutron log: A *well log* made with a mandrel-type *neutron logging* tool having two *neutron* detectors. The *neutron porosity* is derived from the ratio of the counting rates of the two detectors. Use of the count-rate *ratio* greatly minimizes borehole effects. This tool can be run in liquid-filled holes, both cased and uncased, but is not usually recommended for use in gas-filled holes.

Compensated Spectral Density: CSD, a Welex trademark. This tool combines the features of the compensated density tool, which measures density by *compton scattering* cross section of *gamma rays*, and the *lithology* effect by measuring the low gamma-ray energies associated with the *photoelectric absorption cross-section*. This lithology recognition is further enhanced by borehole compensation of the photoelectric gamma response.

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composite log: Several *well logs* of the same or similar types, usually from different logging runs which have been spliced together to form a single continuous record from the shallowest to the deepest log reading. Composite logs are valuable for *correlation* and documentation purposes.

compressibility: The volumetric change in a unit volume of fluid (usually) when the pressure on that volume is changed.

$$\text{compressibility} = \frac{\Delta V}{R_w} \cdot \frac{1}{\Delta P}$$

where ΔV = change in volume, V, due to change in pressure, ΔP.

compression wave, compressional wave: P-wave, longitudinal wave. An *acoustic* wave propagated parallel to the direction of particle displacement. Substances which tend to resist compression support the propagation of compression waves (e.g., liquids and solids).

Compton scattering: The inelastic scattering of *photons* (*gamma rays*) by collision with orbital electrons of an atom. When a gamma-ray photon having an energy in the intermediate range from about 2 keV to about 2 MeV collides with an atom, it may transfer some energy to one of the orbital electrons, which, as a result, is knocked out of the atom. The photon thereby loses some energy (its frequency is lowered) and changes direction according to its energy loss. The Compton scattering power of a material is proportional to the number of electrons in that material. Important in *density logging*. One of the three interactions of gamma rays with matter.

conductivity: The property of a solid or fluid medium which allows the medium to conduct a form of energy; e.g., electrical conductivity or thermal conductivity. In well logging, presently, the

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conventional use of the term means electrical conductivity, which is the reciprocal of electrical *resistivity.*

Usually expressed as the reciprocal of ohm-meters x $\frac{1}{1000}$, or $\frac{\text{mmhos}}{\text{meter}}$.

continuous flowmeter: A velocimeter which is designed to measure fluid velocities in the *casing.* Usually this *tool* is capable of passing through production tubing to make fluid velocity measurements in the casing below. The *tool* is held in the center of the fluid column usually by spring *centralizers* and moved at a constant rate of speed against (or with) the direction of flow. The spinner speed, a linear function of fluid velocity relative to the tool, is recorded continually versus depth.

Primarily, this tool should be used in monophasic flow regimes; i.e., injection wells and high-flow-rate gas wells or oil wells.

continuous guidance log: The continuous guidance tool provides a continuous gyroscopic directional measurement in *cased holes.* The measurement is based on a two-axis gyroscope whose spin axis is maintained horizontal and is aligned towards the north. The position of the gyro is sensed by an accelerometer and a gyro-axis positional resolver. This information is combined with data from another accelerometer to derive the *azimuth* and *inclination* of the hole.

continuous velocity log: A log of the *interval transit time* of a *compressional wave.*

curie: A standard measure of the rate of *nuclear* transformations, or disintegrations equal to that of one gram of radium. This rate is 3.70×10^{10} disintegrations per second.

curve: In well logging, a trace representing a continuous *record* of some property or occurrence in the wellbore environment versus depth. One or more curves may constitute a *well log.*

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cycle skip, cycle skipping: In *acoustic* transit time or *sonic logging*. When the amplitude of the first arrival form (cycle) of the *acoustic wave train* is large enough to be detected by the near *receiver* (of a receiver pair) but not large enough to be detected by the far receiver, then one or more cycles will be skipped until a later cycle arrives which has energy above the detection level. This situation is called "cycle skipping." Its onset is characterized by a sharp deflection on the transit time *curve* corresponding to one or more added cycles of time between receivers. "Short cycle skipping" where the near receiver is triggered a cycle too late can also occur, resulting in an abnormally short *travel time*.

decay: The spontaneous reduction of an effect with time.

(1) The disintegration process of the nucleus of an unstable *isotope* by the spontaneous emission of charged particles and/or *photons*.

(2) The equilibration process of heat transfer after the disturbance of thermal equilibrium.

(3) The progressive reduction in amplitude of a transient signal due to damping or energy absorption.

decentralize: To eccenter. To purposely force a *tool* against the borehole or casing wall by means of an *arm* or bow spring.

decentralizer: See *eccentering arm*.

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deep propagation log: A *well log* that provides the *resistivity* and *dielectric constant* of the *formation*. The deep propagation tool (DPT) radiates electromagnetic energy into the formation surrounding the wellbore. Measurements of the attenuation and velocity of this electromagnetic wave provide values to determine the resistivity and dielectric constant of the formation. The tool operates at a frequency in the tens of megahertz range and measures signal level and relative phase at four *receivers.*

Delaware gradient: An anomalous effect on *guard log* and early *laterolog* curves first observed in the Delaware Basin. It can be recognized as an erroneous high-*resistivity gradient* in conductive beds when these beds are overlaid by thick high resistivity *formations.*

delta-t (Δt): The *interval transit time* from an *acoustic log* in microseconds per foot or microseconds per meter. It is the inverse of velocity. The official symbol of SPE of AIME and SPWLA for Δt is now the symbol t.

density: Mass per unit volume (often expressed as *specific gravity*). Well-logging units are g/cm^3, often written g/cc.

density log: A *well log* which records the formation *density.* The logging tool consists of a *gamma-ray source* (e.g., Cs^{137}) and a *detector* shielded from the source so that it records backscattered *gamma rays* from the *formation.* The backscattering depends on the *electron density* of the formation, which is roughly proportional to the *bulk density.* The source and *detector* usually are mounted on a *skid* which is pressed against the borehole wall. The *compensated density logging* tool includes a secondary detector which responds more to the *mud cake* and small, borehole irregularities; the response of the second detector is used to correct the measurements of the primary detector. The density log applies primarily to uncased holes. Sometimes called a *gamma-gamma log.*

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depth of investigation: radius of investigation. The radial distance from the *measure point* on a downhole *tool* to a point usually within the *formation* where the predominant tool-measured response may be considered to be centered. Varies from one type of device to another because of design and techniques of compensation and focusing. May also change from formation to formation because of changes in formation properties.

detector: A sensor used for the detection of some form of energy. Usually this term is used to refer to the device used in *nuclear logging* tools to detect *neutrons* and *gamma rays.*

differential log: A *well log* which records the depth rate of change of a parameter measurable from the well bore. This kind of log is sensitive to small changes measured in the absolute value of the parameter. An example is the *differential temperature survey.*

differential temperature survey: A *log* consisting of a *curve* which is a continuous record of the temperature *gradient* in the borehole. It can be measured by two separate sensors having identical thermal characteristics separated by a fixed vertical distance on a sonde; or, by a technique involving the use of a single temperature sensor and placing the measured *signal* into storage so it can be played back after the sensor has moved a distance in the borehole equal to a predetermined vertical distance. The differential temperature *curve* enhances small changes in temperature occurring in the borehole. A differential temperature survey should always include a recorded measurement of temperatures in the borehole.

dipmeter, dipmeter tool: A downhole tool used to make a *dipmeter log* or dip log.

dipmeter log: a dip log. (1) A *well log* from which formation *dip* magnitude and *azimuth* can be determined. The *resistivity* dipmeter includes three or four (sometimes eight) microresistivity *readings* made using sensors distributed in azimuth about the logging *sonde* and a measurement of the azimuth of one of these; a measurement of the hole *deviation* or *drift*

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angle and its bearing; and one or two *caliper* measurements. The azimuth, deviation, and *relative bearing* are measured by a system similar to that described for the *poteclinometer*. The microresistivity *curves* are correlated to determine the difference in depth of bedding markers on different sides of the hole.

(2) Other types of dipmeters use three SP curves, three wall scratchers, etc. to produce logs.

(3) A log showing the formation dips calculated from the above, such as a *tadpole plot* or *stick plot*.

dogleg: A sharp bend or change in direction of the *borehole*.

Dual Dipmeter: Four dual electrodes record eight microconductivity curves allowing side-by-side *button* correlations and *pad*-to-pad correlations for high-density *dip* results. The solid state *inclinometer* system has a triaxial accelerometer and three magnetometers for information on tool *deviation* and *azimuth*. Dual Dipmeter is a mark of Schlumberger.

dual guard log: A *formation resistivity* log made from a system consisting of both very deep and shallow investigative guard log schemes. The tool records, in combination, deep and shallow guard curves and a *gamma ray* and/or *SP curve*. The dual guard-FoRxo is a simultaneously recorded dual guard log and FoRxo.

dual induction log: DIL. An *induction log* consisting of two induction curves representing electrical *conductivity* measurements taken at *different depths of investigation*. Usually run in conjunction with a focused resistivity device with a shallow depth of investigation, such as a shallow *laterolog* or *guard log*. See also *induction log*. DIL is a mark of Schlumberger.

dual laterolog: DLL. A *formation resistivity* log made from a system consisting of both very deep and shallow investigative *laterolog* schemes. The tool records, in combination, deep and shallow laterolog *curves* and a *gamma ray* and/or *SP curve*. The dual laterolog-R_{xo} is a simultaneously recorded dual laterolog which also includes *flushed zone resistivity* information derived from a micro-*Spherically Focused Logging* device. See also *laterolog*. DLL is a mark of Schlumberger.

dual-spaced density log: See *compensated density log.*

dual-spaced thermal decay log: TDL. A log made with a *pulsed neutron* tool utilizing two *radiation* detectors. See *Thermal Multigate Decay Log.*

dual-spaced neutron log: DSN. A well log made with a tool having two *thermal neutron detectors.* The neutron *porosity* is derived from the ratio of the counting rates of the two detectors. Use of the count-rate ratio greatly minimizes *borehole* effects. This tool can be run in liquid-filled holes, both cased and uncased, but is not usually recommended for use in gas-filled holes.

dual porosity CNL: DNL. The dual porosity compensated neutron tool has two *thermal* and two *epithermal neutron detectors* for separate *porosity* measurements. The epithermal measurement can also be made in air- or gas-filled holes. Also see *compensated neutron log.*

dual-spacing formation density log: See *compensated formation density log.*

Dual-Spacing Thermal Decay Time Log: TDT. A well log produced by a thermal decay time tool utilizing two *radiation detectors.* TDT is a mark of Schlumberger. See *Thermal Decay Time Log.*

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dynamic measure point: A depth reference point on the downhole instrument where measurements are taken. On most instruments, the *measure point* and the *dynamic* measure point are found at the same point or place on the *sonde*. In *nuclear* tools, *lag* makes the *dynamic* measure point appear below the *static* measure point by the distance of the lag.

eccentering arm: eccentralizer. decentralizer. A protrusible arm (sometimes a bow spring) which presses the *sonde* body against the *borehole* wall.

elastic collision: A collision of particles wherein the resultant sum of kinetic energies of the particles remains the same after collision as before. In well logging, the elastic collision between a fast *neutron* and *nucleus* of a hydrogen atom (*proton*) is the predominant means by which the neutron loses energy to reach epithermal- or thermal energy levels. Elastic collision and the resulting elastic scattering is important in neutron-logging methods involving neutron-neutron interactions. See also *epithermal neutron* and *thermal neutron*.

elastic scattering: Scattering produced by *elastic collisions*.

electromagnetic casing inspection log: See *casing inspection log*.

electromagnetic propagation log: A well log that shows the propagation time and attenuation of a 1.1-GHz electromagnetic energy wave propagation through the *formation* near the borehole. The *pad*-type antenna assembly of the *electromagnetic propagation tool* contains two *transmitters* and two *receivers* to minimize the effect of hole *rugosity* and tool tilt. Because the propagation time of water differs sharply from that of oil, gas, or rock, the electromagnetic propagation tool measurement provides a means to identify hydrocarbon zones regardless of the *formation water* salinity.

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electromagnetic propagation tool: EPT. The EPT is a device that measures the propagation time (TP1) and attenuation rate (A1) of a microwave frequency electromagnetic wave that is propagated through the formation near the borehole. These two measurements can be related to the (composite) *dielectric constant* of the *formation* close to the borehole. The EPT is a shallow investigation device that has a depth of investigation of 1 to 4 inches depending on the formation conductivity. As a result, the EPT responds primarily to the *flushed* or *invaded zone* of the formation. The utility of the EPT arises from two basic facts. First, the dielectric constant of earth formations is dominated by the amount of water contained in the rock pores. This results from the fact that the dielectric constant of water is an order of magnitude greater than that of the other constituents of reservoir rocks; namely, oil, gas, and the rock matrix. Second, at microwave frequencies, the dielectric constant of water saturated rocks is relatively independent of water salinity, except in ranges corresponding to very high salt concentrations. These two facts imply that the dielectric constant inferred from the EPT measurements is effectively a salinity independent datum capable of distinguishing between water and oil in the zone of investigation. Also these measurements can be used to derive values for formation *porosity* and *water saturation* that are essentially salinity independent. EPT is a mark of Schlumberger.

electromagnetic thickness log: the inspection *tool* is composed basically of a *sonde* with two coils. The upper (*transmitter*) coil generates an electromagnetic field in the borehole, casing, and *formation*. For all practical purposes, only the field passing through the casing in front of the coils, and through the medium behind the casing between the coils, creates an electromotive force into the lower (*receiver*) coil. This electromotive force is out of phase with the transmitted *signal*. This difference in phase is recorded and is proportional to the average thickness of the casing in front of both coils. Changes in average casing thickness can generally be attributed to corrosion or other damage. Interpretation is greatly enhanced by having a base *log*, run early in the life of the casing, for comparison with subsequent logs.

electronic casing caliper logging: A technique which uses an electromagnetic noncontact method of relating currents induced on the inner surface of casing or tubing to the inner diameter of that casing or tubing. A coil system generates an electromagnetic field which induces currents on the inner surface of the pipe. These currents are detected by a second coil system. The measurement obtained is related to the average inner diameter of the pipe over a length of one or two inches. The technique can be used to record the inner diameter of pipe through scale, paraffin, or cement adhering to the inner surface, and to detect some vertical splits and holes.

electron density: electron population/unit volume.

electron volt: eV. A unit of energy equal to the kinetic energy acquired by an electron passing through a *potential* difference of 1 volt. Equal to 1.6 x 10^{-12} erg.

epithermal neutron: A *neutron* (with a lower kinetic energy level of a few hundredths eV to an upper energy of about 100 Ev) which has been slowed down in the moderation process from a high kinetic energy level of about 100 kev. The energy level of an epithermal neutron is just above that of a *thermal neutron* (about 0.025 Ev).

fluid travel log: FTL. A record of borehole fluid flow rate. See *radioactive tracer log*.

fluid wave: A *compressional* wave in the liquid column. The wave form arrival which has been transmitted to the *receiver* directly through the liquid column within the well bore.

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flushed zone: The zone at a relatively short radial distance from the borehole, immediately behind *mud cake*, which is considered to be flushed by *mud filtrate* (i.e., is considered to have all mobile *formation* fluids displaced from it).

focused log: Refers to a *well log* produced by any well-logging device in which survey-current flow is focused or otherwise controlled. Examples of focused logs are: *laterolog*, *guard log*, *microlaterolog*, *induction log*, and *spherically focused log*.

There are two main purposes for focusing survey current of resistivity measuring devices: (1) To increase vertical resolution of the logging tool; i.e., improve its capability to resolve thin *beds*. This reduces the influence of adjacent beds on the measurements. (2) To reduce the influences of borehole and mud cake in the presence of saline drilling *mud*.

formation density log. See *density log*.

formation factor log: A *log* in which the *formation resistivity factor curve* derived from a *resistivity* or *porosity* estimating device is shown as a function of depth. Usually recorded on a *logarithmic grid*.

formation resistivity factor: formation factor, F. Equal to the ratio of the *resistivity* of the 100% water-saturated rock framework to the resistivity of the water-solution contained in the rock. The limiting formation factor is an intrinsic characteristic of the rock, obtainable with reliability only when the interpore water solution is highly salt saturated. The apparent formation factor, most often obtained, is a function of *porosity*, *salinity* of water filling the pores, pore geometry, clay content, and presence of electrically conductive solid matter. See *Archie's formulas*.

formation volume factor: The ratio of the volume of gas or liquid with its dissolved gas at reservoir conditions of temperature and pressure to its volume at *standard conditions*.

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FoRxo Log: A focused *resistivity* log recorded from a *pad* which contains a small *button* electrode surrounded by a guarding electrode and which is forced against the side of the borehole. The current from the button electrode is forced to flow out into the first few inches of the formation, which would be the R_{xo} zone in a permeable formation. FoRxo is a Welex trademark.

Fracture Finder log: An *acoustic well log* used in the location of *fractures*. Usually the log consists of one or more *curves* in which the amplitudes of the *compression* and/or *shear wave* forms are shown across a *formation* segment. Fractures may produce attenuation of both compressional and shear waves, if the fractures are properly oriented. Fracture Finder is a Welex trademark.

free fluid index: FFI. The percent of the bulk volume occupied by fluids which are free to flow, as recorded on the *nuclear magnetism log*. Gas gives a log FFI.

free pipe: Pipe or casing in a well bore which is free to vibrate or respond to stress. Casing or tubing which is free of the restraint of a cement sheath or *formation* materials.

free point: The deepest depth in the well bore that stuck casing or drill pipe is free and can be salvaged.

free-point indicator: A tool designed to measure the amount of stretch in a string of stuck pipe and to indicate the deepest point at which the pipe is free. The free-point indicator is lowered into the well on a conducting cable. Each end of a strain-gauge element is anchored to the pipe wall by friction springs or magnets, and, as increasing strain is put on the pipe, an accurate measurement of its stretch is transmitted to the surface. The stretch measurements indicate the depth at which the pipe is stuck.

fullbore-spinner flowmeter: A *flowmeter* with retractable impeller blades which can be used below the bottom of tubing where the impeller blades open to almost full inside diameter of the casing.

The measurement made is related to the velocity of the fluid relative to the *tool*, which in turn is related to the volumetric flow rates. In polyphasic flow, however, much higher threshold flow rates are needed for useful measurements. A continuous *log* can be recorded with or against the flow of fluid.

full waveform recording: A representation of the *acoustic wave train* in the *amplitude-time mode*. A trace in the X-Y plane illustrating the wave amplitude vs. time. See *acoustic log*.

gamma-gamma log: See *density log*.

gamma ray: A *photon* having neither mass nor charge. It is a high-energy electromagnetic wave which is emitted by atomic nuclei as a form of *radiation*. Gamma rays are emitted by nuclei in their transition from an excited state to a lower energy state, in *transmutations*, and in radioactive disintegrations. Gamma rays have characteristic energy levels which can be used to identify the parent substance.

gamma-ray index: GRI. A clayiness index determined from the difference between the *radioactivity* level of the zone of interest and that of *clean* rock compared to the difference between the radioactivity level in clay shale and that in the clean rock.

$$GRI = \frac{GR - GR_{clean}}{GR_{clay} - GR_{clean}}$$

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gamma-ray log: A *well log* of the natural *formation radioactivity* level.

(1) In sediments the log mainly reflects clay content because clay contains the *radioisotopes* of potassium, uranium, and thorium. Potassium *feldspars*, *volcanic* ash, granite wash, and some salt deposits containing potassium (potash for example) may also give significant gamma-ray *readings*. The log often functions as a substitute for the SP for *correlation* purposes in nonconductive borehole fluids in open holes, for thick carbonate intervals, and to correlate *cased-hole* logs with *open-hole* logs.

(2) Used in exploration for radioactive *minerals*.

gamma-ray source: An encapsulated radioactive material used in *density logging*. Usually Cesium-137.

gamma spectrometry log: The gamma spectrometry tool (GST) measures both inelastic and capture *gamma ray* spectra, providing a detailed measurement of formation response to *neutron* bombardment. Eight essential elements are identified and their concentrations are determined. Measurements of carbon, oxygen, silicon, calcium, iron, chlorine, hydrogen, and sulfur are used to compute the hydrocarbon *saturation*, salinity, *lithology*, *porosity*, and shaliness of the formation. See also *carbon-oxygen* log. GST is a mark of Schlumberger.

gate: A window or opening, usually in time, during which certain measurements are made. The gate has specific beginning and ending time boundaries.

Geiger-Mueller counter: A form of *gamma-ray detector*. Similar to the *ionization chamber* in that a center rod electrode is maintained at a positive *potential* relative to the cylindrical chamber wall. The difference is that the Geiger-Mueller tube chamber contains gas at a low pressure and maintains the center electrode at a high positive voltage (e.g., 900-1000 volts). Incident gamma rays cause the ejection of electrons from detector walls into the gas. As the ejected electron is drawn toward the highly charged center electrode, other collisions occur between each electron and gas atoms, thus producing additional electrons which in turn cause additional *ionization* by collision. This results in a multiplication of the ionization events, and an avalanche of electrons arrives at the central electrode. The surge of electrical current must be quenched before another surge can be determined. This results in a number of easily detectable pulses related to the number of gamma-ray interactions. increased length and additional plates and baffles are used to increase the number of interactions by incident gamma rays. The increased length tends to decrease *vertical resolution*.

gradiomanometer: A device used to measure the average *density* of the fluids contained in a fixed length of the well bore located between sensitive membrane-type pressure sensors, irrespective of the fluid distribution. The measurement recorded as a function of depth is called *specific gravity*. The recorded *curve* would represent a specific gravity profile of fluids in the borehole for the conditions under which the *survey* was run. In some cases it may be affected by hole *deviation*, a friction component, and a kinetic component.

grain density: The *density* of a unit volume of a *mineral* or other rock matter at zero *porosity*. The density of the rock framework. Sometimes called *matrix* density. Usual units are g/cm^3.

gravel pack log: The gravel pack logging tool is a *neutron*-type device that evaluates the condition of the *gravel pack*. Count rates from two *detectors* are used to compute *porosity*. The count rates from both detectors are presented with the *cased-hole* porosity and compared to the porosity measured in the *open hole* if open-hole measurements are available. The log provides a quantitative analysis of the areas in the pack that need to be replaced before the well is placed on production.

gravimeter: An instrument for measuring variations in gravitational attraction; a gravity meter.

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Most present gravimeters are of the unstable or astatic type. The gravitational force on a mass in the meter is balanced by a spring arrangement, and a third force is provided which acts when the system is not in equilibrium. This third force intensifies the effect of changes of *gravity* and increases the sensitivity of the system. In the LaCoste-Ramberg gravimeter, the main spring which balances out the gravitational pull on the weight is a "zero-length spring" inclined at an angle. A zero-length spring has a stress-strain curve which passes through zero length when projected back to zero strain. (For example, a spring which requires an initial stress before the coils begin to separate.) Zero-length springs have very long periods and high sensitivity.

gravity unit: A unit of gravitational acceleration, equal to 0.1 mgal or 10^{-6} m/sec^2. Sometimes called G unit.

gross-count gamma-ray tool: Can be applied to a much wider range of radioactivity than natural *gamma-ray logging* tools used in the petroleum industry. Responds to changes in gamma-ray activity at very high *radiation* levels. Used in the exploration for radioactive *minerals*.

guarded electrode: The short center *electrode* of a *guard tool*. The electrode on which most measurements are based.

guard electrode: (1) One of the long *electrodes* above and below the short center electrode, or *guarded electrode*, of a *guard tool*.

(2) Sometimes used, incorrectly, to refer to the guarded electrode or the entire guard tool.

guard log: A well log of formation *resistivity* which involves the use of a *guard tool*.

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guard tool: The guard tool behaves similarly to one elongated current electrode from which current flows radially in all directions to a distant current-return electrode. In practice the current-emitting electrode is separated into three parts by insulation so that the center part, which is made short, can be treated as a discrete electrode without alteration of the current-flow pattern. The current from the center *electrode*, which serves as both a current and measure electrode, flows in a thin horizontal layer at an angle of 90° to the tool because of its central location in the configuration.

Through the method of focusing described above, this arrangement provides good resolution of thin beds and permits use of the tool in boreholes filled with saline muds.

The log usually is presented with one *resistivity curve* and a *gamma-ray curve* and/or *SP curve* (recorded from an electrode not physically a part of the guard electrode).

high-resolution dipmeter tool: A *dipmeter* tool which records four high-resolution microresistivity curves and has an additional electrode on one *pad* which yields another *curve* at displaced depth. The displaced-depth curve is used to correct for variations on *sonde* speed. Provides not only improved *resistivity* resolution, but also improved *dip* resolution or refinement.

high-resolution thermometer: A small-diameter, surface recording, fast-response downhole temperature tool for logging open or cased boreholes.

housing: A cylindrical metal case which protects downhole electrical circuitry. Particularly, a housing which encases the electronic *cartridge* of the downhole logging instrument. The housing protects the cartridge from damage from pressure and moisture.

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Humble formula: A modified form of Archie's formation factor-porosity relationship.

$$F = 0.62\phi^{-2.15},$$

where F = *formation resistivity factor*, and ϕ = porosity.

hydrogen index: The ratio of the number of hydrogen atoms per unit volume of a material to that number in pure water at 75°F. *Neutron logging* response depends mainly on the hydrogen index.

induced polarization: IP. An exploration method involving measurement of the slow *decay* of voltage in the ground following the cessation of an excitation current pulse (time-domain method) or low-frequency (below 100 Hz) variations of earth impedance (frequency-domain method).

induced spectral gamma-ray log: An *activation log* wherein the *formations* have been bombarded by high-energy *neutrons*. Specific atoms upon *irradiation* transform into *isotopes* which emit *gamma rays* exhibiting specific energy levels within the energy spectrum. Identification of the energy levels of the induced gamma *radiation* is a means of identifying the original atoms in place in the formation. The quantity of material containing the original atoms is deduced from the amount of gamma radiation at specific energy levels. Downhole instruments may utilize encapsulated *sources* which emit neutrons continuously as the tool is moved along the formation wall, or *neutron generators* which emit neutrons in cyclic pulses with measurements made between pulses. The type of source used depends on the substances searched for.

Induction-Electrolog: IEL. A log made by combining an *induction logging* device and a *short normal* or *laterolog* device. Induction-Electrolog is a Dresser Atlas trademark.

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induction log: A *log* recorded in uncased boreholes which involves the use of electromagnetic induction principles for the measurement of *formation conductivity* or *resistivity*. The induction logging *tool* has advantages for use in non-conductive borehole fluids (air, oil, gas) where other electrical resistivity logging tools cannot be easily used or should not be used. The induction log is widely used in electrically conductive drilling *muds* where it works well provided the formations are not too resistive and borehole effects are known and not too great (i.e., mud not too saline and hole diameter not too large).

Practical induction *sondes* include an array of several *transmitter* and *receiver* coils designed to provide focusing and deep investigation and to minimize borehole and adjacent-formation effects. A high-frequency alternating current, constant in magnitude, is passed through the transmitter coils. The resulting alternating magnetic field induces currents in the formation which flow in circular ground-loop paths coaxial with the sonde. These ground-loop currents generate their own magnetic fields which induce in the receiver coils signals which at low conductivities are essentially proportional to formation conductivity. At high conductivities, the reading may be affected by *skin effect*. Receiver-coil signals produced by direct coupling with the transmitter coil are balanced out by the measuring circuits.

Induction tools can be run separately or can be combined with other devices to run combination services. Integrated tools, combining in one tool the devices necessary to perform different resistivity-measuring operations, are commonly used in the well-logging industry. Examples of such tools are the induction device with a deep *depth of investigation* in combination with: another induction device having a shallower depth of investigation, *invaded zone* investigative devices (e.g., short *normal device*, short *laterolog* or *guard log*, or *Spherically Focused Logging* device), long *lateral*, and *SP*.

inelastic collision: A collision in which the total kinetic energy of the colliding particles is not the same after the collision as before the collision. For example, in case of a fast moving *neutron* colliding with a *nucleus* of an element, the nucleus becomes excited and excess energy is reduced by emitting a *gamma ray* that is characteristic of the element.

inelastic scattering: Scattering produced by *inelastic collisions*.

intensity modulated-time: An acoustic *wave train display* form. A display mode of the *acoustic wave train* in the *X-Z plane* in which the intensity of the photographic beam is modulated with the amplitude of the wave form to produce a variable photographic density pattern as a function of time. All positive half-cycles appear as dark streaks, and all negative cycles which have been cut off appear as light streaks.

interval transit time: The *travel time* of a *compressional wave* (usually) over a unit distance, hence proportional to the reciprocal of compression wave velocity. Measured in the *sonic log*, usually in microseconds per foot.

interval transit-time stretch: An increase in *interval transit time* which occurs when attenuation of the *acoustic* energy is significantly greater at the far *receiver* (of a receiver pair) than at the near receiver. The stretching of interval transit time is not related to skipping of a cycle.

intrinsic thermal decay time: (1) The *thermal-neutron* decay time intrinsic to a particular material or medium, defined by ($1/v\Sigma_{abs}$) where v is neutron velocity and Σ_{abs} is the macroscopic *capture cross section* of the medium.

(2) The thermal-neutron decay time of a particular *formation* corrected for borehole and *diffusion effects*.

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invaded zone: The portion of a *formation* surrounding a well bore into which drilling fluid has penetrated, displacing some of the formation fluids. This invasion takes place in porous, permeable zones when the pressure of the *mud* is greater than that of the formation fluids. A mud *filter cake* builds on the formation wall, limiting further invasion into the formation by *mud filtrate*. Directly behind the *mud cake* is a *flushed zone* from which almost all of the *formation water* and most of the hydrocarbons have been displaced by filtrate. The invasion process alters the distribution of *saturations* and other properties and, consequently, alters the values which are recorded on logs. The *depth of invasion* is the equivalent depth in an idealized model rather than the maximum depth reached by filtrate. In oil-bearing zones, the filtrate may push a bank of *formation water* ahead of it to produce what is referred to as an *annulus*.

ionization chamber: (1) A type of *gamma-ray detector*. Consists of a gas-filled cylindrical metal shell containing a center rod (i.e., electrode) maintained at about 100 volts positive to the cylinder wall. An incident *gamma ray* interacts with the cylinder wall material or the gas maintained at high pressure in order to produce a high-speed electron. The high-speed electron, drawn to the positively charged center rod, produces additional electrons and ions in the collision with gas atoms. The electrons (along with some negative ions) moving to the center electrode constitute a minute flow of electrical current, the size of which is proportional to the number of *gamma-ray interactions*. Long chamberlengths and high gas pressures are used in order to improve detector efficiency, but *vertical resolution* suffers with increased chamber size.

(2) Has been used as a slow-*neutron* detector.

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irradiation: The exposure of a material to *radiation.* In well logging, irradiation is the process in which the elements in the *formation* are exposed to radiation or bombardment by *nuclear* particles (e.g., *neutrons* in *neutron logging* or *induced spectral gamma-ray logging*).

isotopes: Atoms of a single element which have differing masses. Isotopes are either stable or unstable (radioactive). *Radioisotopes* emit particulate (alpha, beta) or electromagnetic (gamma) *radiation* as they transform or *decay* into stable isotopes. Daughter products produced by primary disintegration or *irradiation* are isotopes.

lateral device: A *resistivity* measuring system using a "lateral" *electrode* configuration. A constant current is passed between an electrode A on the *bridle* and a distant electrode B, while the potential difference is measured across two electrodes, M and N, located on the *sonde.* The MN distance is small compared to the *AO spacing*, which is the distance between the current electrode and the midpoint between the *potential*-measuring electrodes, typically about 18 feet 8 inches. A short lateral sometimes uses a spacing of 6 to 9 feet. The potential electrodes described above are located below the current electrodes, but on the *reciprocal sonde* the functions are interchanged so that potential electrodes are above the current electrodes. The *measure point* is the midpoint between two electrodes separated by the shortest distance (i.e., MN electrodes; or, AB electrodes on the reciprocal sonde).

The lateral device has a deeper depth of investigation than the *normal devices* with which it is generally used, but has the disadvantage that it requires thick homogeneous *beds* for optimum usefulness and produces an unsymmetrical *curve.*

laterolog: A *resistivity* log (run in uncased hole filled with electrically *conductive mud*) made with a *tool* which achieves focusing through the use of additional current *electrodes* above and below a central measure-current electrode. Bucking currents from the additional electrodes serve to confine the measure current to essentially a narrow disc of current flowing outwardly

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perpendicular to the sonde. Should the *survey* current tend to flow vertically in the mud column (because of highly resistive *beds*), currents from the symmetrically positioned *bucking electrodes* are caused to increase or decrease in order to maintain the horizontal attitude of the survey-current flow.

The currents from the bucking electrodes are automatically adjusted for proper focusing of the measure-current beam by use of a monitor voltage *signal*, either from monitor-electrode pairs on either side of the measure-current electrode, or from the voltage difference between bucking and measure electrodes. Because of the comparatively small thickness of the focused sheet of current (which is usually a few inches to a few feet thick), the laterolog gives a very detailed *curve* and puts clearly in evidence the sharp contrasts between successive beds, however conductive the mud may be.

The laterolog tool differs from the guarded electrode logging tool, or *guard tool*, in the use of small sized electrodes and the use of a monitored bucking-current system to achieve focusing.

Litho-Density Log: The Litho-Density tool (LDT) uses a *pad*-mounted *gamma-ray source* and two *scintillation detectors* to measure the *bulk density* and the *photoelectric absorption cross section* (P_e). The P_e measurement is closely related to the *lithology* of the formation. A spectral analysis of the detected gamma rays is used for the P_e measurement and to improve the response of the density measurement. See also *compensated formation density log*. Litho-Density is a mark of Schlumberger.

logging tool: An openhole or cased-hole tool for performing downhole well log data gathering services for determining properties of the *formation*, or characteristics of the *well bore* and its environment.

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long normal curve: A symmetrical *resistivity curve* representing measurements made by a *normal device* with the spacing between the *A* and the *M electrodes* usually equal to 64 inches.

long-spaced sonic log: Long-spaced sonic tools are used to provide *shear wave* analysis, formation travel time through casing, and more accurate *acoustic* data in enlarged boreholes and in areas where formations are altered by the drilling process.

Magnaflux: A trade name for the equipment and processes used for detecting cracks and other surface discontinuities in iron or steel. A magnetic field is set up in the part to be inspected, and a powder or paste of magnetic particles is applied. The particles arrange themselves around discontinuities in the metal revealing defects.

mandrel: A support member for sensors or actuator assemblies of a downhole tool.

mass absorption: The absorption of *nuclear* particles or *photons* by the mass of material through which the energy must pass. In *nuclear logging*, this refers to the loss of *radiation* caused by the collective mass of materials in the wellbore environment through which the radiation energy must pass before being detected. With respect to the natural *radioactivity* level of some rock *formations*, it is sometimes referred to as *self-absorption*.

matrix: (1) The solid framework of rock which surrounds pore volume.

measure point: A depth reference point on a logging *tool* at which measurements are taken. Usually the lowermost sensor or lowermost measure point. Static measure point.

M electrode: The *potential*-measuring *electrode* nearest the *A electrode* in the electrode configuration of a *resistivity* measuring device.

mho: A unit of electrical conductance. Equal to the reciprocal of *ohm*.

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mho per meter: 1000 mmho per meter. A unit of electrical *conductivity*. The conductivity of a cubic meter of material which offers a resistance of one ohm between opposite faces. Reciprocal of *ohm-meter*.

microinverse: A very short *lateral* electrode arrangement used in obtaining microresistivity measurements for one of the *curves* of a *microlog*.

microlaterolog: A microresistivity log made from a tool of the *laterolog* type with a *bucking electrode* and two monitor *electrodes* arranged concentrically on a *sidewall pad* which is pressed against the *formation*. The survey-current flow is concentrated into a gradually flaring tube shape. Because the spacing is small, the measurement is responsive to the *resistivity* of a small volume of formation in front of the pad. Measurements of the resistivity of the *flushed zone* are made. A caliper curve is recorded simultaneously.

microlog: A type of *microresistivity log* recorded from a tool which uses three *button* electrodes spaced one inch apart in a line, located on a *pad* which is pressed against the *formation* wall. The lower electrode is the *A* current *electrode*. The *potential* of the upper electrode with respect to a remote reference electrode gives a two-inch *micronormal*, and the difference between the two upper electrodes gives a 1.5-inch *microinverse* (*lateral* type) measurement. Because *mud cake* usually has appreciably lower *resistivity* than the formation, the microinverse will read less than the micronormal when mud cake is present. This difference (called *positive separation*) usually indicates a permeable formation. A *caliper* curve is usually recorded at the same time.

micronormal: A very short *normal*- electrode arrangement used in obtaining microresistivity measurements for one of the *curves* of a *microlog*.

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microresistivity log: A *log* of the *resistivity* of the *flushed zone* around a borehole, measured with *electrodes* on a *pad* pressed against the *formation* wall.

Micro-Seismogram: MSG. An *acoustic log* showing the *wave train* in the *intensity modulated-time* mode. Micro-Seismogram is a Welex trademark.

microspherically focused log: A *microresistivity log* produced by a tool of the spherically-focused type which has *electrodes* mounted on a *sidewall pad* which is pressed against the drilled *formation*. Because of the kind of focusing method used, the tool gives improved flushed-zone measurements over those made from *microlaterolog-* and *proximity log* type tools. *Mud cakes* with thicknesses up to ¾ in. have little effect on the measurements of the microspherically focused tool; and, resistivity measurements are made from the region just behind the mud cake where the flushing is most effective. A caliper curve usually is recorded simultaneously.

mmho: millimho. A unit of electric conductance equal to 1/1000 of a *mho*, the reciprocal of *ohm*.

MN spacing: The distance between the two *potential*-measuring electrodes in the *electrode* configuration of an electrical *resistivity*-measuring device.

monoelectrode: A single *electrode* for measuring *formation resistance* in electrically-conductive, liquid-filled boreholes. See *single-point resistance log*.

mud resistivity log: A *log* made with a *microlog-* or *microlaterolog*-type *sonde* with the *arms* collapsed so that the measuring *pad* loses contact with the *formation* wall. Used to record the mud *resistivity* at downhole conditions.

natural gamma ray log: See *gamma ray log*.

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natural gamma ray spectrometry log: The natural gamma spectrometry (NGS) tool uses five-window spectroscopy to resolve total natural *gamma ray* spectra into the three most common components of naturally occurring radiation — potassium, thorium, and uranium. NGS is a mark of Schlumberger.

N electrode: The *potential*-measuring electrode most distant from the current *A electrode* in the electrode configuration of electrical resistivity measuring devices.

neutron: An electrically neutral, elementary *nuclear* particle having a rest mass of $1.674x10^{-24}$ gram or an atomic mass of 1.00898, (i.e. very nearly the same as that of a *proton*), which exists in all nuclei except that of hydrogen.

Neutrons exhibit a broad variation of kinetic energies ranging from as little as 0.025 Ev to as much as 50 MeV. Neutrons are used in logging as a means of measuring the quantity of hydrogen important in the moderation process (energy transfer) or as a means to induce *radiation* in stable *isotopes.*

neutron activation: All stable *isotopes* are capable of capturing *thermal neutrons.* In well logging, *neutron* bombardment of a formation and the subsequent capture of *thermal neutrons* causes excitation of certain elements. Following the capture of a thermal neutron by a stable isotope, the compound nucleus de-excites by the prompt emission of one or more *gamma-ray photons.* If the resulting product nucleus is a *radioisotope*, its later *decay* to a stable state can be detected and the energy level of emitted gamma rays is characteristic of the specific element. The analysis of the energies of the decay gamma rays is neutron activation analysis.

neutron capture cross section: See *capture cross section.*

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neutron generator: An electromechanical device operating at high voltage (125-130,000 volts DC) which focuses a beam of high-energy deuterons on a target surface containing tritium. *Nuclear* fusion of the deuteron *ions* and target atoms produces high-energy (14-MeV) *neutrons*. The neutron *radiation* can be controlled in precise cyclic bursts or pulses, with time in between pulses for the measurement of induced-*radioactivity* and *decay-time* schemes.

Neutron Lifetime Log: NLL. The neutron Lifetime logging technique employs a pulsed *neutron source* which is periodically actuated to produce short bursts of *neutrons* and is quiescent between bursts. During the interval between bursts, the *neutrons* (as well as the various types of *radiation* which always result from neutron interactions) die away. Their average lifetime can be measured by measuring the length of time required for the neutron population at a particular instant to die away to half value. The radiation intensity is measured in each of two preselected intervals, and, by intercomparing these measurements, determine the rate of neutron die-away. This measured rate has been shown both by theory and experiment to be a measure of the *thermal-neutron* capture cross section of the medium in which the neutrons are captured. The thermal-neutron *capture cross section* per unit volume of *formation* material is referred to as Σ. It is related to L, termed the lifetime of neutrons in a material, by the equation

$$\Sigma = \frac{3.15}{L}$$

Thermal neutrons are captured mainly by the chlorine present and hence the tool responds to the amount of salt in *formation waters*. Hydrocarbons result in longer lifetimes than salt water. Tool measurements are *porosity* dependent and sensitive to clay content. Can be used in cased holes where *resistivity logs* cannot be run or to monitor reservoir changes to optimize production. It resembles a *resistivity log* with which it is generally correlatable. Neutron Lifetime Log is a Dresser Atlas registered trademark.

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neutron log: A *log* of a response primarily related to hydrogen concentration but also affected by mineralogy and borehole effects. The neutron log does not distinguish between the hydrogen in the pore fluids (i.e., water, oil, gas), in water of crystallization, or water bound to solid surfaces. In *clean* oil-filled or water-filled *formations*, the apparent *porosity reading* of the neutron log is useful to ascertain the presence of gas and determine mineralogy and shaliness.

The *tool* contains a continuously emitting *neutron source* and either a neutron- (n-n tool) or a *gamma-ray detector* (n-γ tool). High-energy *neutrons* from the source are slowed down by collisions with atomic nuclei. The hydrogen atoms are by far the most effective in the slowing-down process because their mass is nearly equal to that of the neutron. Thus, the distribution of the neutrons at the time of detection is primarily determined by the hydrogen concentration. Depending on the tool type, detection is made of either (1) *thermal neutrons*; (2) gamma rays, generated when thermal neutrons are captured by thermal-neutron absorbers in the formation (primarily chlorine); or (3) *epithermal neutrons* (neutrons having energies higher than thermal).

Neutron *curves* are scaled in *API units* or in terms of *apparent* porosity. The neutron log can be recorded in open or cased liquid-filled holes for running tools in which the detector does not contact the formation wall.

neutron source: (1) An encapsulated radioactive material which produces *neutrons* for *neutron logging*. The neutrons usually are produced in alpha beryllium reactions. The *alpha particle* producing element may be americium, plutonium, or sometimes radium. californium-252, which is sometimes used in special applications, is an intense source of 2.3-MeV *neutrons* but has a short *half life* of 2.65 years.

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(2) A *neutron generator.* An electromechanical device which emits high-energy (14-MeV) neutrons in controlled cyclic pulses. Pulsed neutron radiation is required in *Thermal Decay Time Logging*, *Neutron Lifetime Logging*, *carbon-oxygen logging*, and *activation logging* instruments.

noise logging: audio logging. A logging process for measuring the amplitude of background *noise* in the wellbore environment, for specific frequencies in the audible range, at selected stations in the hole. Moving fluids, liquids or gases, generate characteristic sounds having frequency spectra and amplitudes which can be interpreted. The *signal* amplitude is proportional to the amount of work performed by the fluids in motion and to the location of the *tool* with respect to the level from which noise emanates. Can be useful in ascertaining fluid movement profiles and fluid movements behind tubing or casing.

normal curve: A symmetrical *resistivity curve* recorded by a *normal device.*

normal device: A *resistivity*-measuring system using a "normal" electrode configuration. A constant current is passed between a current *electrode* on the *sonde* (*A electrode*) and one at the surface (*B electrode*) while the *potential* difference is measured between another electrode on the sonde (*M electrode*) and a reference electrode (*N electrode*). The "spacing" is the distance between the A and M electrodes. Usually a spacing of about 16 inches is used for the short normal and 64 inches for the medium or long normal. The *measure point* is midway between the A and the M electrodes.

A normal investigative device has a *depth of investigation* said to be about twice the *AM spacing.* The normal is an unfocused device which produces a symmetrical curve which has been particularly useful in *correlation* and in the determination of *lithology. Formation* detail can be increased by decreasing the AM spacing, but depth of investigation suffers.

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normalize: (1) To adjust two *log curves* (or any other pairs of data) for environmental differences in order that one value may be compared with others.

(2) To adjust two log curves or similar data to the same, or equivalent, units so that the data values can be compared.

nuclear cement log: A *well log* of scattered *gamma rays*, differing from the *density log* in that the gamma-ray *source* and *detector* are so spaced as to be sensitive to the *density* of material in the *annulus* between casing and formation. Used for distinguishing between cement and fluids behind casing. Can be run in liquid-filled or *empty* holes.

nuclear log: A well log of some parameter in the well bore environment derived from techniques utilizing nuclear reactions taking place in the downhole logging tool and/or in the formation. Nuclear logs usually are well logs obtained by using radiation sources in the logging tool.

nuclear magnetic resonance: A phenomenon exhibited by atomic nuclei which is based on the existence of nuclear magnetic moments associated with quantized nuclear spins. In *well logging*, it pertains to the measurement of properties related to the *nuclear* spin states of hydrogen nuclei.

nuclear magnetic resonance log: See *nuclear magnetism log.*

nuclear magnetism log: a free fluid log. A *well log* which is dependent on the alignment of the magnetic moment of *protons* (hydrogen nuclei) with an impressed magnetic field. Protons tend to align themselves with the magnetic field; and when it is removed, they precess in the earth's magnetic field and gradually return to their original state. Proton *precession* in free fluid produces a radio frequency *signal.* The amplitude of this radio frequency signal is measured in the nuclear magnetism log as the *free fluid index.* The rate of *decay* of the precession signal depends on interactions with neighboring atoms and hence on the nature

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of the molecule of which the proton is a part. The signal from the borehole fluid decays very rapidly when disseminated iron is present (artificially introduced, or from steel worn from drill pipe and bits). By slightly delaying the time of measuring, the hole signal is minimized. Fluids bound to surfaces (as water adsorbed to clay and silts) and *dead oil* do not give appreciable response. Thus, the free fluid index indicates the free fluid (the hydrogen in free-fluid hydrocarbons and water). Gas gives a low signal because of its low hydrogen content.

nuclide: A species of atom characterized by the number of *neutrons* and *protons* in its nucleus. An *isotope*. The atom must be capable of existing for a measurable lifetime, generally greater than 10^{-10} second.

ohm: A unit of electrical resistance. The resistance of a conductive material in which a *potential* difference of one volt produces a current of one ampere.

ohm-meter: A unit of electrical *resistivity*, also written ohm meter^2/meter. The resistivity of a cubic meter of material which offers a resistance of one *ohm* to the flow of electrical current between two opposite faces. The reciprocal is *mho* per meter.

Ohm's law: E = IR, where E is the *potential* in volts produced by the flow of current (I) in amperes through a length of material exhibiting resistance (R) in ohms.

packer flowmeter: A *spinner*-type velocimeter which utilizes an inflatable packer bag. After the proper size bag is pumped up to fill the *annulus* between tool and casing, all the fluid is diverted through the spinner assembly which measures the velocity of the fluid, which, in turn, is related to the volumetric flow rate. A profile in bbl/day for either "up or down" flow is recorded; also flow direction. The profiles are determined by fixed point recordings. The tool operates at lower rates than the minimum required for a *continuous flowmeter*.

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pair production: The conversion of a *photon* (*gamma ray*), which has more than twice the rest mass energy of an electron (about 0.51 MeV per electron), into an electron and a positron when the incident photon passes through the strong electric field surrounding an atomic nucleus and vanishes. This is an example of creation of matter (the electron pair, one negative and one positive) from energy (the photon), according to Einstein's law: $E - mc^2$. Relatively unimportant in *density logging* because of the high threshold energy (greater than 1.02 MeV) required for the incident gamma ray. Important in the detection of gamma rays in the *ionization chamber* and *Geiger-Mueller counter.* One of the three interactions of gamma rays with matter.

photoelectric absorption: When a *photon* (*gamma ray*) collides with an *atom*, it may be completely absorbed and its total energy used to eject one of the orbital electrons from those surrounding the nucleus. Part of the photon's energy is used to overcome the binding energy holding the electron in the atom; the remainder serves to impart a velocity to the recoiling electron. In general, this photoelectric effect is greater for low energy incident gamma rays (below about 100 keV), and occurs at higher energies for atoms of higher atomic number. The rate of absorption varies only with the energy of the incident gamma ray and the nature of the atom.

Photoelectric absorption is the process which produces the high-speed ionizing particle (i.e., electron) which causes the *scintillation* to appear in the phosphors of *scintillation detectors.* Produces an effect in the *formation* which influences some *density logging* measurements.

photoelectric absorption cross section index: P_e. A down-hole measurement recorded with the *Litho-Density* and *Compensated Spectral Density tools* that is related to the *atomic number* of the formation and therefore the *lithology.*

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photoelectric effect: Changes in the electrical characteristics of substances due to radiation, generally in the form of light. The *photoelectric absorption* of *photons* (*gamma rays*) in the photoelectric effect is one of the interactions between gamma rays and matter.

photon: A quantity of energy emitted in the form of electromagnetic *radiation*; e.g. radio waves, light, *x-rays*, and *gamma rays*.

photon log: A *well log* of scattered *gamma rays*, differing from a *density log* in that the tool is not pressed against the borehole wall and hence is especially sensitive to changes in hole diameter or density of the fluid in the borehole. It has been used for determining changes in the density of fluids in the well bore and location of cement in the casing-formation *annulus*.

Pipe Analysis Log: PAL. A well *log* which combines magnetic-flux-leakage and eddy-current measurements in such a manner as to locate defects or flaws on the inner or outer wall of a casing, as well as to provide a measurement which is indicative of the extent of such defects.

Magnetic-flux-leakage testing relies upon the detection of perturbations in a magnetic field caused by defects anywhere on the inside or outside of the casing wall. For the eddy-current test, the frequency of the eddy current is chosen so that the *depth of investigation* will be limited to the inner casing wall. The *electromagnetic thickness log* is frequently run in conjunction with the Pipe Analysis Log where concentric casing strings are set in order to provide information helpful in the analysis of the outer casing string. PAL is a mark of Schlumberger.

pipe inspection log: See *casing inspection log* and *Pipe Analysis Log*.

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porosity exponent: The exponent (m) of the *porosity* term in *formation resistivity factor*-porosity relationship. (See *Archie's formulas.*) The porosity exponent is influenced by those properties of the rigid rock which influence the shape of the electrically conductive solution occupying the pore volumes. Sometimes referred to as cementation factor and shape factor.

probe: In *well logging*, a probe is a downhole logging instrument. A *sonde*. A *tool.*

proportional counter: Similar in construction and operation to an *ionization chamber.* usually the proportional counter is a metal chamber, filled with gas, with a central electrode maintained at a positive voltage with respect to the shell. The voltage level of the central electrode is related to the critical voltage value where gas amplification begins. The proportional counter is operated in that voltage range where the charge flow across the counter is proportional to the primary *ionization.*

In well logging, it is designed for the detection of *neutrons.* A gas is used which is suitable for the production of ionizing particles upon reaction with incident neutrons. The gas commonly used is He^3 but may be BF_3. The BF_3 gas maintained at about 1 atmosphere, requires a voltage level of 2400-2500 volts and produces a larger pulse than in He^3; but, the He^3 maintained at higher pressure and operating at about 1300 volts is more efficient in the detection of neutrons.

proximity log: A *microresistivity log*, similar to the *microlaterolog*, made from a tool which focuses survey current issuing from a *sidewall pad.* The *electrodes* are mounted on a wider pad than that used by the microlaterolog, and survey current is focused deeper into the *formation.* These design features result in measurements which have less sensitivity to the *mud cake.* A caliper curve usually is recorded simultaneously.

pulsed neutron capture log. *Neutron Lifetime Log*, *Thermal Decay Time Log*, or *Thermal Multigate Decay Log*.

pulsed neutron log: A term with broad application which includes all logs made while using *neutron* bursts or pulses. This term quite often is used in referring to neutron decay time logs such as the *Thermal Decay Time Log*, *Neutron Lifetime Log*, and *Thermal Multigate Decay Log*. A *neutron generator*, which emits *neutrons* in controlled cyclic pulses, is the source of *radiation*. The term also applies to other *nuclear* logs where cyclic neutron pulses must be used; e.g., some *induced spectral gamma-ray logs*.

radioactive-tracer log. A form of *radioactivity log* used in *production logging* for the study of tracer movements and, therefore, fluid movements in the immediate vicinity of the well bore (e.g., in casing, tubing, *annulus*, open hole). Usually one or more *slugs* of radioactive material are ejected into the fluid phase to be studied, and the direction and velocity of the introduced slug is monitored over different parts of the well bore. *Tracer logs* are helpful in estimating fluid-flow rates, points of fluid exit or entry into the well bore, *crossflow*, leaks, etc.

radioactivity log: A *well log* of natural or induced *radiation*. Usually refers to a *gamma-ray log*; but, sometimes the expression *radioactivity log* is used to refer to a *density log*, *neutron log*, or other *nuclear logs*.

redox logging: The continuous measurement of the *oxidation-reduction potential* of *formation* penetrated by the well bore. Chemical reactions depending on the transfer of *protons* and electrons depend on the Ph and Eh of the systems in which the reactions occur. A measurement of the oxidation-reduction *potential* is a measurement of the tendency for such reactions to occur.

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resistance: (1) The opposition to the flow of direct current. Equal to the voltage drop (E) across the material in which the current is flowing divided by the current (I) flowing through the material. See *Ohm's law* and *IR drop*. Also, see *impedance*.

(2) In fluid flow, see *viscosity*.

resistivity: specific resistance. The property of a material which resists the flow of electrical current. The reciprocal of *resistivity* is *conductivity*. See *ohm-meter*. See also *apparent resistivity*.

resistivity logs: Any of a number of basic *logs* on which some aspect of *formation resistivity* has been recorded.

(1) Most resistivity logs derive their readings from 10 to 100 ft^3 of material about the *sonde*.

(2) *microresistivity logs*, on the other hand, derive their readings from a few cubic inches of material near their borehole wall.

saturation exponent: The exponent (n) of the *saturation* term in Archie's saturation equation (see *Archie's formulas*). The saturation exponent is related to the influence of insulating fluids on the shape and *continuity* of the electrically conductive solutions occupying pore volume.

scintillation counter: Used in the detection of *gamma* or *neutron radiation*. Consists of both a *detector* of incident *radiation* and a *photomultiplier* to produce countable pulses. The type of phosphor used as the detector is dependent on the type of radiation (i.e., gamma ray or neutron) to be detected. Gamma radiation produces *scintillations* in the phosphor as a result of *photoelectric absorption*, *Compton scattering*, or *pair production*, depending on the energy of the incident gamma. The intensity of the scintillation and the amplitude of the resulting pulse are proportional to the energy of the incident neutron or gamma ray. Scintillation

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detectors are efficient and can be made in small sizes. This results in high *vertical resolution*. Scintillation detectors are used in *radioactive logging*, *neutron logging*, and *pulsed neutron logging*.

shear wave: S-wave. In acoustics, a transverse wave. Direction of propagation is perpendicular to direction of particle displacement. For transmission of a shear wave, particles in lateral motion must drag neighboring particles in similar lateral motion. Substances which tend to oppose shear can support propagation of a shear wave (i.e., rigid substances, solids).

short normal curve: A *resistivity curve* made with a normal electrode configuration in which the spacing between the *A* and *M electrodes* is short. Usually the *AM spacing* is 16 inches.

shoulder-bed effect: adjacent bed effect. Effect of adjacent *beds* on a well-logging measurement. The amount of the effect is related to the *vertical resolution* of the measuring *tool*.

sidewall acoustic log: A *well log* of the *acoustic* properties of rock made by a contact *pad* device which presses the acoustic *transducers* against the *formation* wall. The span of the acoustic *receivers* is 6.0 inches, producing a transit time *curve* with much sharper interface resolution which aids recognition of thin, interbedded strata and finding of low-angle fractures. The Sidewall Acoustic Log (SWA) is a Dresser Atlas trademark.

sidewall epithermal neutron log: See *sidewall neutron log*.

sidewall neutron (porosity) log: An *epithermal neutron log* made with the neutron *source* and *detector* mounted in a *skid* which is pressed against the borehole wall and may cut into the *mud cake* to minimize borehole effects.

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signature log: A display of the *acoustic wave train* in the *amplitude-time* mode wherein the amplitudes of the different acoustic wave forms are shown as a function of time.

single-point resistance log: A resistance *log* (units - ohms) made from a monoelectrode or a single downhole electrode. One electrode serves as both the *A* and *M electrodes*. Since the electrode is short, thin *beds* and laminations can be sharply delineated; but investigation depth is very shallow. Usual application is in minerals exploration.

sonar caliper: A *logging* tool used in solution caverns to determine cavern size. Using the *sonar* principle, one or more rotating *sound* emitting and receiving devices are used to record a 360° profile of the cavern walls.

sonde: A detachable probe or downhole tool. A downhole instrument connected to a well-logging cable. Used in making measurements of parameters related to the borehole or its environment. A general term used for any subsurface logging tool that carries electrodes, *detectors*, etc. into the borehole. The cartridge, which consists of the electronics, might or might not be an integral part of the sonde. The term "sonde" has been modernized through use by some users to include the entire downhole, detachable tool.

sonic log: An *acoustic* log. A well-logging record of the *travel time* (*interval transit time*) of the *compression wave* over a unit distance; and hence, a record of the reciprocal of the compressional wave velocity. The time for acoustic energy to travel a distance through the *formation* equal to the distance spanned by two *receivers* is the desired measurement. The units of such measurement are usually expressed in microseconds per foot. The interval transit time can be *integrated* to give the total travel time over the logged interval. For the *borehole compensated sonic log*, two *transmitters*, (one above the receivers and one below) are pulsed alternately to produce an improved log; averaging the measurements tends to cancel errors due to *sonde* tilt or changes in hole size.

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The sonic log is used in combination with other logs (e.g., density and neutron) for *porosity*, shaliness, and *lithology* interpretation. *Integrated transit time* is helpful in interpreting seismic records.

source: In well logging, the source of *radiation* used in the operation of *radioactivity logging* or *nuclear logging* tools. A distinction should be made between the encapsulated radiation sources of *gamma rays* or *neutrons* and the *neutron generator*, also a producer of radiation.

SP: spontaneous potential, self potential. The difference of *potential* (DC voltage) between a movable electrode in the borehole and a distant reference electrode usually at the surface. The SP results from the *IR drop* measurable in the borehole produced by the flow of SP currents in the hole. These currents are generated by the *electrochemical* and *electrokinetic potentials*.

In impermeable *shales*, the SP tends to follow a fairly constant *shale base line*. In permeable *formations*, the *deflection* depends on the contrast between the *ion* content of the *formation water* and that of the drilling *mud filtrate*, the clay content, the bed thickness and *resistivity*, hole size, invasion, and bed boundary effects, etc. In thick, permeable, *clean*, nonshale formations, the SP value approaches the fairly constant *static SP* value which will change if the formation water *salinity* changes. In *dirty* reservoir rocks, the SP will not reach the same value, and a *pseudo-static SP* value will be recorded.

The SP is most useful when the *mud* is fresher than the formation water, a good contrast exists between *mud filtrate* and formation water resistivities, and formation resistivity is low to moderate. In these cases, it indicates permeable beds by large negative deflections, permits easy sand-shale discrimination, is useful for *correlations*, and under favorable conditions, can be used for the estimation of formation water resistivity.

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The *curve* still remains useful in some saline muds. If the formation water is less saline than the mud filtrate, the SP deflection will be positive. However, when the mud column becomes co conductive it will not support a demonstrable IR drop, the SP curve becomes featureless.

spectral gamma-ray log: natural gamma-ray spectral log. Unstable *isotopes* emit particulate (alpha, beta) and electromagnetic (gamma) *radiation*. Penetrating *gamma rays* are suitable for borehole detection. Isotopes of specific elements radiate gamma rays exhibiting specific energy levels within the energy spectrum. Identification of the specific energy level(s) and the amount of gamma radiation (at the specific level) provides a means of identifying the isotope and the quantity of the element.

spherically focused log: SFL. A *log* of formation *resistivity* measured by a *tool* developed for the limited investigation of the *invaded zone*.

Focusing is used to enforce an approximately spherical shape on the equipotential surfaces within the *formation* in spite of the presence of the borehole. Borehole effect is virtually eliminated for hole diameters up to 10 in., yet investigation of the tool is kept shallow enough that its response is, in the majority of cases, mostly from the *invaded zone*. SFL is a mark of Schlumberger.

spine-and-ribs plot: The spine-and-ribs plot is used in the computation of the compensation to be added to the measured value of *bulk density* from the dual-spacing formation density log; i.e., *compensated formation density log*. The spine-and-ribs plot is a *crossplot* of the long-spacing *detector* counting rate versus the short-spacing detector counting rate. For small thicknesses of *mud cake* and other borehole irregularities of small dimension, the slope of the line, passing through the value for correct bulk density and the measured values of density (from each detector), is virtually the same for the usual *densities* and thicknesses of intervening materials separating the detectors and the *formation* wall. The importance of this finding with dual-spacing density measuring systems is that it provides a means for estimating the amount of correction to be added to or subtracted from the measured response from the long-spacing detector. Both the *compensated* density measurement and the amount of compensation, $\Delta\rho$, are then recorded on the *log*.

spinner: a *flowmeter*. The downhole instrument consists of an impeller, inside a protective cage, which is caused to rotate by the motion of borehole fluid past the blades. An alternating current, or the frequency of pulses, constitutes the *signal* sent to the surface and is related to the rate of fluid flow past the impeller. A *survey* is made by moving the *tool* against the flow of fluid, with the flow, or maintained stationary in the hole. Its primary use is in monophasic flow streams.

spinner survey: A *well log* of the fluid flow rate over parts of the well bore as determined from responses of a *spinner*-type device placed in the fluid flow stream (i.e., in *casing* or tubing, etc.)

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SSP: static spontaneous potential. The maximum *SP* that would be recorded when the SP electrode passes from a position well inside a very thick, porous, permeable *clean* sand (or other reservoir rock) to a point well within a thick shale. The static spontaneous potential given by the sum of the components of the *electrochemical potential* is:

$$SSP = -K \log_{10} (a_w/a_{mf}),$$

$$\text{where } K = -70.7 \left[\frac{460 + T°F}{537} \right] = -(60.56 + 0.132T°F),$$

and a_w and a_{mf} are the *activities* of the *formation water* and *mud filtrate*, respectively. Because of the inverse relationship between activity and equivalent resistivity in dilute solutions, this equation is approximated by:

$$SSP = -K \log_{10} (R_{mfe}/R_{we})$$

where R_{mfe} and R_{we} are the equivalent resistivities of mud filtrate and formation water, respectively. For NaCl solutions which are not too saline, $R_{mfe} = R_{mf}$ and $R_{we} = R_w$; for more concentrated solutions, an activity correction should be made. since the static SP in a sandstone is equal to the *potential* causing current (I) to flow in a *mud* column of resistance (R_m), *shale* of resistance (R_{sh}), and a sandstone of resistance (R_{ss}), then

$$SSP = IR_m + IR_{sh} + IR_{ss}$$

where the measured SP is IR_m.

standoff: (1) The distance separating a *sonde* from the wall of the borehole.

(2) A device for producing the separation in (1).

statistical variations: *Nuclear* emissions are random in nature. Variations in the number of specific nuclear emissions observed over a period of time are referred to as statistical variations. Because of the statistical nature of these emissions, *radioactivity* measurements

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must be averaged over a length of time in order to determine the representative level of radioactivity for the *formation*.

Stoneley wave: A boundary *acoustic* wave as a liquid-solid interface (i.e., *formation* wall at the borehole) resulting from the interaction of the *compressional wave* in the liquid and the *shear wave* in the solid. By definition, the Stoneley wave must have a *wavelength* smaller than the borehole diameter. Particle motion in the solid wall will be elliptical and retrograde similar to a *Rayleigh wave*. The velocity of the Stoneley wave will be less than that of the compressional wave in fluid or the shear wave in the solid.

temperature log: A *well log* of temperatures recorded within the borehole, utilizing a temperature-sensitive element exposed to wellbore fluid. The temperature *survey* is often used to locate permeable gas producing zones in empty holes, and to locate producing or injection intervals, acid treatment intervals, and casing leaks, crossflows, etc. in cased holes. The *differential temperature survey*, recorded with either one or two temperature sensors, records the rate of change in temperature with respect to depth. It is very sensitive to small changes in temperature resulting from small thermal events.

thermal decay time: τ. The time for the *neutron* population to fall to 1/e (37%) of its original value. When the macroscopic *capture cross section*, Σ, is in capture units (1 c.u. = 10^{-3} cm^{-1}) and τ is in microseconds, Σ and τ are related by $\Sigma = 4{,}550/\tau$.

Thermal (Neutron) Decay Time Log: TDT. The Thermal Decay Time Log is a record of the rate of capture of *thermal neutrons* in a portion of *formation* after it is bombarded with a burst of 14-MeV *neutrons*. An electronic *neutron generator* in the *tool* produces pulses of neutrons which spread into the borehole and formation.

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The neutrons are quickly slowed down to thermal energies by successive collisions with atomic nuclei of elements in the surrounding media. The thermalized neutrons are gradually captured by elements within the neutron cloud, and, with each capture, *gamma rays* are emitted. The rate at which these neutrons are captured depends on the nuclear *capture cross sections* which are characteristic of the elements making up the formation and occupying its pore volume. The gamma rays of capture which are emitted are counted at one or more *detectors* in the *sonde* during different time *gates* following the burst, and from these counts the rate of neutron *decay* is automatically computed. One of the results displayed is the *thermal decay time*, τ, which is related to the macroscopic capture cross section of the formation, Σ, which is also displayed.

Because chlorine is by far the strongest neutron absorber of the common earth elements, the response of the tool is determined primarily by the chlorine present (as sodium chloride) in the *formation water*. Like the *resistivity log*, therefore, the measured response is sensitive to the *salinity* and amount of formation water present in the pore volume. The response is relatively unaffected by the usual borehole and casing sizes encountered over pay zones. Consequently, when formation water salinity permits, Thermal Decay Time logging provides a means to recognize the presence of hydrocarbons in formations which have ben cased, and to detect changes in *water saturation* during the production life of the well. The TDT log is useful for the evaluation of oil wells, for diagnosing production problems, and for monitoring reservoir performance.

The TDT-K system utilizes two *detectors* and two variable time *gates* (plus a background gate) to sample the capture gamma radiation decay following the neutron burst. The width and positions of the time gates, as well as the neutron burst width and burst repetition rate, are varied in response to signals that are related to Σ (or more precisely, related to the formation decay rate τ, where $\tau = 4550/\Sigma$).

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The TDT-M system utilizes sixteen time gates and one of four possible neutron burst widths and burst repetition rates. Counts from the sixteen gates are combined to form two "sum" gates (plus a background gate) from which Σ is computed. As in the TDT-K system, the combination of gates used to form the "sum" gates, as well as the burst width and repetition rate, are selected according to Σ (or τ) of the formation.

The ratio of counts (R) in the near-spaced to far-spaced detector is recorded and used as an estimate of formation *porosity*. TDT is a mark of Schlumberger.

Thermal Multigate Decay Log: TMD. A record of the macroscopic thermal neutron cross sections of the formation (Σ_F) and the borehole (Σ_B).

An electronic *neutron generator* produces bursts of pulses of 14-MeV neutrons which spread into the formation and borehole. Following each burst, the neutrons are quickly slowed to thermal energies by successive collisions with nuclei in the surrounding media. The thermalized neutrons are then captured by elements within the formation and borehole, producing gamma *radiation*. Gamma radiation intensity is sampled in two detectors at six time intervals (time *gates*) following each burst. These data are used to compute Σ_F and Σ_B. Also, the ratio (R) of counts in the near-spaced to far-spaced detector is recorded and used to estimate formation *porosity*.

Of the common earth elements, chlorine is by far the strongest neutron absorber and is found mainly in the formation water (as sodium chloride) rather than in the formation matrix. Σ_F is primarily a function of the salinity and amounts of water present in the pore volume. Therefore, Σ_F is used with porosity from R to compute formation hydrocarbon *saturation* if the formation water is saline. The Σ_F curve is relatively unaffected by casing and tubing. Σ_B is used with Σ_F to obtain a very accurate true (intrinsic) formation cross section and an improved porosity estimate. In addition, Σ_B can indicate a variety of well bore conditions such as gas between the tubing and casing, and oil-water contacts. Thermal Multigate Decay Log (TMD) is a Welex trademark.

thermal neutron: A *neutron* which has the kinetic energy of about 0.025 eV. The thermal neutron is in thermal equilibrium with the substance in which it exists and will neither gain nor lose energy statistically until it is captured by a neutron absorber.

time-average relationship: An empirical expression used for calculating *porosity* from *interval transit time* determined from *acoustic logs*;

$$\phi = \frac{t - t_{ma}}{t_f - t_{ma}}$$

where t = observed interval transit time, t_f = transit time in the pore fluid, and t_{ma} = transit time in the rock *matrix*. This relation works well in *clean consolidated formations* with uniformly distributed pores. In vuggy formations, the *sonic log* may not reflect the *secondary porosity*; and in *unconsolidated* formations, this relationship may overestimate porosity. In such cases, the formula may be empirically modified to give better values.

time constant: (1) The time in seconds for a measuring instrument to register a 63% change from a former level of response toward a new level of response.

(2) In *nuclear logging*, because of the random nature of *nuclear* emissions, the *detector* output is averaged over a selected time interval in order to record the representative *radiation* level of the environment. Instrument response will thus adjust gradually to environmental changes depending on the length of the averaging time (i.e., time constant).

travel time: *Acoustic* travel time over a specific distance. For example, travel time may refer to *interval transit time* or to *integrated transit time*.

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true resistivity: The *resistivity* of fluid-filled rock where the fluid distributions and *saturations* are representative of those in the uninvaded, undisturbed part of the rock.

ultra-long-spaced electric log: ULSEL. A well log recorded with the use of a modified *long normal* electrode configuration mounted on a 5,000-foot *bridle*. The *AM spacing* can be made 75, 150, 600, or 1000 feet. Differences between the measured *resistivities* and anticipated resistivities calculated from conventional *resistivity logs* indicate nearby resistivity anomalies. Used to define the distance to a salt dome flank. May have important application in locating salt overhangs or casing in nearby well bores.

variable density: variable intensity. *Intensity modulated-time* presentation of the acoustic *wave train* in which the amplitude of the wave form produces a variable photographic density which is displayed versus time. The variations in darkness or density represent relative amplitude.

variable density log: An *acoustic log* in which the acoustic *wave train* is recorded in the variable photographic density or *intensity modulated-time* mode.

wave train: The response of an elastic system to an *acoustic* energy impulse describes a wavelet of several cycles of sinusoidal character. At the onset, the wavelet will be rich in all frequencies but the high frequency components are attenuated rapidly by transit through earth materials because of inelastic *absorption* and conversion to heat.

Wavelets are generated for each energy mode and the composite particle motion resulting from the *compressional*, *shear*, fluid, and boundary waves becomes the wave train with characteristics of the transmitting source, coupling, and the transmission media.

wave train display: The *acoustic wave train* can be displayed in different modes on some *acoustic well logs*. For example:

From: **Ransom, R. C.(Editor), 1984, Glossary of terms & expressions used in well logging: Society of Professional Well Log Analysts (SPWLA), 116 p. Selected terms copied with permission of the SPWLA.**

(1) The *intensity modulated-time* mode in which the wave train is shown in the variable photographic density form.

(2) The *amplitude-time* mode in which the wave train is shown as a full wave form.

wave train log: An *acoustic log* in which the acoustic *wave train* is displayed in either the *intensity modulated-time* mode or the *amplitude-time* mode.

well log: wireline log, borehole log. The product of a *survey* operation, also called a survey, consisting of one or more *curves*. Provides a permanent record of one or more physical measurements as a function of depth in a well bore.

Well logs are used to identify and *correlate* underground rocks, and to determine the mineralogy and physical properties of potential reservoir rocks and the nature of the fluids they contain.

(1) A well log is recorded during a *survey* operation in which a *sonde* is lowered into the well bore by a *survey cable*. The measurement made by the downhole instrument will be of a physical nature (i.e., electrical, acoustical, nuclear, thermal, dimensional, etc.) pertaining to some part of the wellbore environment or the well bore itself.

(2) Other types of well logs are made of data collected at the surface; examples are core logs, *drilling-time logs*, *mud* sample logs, hydrocarbon well logs, etc.

(3) Still other logs show quantities calculated from other measurements; examples are *movable oil plots*, computed logs, etc.

Z/A: The ratio of *atomic number* (Z) to *atomic weight* (A). Nuclei of the same Z but different A are different forms of the same element and are called *isotopes*.

From: **Ransom, R. C.(Editor), 1984, Glossary of terms & expressions used in well logging: Society of Professional Well Log Analysts (SPWLA), 116 p. Selected terms copied with permission of the SPWLA.**

APPENDIX B

REFERENCE TABLES DESCRIBING PRINCIPLES OF SELECTED LOGGING METHODS

TABLE 33

CALIPER LOG

Class	**mechanical**, acoustic
Mineral/Groundwater Logging Nomenclature	**Caliper Log (CAL)**, Caliper (CAL), Acoustic Televiewer (ATV)
Oilfield Nomenclature & Trademarks	Caliper Log (CAL), Caliper (CAL), Borehole Geometry Log (BGT), Powered Caliper Device (PCD), X-Y Caliper (XYC), Acoustic Televiewer (ATV)
Measurement	open hole: measures the borehole diameter cased hole: measures the inside diameter of the casing o Caliper tools may independently measure diameters in as many directions as the tool has arms, but mineral logging tools commonly average diameters. o Acoustic caliper logs generally average time-of-travel data for about 5 degrees of transducer rotation.
Units	units of length: inches, centimeters
Principals of Operation	mechanical: A rigid arm or arms extend from tool to borehole or casing acoustic: A rotary transducer emits pulses. Echos are detected and travel times determined to calculate distances.
Tool Design (Mineral/ Groundwater Logging)	o Single-arm calipers are used to decentralize logging tools. o Multiple-arm calipers are centralized within the hole.
Most Commonly Used Combinations	o Single-arm caliper logs are built into most eccentered or decentralized tools. o Multiple-arm caliper logs are generally run independently, or are recorded with centralized tools such as acoustic logs.
Volume of Investigation	REGION II mechanical: depends on the maximum extension of caliper arms acoustic: without modification, most acoustic calipers will operate in wells as much as 16 inches in diameter
Vertical Resolution	mechanical: a function of the response of the mechanical and electronic components of the system, and the length of the contact surface at the end of the caliper arm
Logging Response Factors	magnetism: Parts of the logging unit, especially moving parts, may become magnetized. bimetallic effects: A bimetallic cell will form where two dissimilar metals are in contact, as a result of poor insulation within the logging tool or cable head.
Conventional Applications	o provides estimate of hole diameter and volume o used for correcting responses of certain logging methods for hole size
Present Applications	same as conventional applications
Related Terms (Appendix A)	acoustic, sonar caliper

Terms and acronyms used in text are in **bold** type.

TABLE 34

CASING COLLAR LOCATOR LOG

Class	**magnetic** or mechanical
Mineral/Groundwater Logging Nomenclature	**Casing-Collar Locator (CCL)**
Oilfield Nomenclature & Trademarks	Casing-Collar Locator (CCL)
Measurement	magnetic: Event markers are triggered when AC current exceeds a level specified for the tool. mechanical: Signals are generated when mechanical feelers cross pipe connections or other rugose features.
Units	qualitative and arbitrary; various units are used, including cps, dcps, volts
Principals of Operation	Two opposed permanent magnets produce characteristic magnetic fields. These fields are disturbed by changes in the magnetic fields when the tool passes through a ferrous discontinuity. As a result, the current induced by the magnetic fields changes.
Tool Design (Mineral/ Groundwater Logging)	free-swinging, omnidirectional
Most Commonly Used Combinations	GR, CBL, NL, DL, NFDD
Volume of Investigation	REGION II, mostly; REGION III to the extent that centralizers might be considered a part of that region
Vertical Resolution	several tenths of a foot
Logging Response Factors	The signal is proportional to the velocity at which the tool is moving.
Conventional Applications	Used in steel casing: to determine depths and locations of casing collars and packers; to locate fish; to locate separated, damaged, or lost pipe; under some conditions to locate perforations; and, to correlate depths for perforating and other wireline services
Present Applications	In steel casing: same as conventional applications In PVC casing: used to determine depths and locations of metallic objects in the annular space (e.g. metallic centralizers)
Related Terms (Appendix A)	casing collar log

Terms and acronyms used in text are in **bold** type.

TABLE 35

DENSITY LOG

Class	nuclear
Mineral/Groundwater Logging Nomenclature	Gamma-Gamma, **Density, Long-Spaced Density (LSD), Short-Spaced Density (SSD), High-Resolution Density (HRD), Omnidirectional or 4-pi Density (LSD-4pi, SSD-4pi)**, Compensated Density (CDL)
Oilfield Nomenclature & Trademark Names	Compensated Density (CDL), Compensated Densilog, Formation Density Log (Compensated) (FDC), Density Log, Gravel Pack Log (NFDD)
Measurement	scattered gamma rays, electron density, photoelectric absorption (lithodensity tool)
Units	counts per second, density units (e.g. g/cc), porosity units (p.u.), percent porosity
Principals of Operation	Gamma rays from a medium-energy gamma-ray source bombard the volume of investigation, and gamma rays are backscattered as a result of Compton scattering collisions and in proportion to the electron density of the materials bombarded. One or more detectors, shielded from the source, record the backscattered gamma rays. The lithodensity tool also measures the photoelectric absorption index.
Tool Design (Mineral/ Groundwater Logging)	single-spacing tools: omnidirectional (4-pi), free-swinging; collimated, eccentered dual-spacing tools: omnidirectional (4-pi), free-swinging; collimated, eccentered
Most Commonly Used Combinations	commonly run with caliper, gamma ray, one or more of the resistivity logging methods, and with neutron porosity log
Volume of Investigation	REGION III (mostly); REGION I to the extent that the log is affected by borehole fluid, especially the HRD; REGION II to the extent that log responds to holes or slots in casing, especially dense (metallic) casing, and especially the HRD ovaloid with major diameter slightly greater than source to detector spacing, and with minor radius about one-third source to detector spacing (Hallenburg, 1984); dependent on density of material
Vertical Resolution	o equal to source-to-detector spacing, or o equal to sum of: source-to-detector spacing and detector length; for analalog tools, add lag, where lag = time constant x logging speed (Hoffman, Jordan, and Wallis, 1982)
Logging Response Factors	rugosity, density of pore fluid, casing density and uniformity, mudcake thickness and density
Conventional Applications	bulk density, porosity, lithology, mechanical parameters, diameter of air-filled boreholes
Present Applications	apparent bulk density of annular space and/or casing, annular materials, voids
Related Terms (Appendix A)	bulk density, compensated formation density log, Compton-scattering collisions, density, density log, electron density, gamma-gamma log, gamma ray, gamma-ray interactions with matter, gamma-ray source, photon, radiation, spine-and-ribs plot, Z/A effect

Terms and acronyms used in text are in **bold** type.

TABLE 36

GAMMA-RAY LOG

Class	nuclear or radiation logging
Mineral/Groundwater Logging Nomenclature	**Gamma Ray (GR)**, Natural Gamma, Gross Count Gamma Ray (GCGR), Total Count Gamma Ray, Shielded Gamma Ray
Oilfield Nomenclature & Trademarks	Gamma-Ray Log (GR)
Measurement	passive measurement of radiation within the borehole or wellbore principal sources of radiation are potassium-40 (^{40}K), uranium-238 (^{238}U) daughter products, and thorium-232 (^{232}Th) daughter products Keys (1989) summarizes the decay series for each of these isotopes
Units	counts or pulses per second (cps), API units, AEC units
Principals of Operation	gamma radiation penetrates a detector, usually an ionization chamber, a Geiger-Mueller tube, a proportional counter, a scintillation detector, or an electroscope Pulse discharges and photoemissions or changes in electrical current within a detector are proportional to the rate or number of gamma rays or photons available to the detector (see Related Terms, Appendix B)
Tool Design (Mineral/ Groundwater Logging)	omnidirectional (4-pi); free-swinging or eccentered
Most Commonly Used Combinations	run with most logs
Volume of Investigation	REGION IV (mostly); REGION III to the extent that certain annular materials (e.g. bentonite) emit more gamma rays than they absorb from the formation; spherical: volume is dependent on energy of radiation and density of material (Hallenburg, 1984), typical radius of investigation, one to three feet
Vertical Resolution	estimates range from a minimum of 2 feet in a dolomite (Hallenburg, personal communication) to approximately 2.5 feet (Hilche, 1978)
Logging Response Factors	downhole environment: boundaries, borehole & casing size, position of tool within borehole or casing, fluid in borehole or casing, casing material and thickness, material in annular space, mineralization due to fluid movement tool design: detector type and size, housing material and thickness operations: response is statistical; for analog tools, time constant and logging speed affect log response; for digital systems, resolution degrades as logging speed increases
Conventional Applications	lithology, correlation, bed boundaries, shale volume percent, clay volume percent, radioactive mineral ore grade
Present Applications	o lithologic classification of formation o identification of annular materials, especially when open-hole and cased-hole logs are available
Related Terms (Appendix A)	API unit, gamma ray, gamma-ray detectors, gamma-ray index, gamma-ray log, photon

Terms and acronyms used in text are in **bold** type.

TABLE 37

GUARD LOG

Class	electric
Mineral/Groundwater Logging Nomenclature	**Guard Log (GL)**, Focused Electric Log (FE)
Oilfield Nomenclature & Trademarks	Dual Dynamically Focused Guard Log (DDFG), Focused Electric Log (FE), Guard Log (GDL, GL, DGL), Guard-FoRxo (GFL, DGFL), Laterolog (L, LL, DLL), Spherically Focused Log (SFL)
Measurement	apparent resistivity
Units	ohm-meters or ohms m^3/m
Principals of Operation	A current-emitting electrode is separated into three parts by insulation. The center electrode serves as the current and measure electrode. The outer or guard electrodes focus the current into a thin horizontal layer at an angle of 90° to the tool. Additional auxiliary electrodes may be used to maintain the vertical voltage gradient.
Tool Design (Mineral/ Groundwater Logging)	omnidirectional; generally free-swinging
Most Commonly Used Combinations	Gamma-ray log, density log, neutron log
Volume of Investigation	REGION II volume dependent on electrode diameter; very small volume of investigation
Vertical Resolution	depends upon electrode configuration
Logging Response Factors	correction factor for mud conductivity and hole size; corrections for shoulder beds
Conventional Applications	bed boundaries for thin beds, resistivity measurements in saline muds
Present Applications	REGION I water level REGION II PVC casing: slotted intervals, casing joints, holes in casing
Related Terms (Appendix A)	apparent resistivity, ohm-meter, Ohm's law, resistivity

Terms and acronyms used in text are in **bold** type.

TABLE 38

INDUCTION LOG

Class	electric
Mineral/Groundwater Logging Nomenclature	**Induction Log (IL)**, Array Induction Log
Oilfield Nomenclature & Trademarks	Induction Log (IL, IS), Induction Electrolog (IEL), Induction Electrical Survey (IES), Induction Electric Log (IES), Dual Induction Focused Log (2IL, DIFL), Dual Induction Log (DIL), Dual Induction Laterolog (DIL®), Dual Spaced Induction (DSI), Dual Induction-SFL, Dual Induction Guard (DIGL), Dual Induction Short Normal Log (DISN), Phasor Induction Log, Array Induction Log
Measurement	formation conductivity (reciprocated to resistivity)
Units	millimhos/meter, ohm-meters or ohms m^3/m
Principals of Operation	A magnetic field moving across a conductive medium will induce an electrical current in the medium. An alternating current of constant magnitude flows through a coil of wire with the solenoid axis parallel to the borehole. The resulting alternating magnetic field extends into the formation where alternating currents are induced. These currents, in turn, generate magnetic fields which induce signals in receiver coils. At low conductivities, the signals are proportional to formation conductivity. (see Related Terms, Appendix B)
Tool Design (Mineral/ Groundwater Logging)	omnidirectional; generally centralized
Most Commonly Used Combinations	SP, guard log, gamma ray
Volume of Investigation	REGION IV toroidal: volume dependent on well bore and formation fluid resistivity and other down hole environment factors; Century Geophysical Corporation Model 9510 receives 50% of signal within 18-inch radius; dual induction has radius of investigation of over 100 inches
Vertical Resolution	estimates range from ≤ 1 foot (mineral logging experience) to approximately 2.5 feet (Hilche, 1978) or as much as 5 feet in evaporites (Hallenburg, personal communication); Century Geophysical Corporation Model 9510 tool has 11-inch bed resolution
Logging Response Factors	down-hole environment: for low-conductivity environments (Rmf > 3·Rw), the noise-to-signal ratio becomes significant; at high conductivities, skin effect may affect response; boundaries; borehole and casing size; casing material and thickness; position of tool within borehole or casing; fluid in borehole or casing; fluid temperature; material in annular space, mineralization due to fluid movement tool design: crystal size operations: response is statistical; time constant for analog tools and logging speed affect log response
Conventional Applications	lithology, correlation, porosity, saturation, sea-water salinity
Present Applications	REGION IV lithologic classification of formation, REGION III location of metallic objects (e.g. centralizers)

Terms and acronyms used in text are in **bold** type.

TABLE 38 (CONTINUED)

Related Terms (Appendix A)	apparent resistivity, conductivity, mho, mho per meter, mmho, ohm, ohm-meter, Ohm's law, resistance, resistivity

Terms and acronyms used in text are in **bold** type.

TABLE 39

NEUTRON LOG

Class	nuclear or radiation
Mineral/Groundwater Logging Nomenclature	neutron neutron [n-e, n-t] logs: (epithermal neutron detector [n-e] and thermal neutron detector [n-t]) **Neutron Log [n-e, n-t] (NL), Dual Spaced Neutron [n-t] (DNL)** (most slimhole logging detectors count thermal neutrons, but some count both thermal and epithermal neutrons)
Oilfield Nomenclature & Trademarks	neutron neutron [n-e, n-t] logs: (epithermal neutron detector [n-e] and thermal neutron detector [n-t]) Neutron Log [n-e, n-t] (NL), Epithermal Neutron Log [n-e] (ENP), Sidewall Epithermal Neutron [n-e] (SWN), Sidewall Neutron Log [n-e] (SNL, SNP), Dual Spaced Neutron [n-t] (DNL), Neutron/Borehole Compensated [n-t] (NBC), Compensated Neutron Log [n-t, n-e] (CNLog), Dual Spaced Compensated Neutron [n-t] (CNL), Compensated Neutron Log [n-t] (CNL), Compensated Neutron Survey (n-t) (CNS), Borehole Compensated Neutron Log (BCN) neutron gamma [n-γ] logs: (gamma-ray detector [n-γ]), Neutron Log [n-γ] (NL)
Measurement	neutron neutron [n-e, n-t] logs and neutron gamma [n-γ] logs: hydrogen index (I_H) - ".....the volume fraction of fresh water that would contain the same amount of hydrogen." (Hearst and Nelson, 1985)
Units	counts or pulses per second (cps), API units
Principals of Operation	neutron neutron [n-e, n-t] logs: o neutrons from a source are moderated, losing energy at a rate inversely related to the atomic weights of the atoms in the moderating material o dependent upon the moderating ability of the material being logged o epithermal and/or thermal neutrons ("slow" neutrons) are counted by a detector in successive collisions neutron gamma [n-γ] logs: o gamma rays are emitted when neutrons are captured by a nucleus o gamma rays are counted by the same types of detectors used by gamma-ray logs (see Related Terms, Appendix B)
Tool Design (Mineral/ Groundwater Logging)	generally omnidirectional (4-pi), but sometimes collimated for petroleum applications; free-swinging or eccentered
Most Commonly Used Combinations	gamma-ray, density
Volume of Investigation	neutron-neutron: spherical; volume dependent on energy of neutrons detected; Hallenburg (1984) estimates that in a 35% porosity (water saturated) sandstone, about 90% of the thermal neutrons detected come from a radius of less than 10 inches, and the peak of the distribution occurs at a radius of about 4-5 inches from the source
Vertical Resolution	estimates range from ≤ 1 foot (mineral logging experience) to approximately 2.5 feet (Hilche, 1978)

Terms and acronyms used in text are in **bold** type.

TABLE 39 (CONTINUED)

Logging Response Factors	downhole environment:	boundaries, borehole & casing diameter, position of tool within borehole or casing, fluid in borehole or casing, casing composition and thickness (boron in steel and chlorine in PVC have large thermal neutron capture cross sections), material in annular space, clay, natural gas
	tool design:	omnidirectional or collimated design; crystal size; count rate in dry holes may saturate detector systems designed for wet holes
	operations:	response is statistical; time constant for analog tools and logging speed affect log response
Conventional Applications	lithology, correlation, porosity, natural gas, water saturation, top of cement behind pipe	
Present Applications	REGION I determination of water level REGION III determination of void- or channel-filling fluids REGION IV comparison of depths of lithologic units and well construction features, lithologic classification of formation	
Related Terms (Appendix A)	API unit, capture cross section, capture unit, chlorine log, hydrogen index, neutron, neutron log, neutron source, thermal neutron	

Terms and acronyms used in text are in **bold** type.

TABLE 40

SINGLE-POINT RESISTANCE LOG

Class	electric logging
Mineral/Groundwater Logging Nomenclature	**Single-Point Resistance Log (SPR),** **Differential Single-Point Resistance Log (DSPR)**
Oilfield Nomenclature & Trademarks	Single-Point Resistance Log (SPR), Differential Single-Point Resistance Log (DSPR)
Measurement	apparent resistance
Units	ohms
Principals of Operation	Conventional systems: The resistance between an electrode on the logging tool and an electrode at the surface. Differential systems: The resistance between an electrode on the logging tool and the tool housing at a point insulated from the electrode.
Tool Design (Mineral/ Groundwater Logging)	omnidirectional; generally free-swinging; generally differential single-point resistance
Most Commonly Used Combinations	Gamma-ray log, density log
Volume of Investigation	REGION II volume dependent on electrode diameter; very small volume of investigation
Vertical Resolution	≤ 0.1 foot
Logging Response Factors	borehole or casing rugosity; position of tool within borehole or casing; fluid conductivity
Conventional Applications	bed boundaries, lithology, correlation
Present Applications	REGION I water level REGION II PVC casing: slotted intervals, casing joints, holes in casing
Related Terms (Appendix A)	apparent resistivity, ohm, ohm-meter, Ohm's law, resistance, resistivity

Terms and acronyms used in text are in **bold** type.

APPENDIX C

REFERENCE TABLES DESCRIBING MATERIALS' PROPERTIES REQUIRED FOR DENSITY AND NEUTRON LOG INTERPRETATION

TABLE 41

PROPERTIES OF MATERIALS USED FOR IDENTIFICATION USING DENSITY LOGS

MATERIAL	DENSITY (G/CC)			Z/A[a]
	MATRIX	BULK	APPARENT	
Annular Matl's[1,7]:				
Bentonite Grout Slurry		1.4		
Cement		1.9 - 2.1		
w/ 2% Bentonite		1.73 - 1.88		
w/ 6% Bentonite		1.59 - 1.68		
Concrete		1.98 - 2.35		
Sand, unsaturated		1.7		
Sand, saturated		2.0		
Elements[2,3]:				
Aluminum, Al	2.70	2.70	2.60	0.4818
Calcium, Ca	1.50	1.50	1.50	0.4990
Copper, Cu	8.92	8.92	8.14	0.4564
Iron, Fe	7.87	7.86	7.37	0.4687
Magnesium, Mg	1.74	1.74	1.73	0.4975
Silicon, Si	2.40	2.40	2.39	0.4985
Fluids[2,3]:				
Air	0.001224		0.001223	0.4997
Natural gas (stp)	0.0007726		0.000886	0.5735
Methane	0.000677		0.00076	0.5703
Oil, (nCH_2)				
10° API, stp	1.00		1.14	0.5703
40° API, stp	0.85		0.97	
Water, NaCl				
300,000 ppm	1.219		1.298	0.5325
30,000 ppm	1.022		1.130	0.5528
pure water	1.00		1.11	0.5551
Minerals[2,3,5]:				
Calcite	2.71		2.71	0.4996
Hematite	5.26		5.04	0.4787
Montmorillonite	2.35		2.35	0.5009
Orthoclase (Feldspar)	2.57		2.55	0.4958
Plagioclase (Feldspar)	2.69		2.65	0.4925
Pyrite	5.06		4.91	0.4850
Quartz	2.654		2.65	0.4993
Rocks & Soils[4,5,7]:				
Limestone, saturated		2.54 - 2.66		
Sandstone, dry (medn)	2.66	2.2		
Sandstone, saturated		2.1 - 2.57		
Shale, saturated		2.4 - 2.65		
Brick Clay, dry[b]	2.75	1.41		
Sandy loam, dry[b]	2.66	1.62		
Silt loam, dry[b]	2.66	1.19		

TABLE 41 (CONTINUED)

MATERIAL	DENSITY (G/CC)			Z/A[a]
	MATRIX	BULK	APPARENT	
Well Casing[1]:				
ABS		1.04		
PTFE		2.19		
PVC		1.40		
Fiberglass Epoxy		1.89		
Steel:				
Low-Carbon		7.85		
Stainless 304		8.00		

SOURCES OF DATA

[1] Driscoll (1986, Table 13.3, p. 419; Table 13.9, p. 426)

[2] Hallenburg (1984, Table 5-5, p. 133-136)

[3] Hallenburg (1993, Table 16-2a,b, p. 368-369)

[4] Hearst and Nelson (1985, Table 6-1, p. 236-237; Table 9-1, p. 370-371)

[5] Olhoeft and Johnson (1989, Table 3, p. 151-161, Table 4, p. 161)

[6] Schlumberger (1969, Table 8-2, p. 44)

[7] Yearsley, Crowder, and Irons (1991, Table 1, p. 104)

COMMENTS

[a] See Appendix B, definition of Z/A

[b] Dry bulk density of "tapped" sample

TABLE 42

NEUTRON CAPTURE CRITERIA FOR SELECTED MATERIALS

MATERIAL	HYDROGEN INDEX, I_H	MACROSCOPIC THERMAL NEUTRON CAPTURE CROSS SECTION, $\sum$, b/cm^3
Annular Matl's[1]:		
Montmorillonite	0.17	14.12
Cement	≈ 0.50	≈ 13.
Quartz	0.04	4.26
Water	(see Fluids)	(see Fluids)
Metals[2]:		
Aluminum, Al		13.99
Iron, Fe		214.90
Fluids[2]:		
Nitrogen		0.004
Oxygen		0.00001
Methane	0.0015	0.028
Oil, (nCH_2)		
10° API, stp		28.02
40° API, stp		24.22
Water[c], NaCl		
300,000 ppm		146.22
200,000 ppm	0.92	100.08
100,000 ppm		58.69
30,000 ppm		32.56
pure water	1	22.08
Minerals[1]:		
Calcite		7.48
Hematite		100.47
Montmorillonite	0.17	8.10
Orthoclase (Feldspar)		16.00
Plagioclase (Feldspar)		6.99
Pyrite		89.06
Quartz	0.04	4.36
Rocks[1]:		
Limestone		8.72
Sandstone		8.66

SOURCES OF DATA

1 Hallenburg, J. K., 1993, Formation Evaluation, Volume 2, Table 17-3b, p. 405: James K. Hallenburg, publisher.

COMMENTS

[a] See Appendix A, definition of *hydrogen index*

[b] See Appendix A, definition of *capture cross section*

[c] 60°F, 14.7 psi

TABLE 43

CONCENTRATIONS OF SELECTED ELEMENTS IN WATER AND WELL CASING AND THEIR MICROSCOPIC THERMAL NEUTRON CAPTURE CROSS SECTIONS

ELEMENT	FRESH WATER	SEA WATER	PVC	PTFE (TEFLON®)	304 STAINLESS STEEL	MICROSCOPIC THERMAL NEUTRON CAPTURE CROSS SECTION (BARNS)[1]
	CONCENTRATION (PPM)					[1] (these estimates sometimes change)
aluminum	0.30	0.001	0	0	0 - 0.3	0.232
barium	0.04	0.013	< 1	0	0	1.20
boron	0.02	4.8	0	0	< 0 - 69	758.86
calcium	17.5	400	0	0		0.44
carbon		28	384,000	240,000		0.0034
chlorine	6.7	18,980	567,000	0		33.44
cobalt		0.00001	0	0		37.5
fluorine	0.20	1.3	0	760,000		0.0098
hydrogen		108,000	48,000	0		0.33
iron	0.23	0.007	0	0	4 - 99.2	2.56
magnesium	3.8	1,270	0	0		0.064
manganese	0.009	0.003	0	0		13.30
molybdenum	0.001	0.013	0	0		2.65
oxygen		875,000	0	0		0.178
silicon	17	3	0	0		0.160
sodium	6.0	10,560	0	0		0.534

VITA

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