The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the State's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, RWQCBs work closely with DTSC in protecting the environment.

The DTSC is issuing this guidance on the application of borehole geophysics for immediate use in investigations and cleanups at contaminated sites. This document supersedes previous DTSC issued guidance dated July 1995, Application of Borehole Geophysics at Hazardous Substance Release Sites, and is one in a series of DTSC guidance documents pertaining to the characterization and cleanup of contaminated sites.

This document was prepared by staff in the Geological Services Unit (GSU) within DTSC. The GSU provides geologic assistance, training and guidance to DTSC and outside stakeholders. This document has been prepared to provide guidelines for the characterization and remediation of contaminated sites. It should be used in conjunction with the companion reference for groundwater characterization activities:

Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites (DTSC, 2012).

Please note that within this document, the more commonly used terms, hazardous waste site and toxic waste site, are used synonymously with the term contaminated site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

Comments and suggestions for improvement of this revised guidance, Application of Borehole Geophysics at Contaminated Sites, should be submitted to:

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This document was developed by the Department of Toxic Substances Control under the direction of Ms. Deborah O. Raphael, Director, and Mr. Stewart Black, Deputy Director of the Brownfields and Environmental Restoration Program. Without their support, completion of this guidance would not have been possible.

The preparation of this guidance was achieved through the efforts of many individuals. The following people had primary responsibility for writing:

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- Michael Finch, PG       Senior Engineering Geologist
- Stephen Sterling, PGP, CEG, CHG  Senior Engineering Geologist
- Lora Jameson, PG        Engineering Geologist

This revised guidance relies heavily on the work of the authors of the original guidance document. The contributions of Bill Owen and Steve Belluomini continue to be appreciated.

This guidance has benefited greatly through input received from several sources, including:

- DTSC’s Geological Services Branch;
- Internal reviewers of draft versions of the guidance; and
- External reviewers at the California Regional Quality Control Board.

In particular, the authors wish to thank the following individuals for their thoughtful technical support throughout the development of this guidance: Theo Johnson, Brian Lewis, and Eileen Hughes. The authors would also like to thank Marie McCrink of the California Regional Quality Control Board, Central Valley Region for her contributions.

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ABBREVIATIONS AND SYMBOLS

API  American Petroleum Institute
ASTM American Society for Testing and Materials
BHC  Borehole Compensated Acoustic Log
BHTV Acoustic Borehole Televiewer Log
BVL  Borehole Video Log
d_h  borehole diameter
d_i  flushed zone diameter
d_j invasion zone diameter
CL  three-arm caliper log
DTSC Department of Toxic Substance Control
e-log electrical resistivity log
GSU Geological Services Unit
h_b  bed thickness
h_mc mud cake thickness
IL  electromagnetic induction log
NGL natural gamma log
NL  neutron log
QA/QC Quality Assurance and Quality Control
R_m mud resistivity
R_mc mud cake resistivity
R_mf mud filtrate resistivity
R_s  adjacent bed resistivity
R_t true formation resistivity
R_xo flushed zone resistivity
R_w  formation water resistivity (undisturbed zone)
SP  spontaneous potential
S_xo  flushed zone water saturation
S_w  water saturation (undisturbed zone)
1.0 INTRODUCTION

1.1 Purpose

This document presents guidelines for the application of borehole geophysical techniques. This document provides:

- Guidelines to select the appropriate borehole geophysical tools;
- Recommended quality assurance and quality control (QA/QC) procedures; and,
- Guidelines for standardized presentation of the resulting data.

Other professional organizations, including the American Society for Testing and Materials (ASTM) and the American Petroleum Institute (API), continue to update and develop guidelines for borehole geophysical techniques. Every attempt has been made to incorporate elements of those documents into the DTSC guidelines. As new techniques gain acceptance and existing techniques are refined, these guidelines will be updated periodically to meet the state of the science.

The recommendations presented herein represent a subset of the larger site characterization process. Additional investigative tools necessary to adequately characterize a site are outlined in *Guidelines for Hydrogeologic Characterization of Contaminated sites* (DTSC, 2012).

1.2 Application

Borehole geophysical techniques provide an efficient and cost-effective means to collect lithologic and hydrologic information from wells and boreholes. These methods provide continuous measurements of physical properties along the entire length of the borehole, supplementing discrete information gathered by coring, sampling, and testing.

Calibrating the geophysical response with the data obtained from a representative number of continuously cored holes reduces the amount of coring needed to characterize a site with a corresponding reduction in cost.

1.3 Limitations

The recommendations presented in this document represent the minimum criteria necessary to obtain quality data and assure reasonable and independently verifiable interpretations. Some sites may require borehole geophysical studies above and beyond the scope of this document, while at other sites a less rigorous application of this guidance may be appropriate. Practitioners performing site investigations should consult with pertinent regulatory agencies for site-specific requirements.

This document does not define operating procedures for conducting borehole geophysical logging or for interpreting the results. The qualified professional in charge of the field investigation must specify the operating procedures in an appropriate work...
plan and document any significant departures from the work plan that were necessary during the course of the investigation.

Existing statutes and regulations including Federal, State and local regulations, statutes, and ordinances are not superseded by this document. Site characterization activities must be performed in accordance with these requirements where applicable, relevant and appropriate.

2.0 RECOMMENDED APPROACHES AND SPECIFICATIONS

2.1 Personnel Qualifications

When discussing the qualifications of personnel interpreting geophysical logs, one should distinguish between qualitative and quantitative interpretation. Environmental studies commonly use qualitative interpretation of different soil and lithologic types by comparing the general response of the logging probes from borehole to borehole.

Quantitative interpretation uses the numerical data provided by the logging probes to define the physical parameters, such as clay/shale volume, density, and porosity of the soil and rock types encountered by the probe. Although quantitative interpretation is not routinely performed in environmental studies, its use may increase as algorithms for freshwater aquifers become refined.

Pages 13 through 16 of Keys (1989) provide further discussion of qualitative and quantitative interpretation.

The Geologist and Geophysicist Registration Act requires personnel to be registered to practice geology or geophysics in the State of California. If not registered, these personnel must be overseen by a Professional Geologist or Professional Geophysicist licensed in the State of California who accepts responsibility for the interpretations. This registered professional must accept responsibility for the work by signing or stamping any reports containing borehole geophysical proposals or interpretations. The State currently requires no specialty certification for log analysts.

2.2 Quality Control Parameters for Geophysical Logging

2.2.1 Documentation

A site characterization work plan defines QA/QC procedures for borehole geophysical logs. The work plan outlines the rationale for the selection of the basic logging suite and identifies the objectives of the study.

The final report presents the interpreted results of the geophysical logs and discusses any problems encountered in the field and any deviations from the work plan needed to solve those problems.
Adequate interpretation of borehole geophysical data requires recording both logging procedures and borehole information (Keys, 1989) as documented on the well log, commonly referred to as header information.

As with surface geophysical techniques, borehole logging becomes susceptible to interference due to equipment malfunction, electromagnetic radiation, and borehole conditions, collectively referred to as noise. Fortunately, borehole geophysical noise is usually less problematic compared to noise associated with surface surveys. However, the effect of noise on borehole logging must be assessed and appropriate measures taken to reduce any undue influence. The final geophysical report must document any interference during geophysical logging and the procedures used to correct such interference.

2.2.2 Calibration and Field Checks

The quality of instrument response can be achieved through regular calibration and by conducting field checks prior to each survey. All logging probes require testing and calibration on a regular basis, as appropriate for each probe. Testing and calibration should take place according to the manufacturer's recommendations, or should follow the guidelines presented in the United States Geological Survey Water Resources Investigation Report 88-4058 (Hodges, 1988). Additionally, all logging probes should be field checked and recalibrated as necessary at the beginning of each field day. The appropriate field form or field notebook should document calibration and field-check information for any particular logging probe. The potential for operator or instrument error should be evaluated on a regular basis.

When logs are to be used for qualitative analyses, this requirement may be met by careful observation of the logs while they are being run and by calibration and daily field checks. However, when quantitative analyses are needed, the probes should be checked with an appropriate standard both before and after the probes are run in the borehole. Field checks can be made by using built-in standards, external calibration tools, or a known reference within the borehole, such as the casing. At least two standards should be available for each probe so that both scale position and sensitivity can be checked (Keys and MacCary, 1983). The type of field standard used and the values obtained from the field checks should be recorded on the appropriate field form or field notebook.

Increasingly, hydrogeologic logging uses internally calibrated probes. For these probes, calibration adjustments occur automatically during logging, making the standard "before-and-after" field checks of little use. Instead, a continuous indicator or summary of calibration values from a log run is needed, as well as a record of the most recent shop calibration. This information should be recorded on the appropriate field form or field notebook. The final report should provide a continuous log of calibration values, indicate log intervals where calibration is outside an acceptable range, or should provide a statistical summary of calibration changes.
2.2.3 Logging Speed

The geophysicist is responsible for selecting the appropriate logging speed for each probe to achieve the project-specific data quality objective. Since logging speed affects resolution, an appropriate speed is selected to obtain the desired data quality for each type of probe used. It is not possible to define maximum logging speeds for every technique or site condition. Logging speed is tool-specific and influenced by data requirements and site conditions. The exceptions to this rule are the nuclear logs. Maximum logging speeds for nuclear logs are discussed in Section 2.5.3.

2.2.4 Borehole Location and Reference Elevation

All borehole locations (including exploratory boreholes and wells) should be located with reference to a permanent datum for quality control. The starting depth of the log should also be referenced to the elevation of a permanent datum. Initially, for lithologic control, elevations derived by simple sighting from a nearby benchmark may suffice; however, accuracy of location survey data should be based on the site-specific objectives of the investigation. The importance of ensuring a borehole’s location is accurately referenced to a permanent datum cannot be overemphasized and the registered professional overseeing the work needs to ensure that the starting depths of all geophysical logging runs in the borehole are ultimately referenced to a permanent datum. A California-licensed land surveyor should perform detailed surveying, when necessary. If a borehole or well will be logged periodically over time, starting depths should be referenced to a marker permanently affixed to the surface completion or well casing.

2.2.5 Repeat Logs

The repeat log or portion of the hole that is logged twice to check instrument function, provides additional QA/QC. Every log should be rerun either partially or entirely, depending on project-specific data quality objectives and the judgment of the field personnel. The partially repeated portion of the log should span an interval of maximum signal variation and any intervals of particular interest to the study. The necessity of additional reruns should be evaluated during the actual logging, while the logging equipment is onsite. Repeat logs should be documented and the logs included in the site characterization report.

2.2.6 Depth Correction

With many borehole techniques, it is possible to record several measurements simultaneously through the use of combination probes. When combination probes are used, borehole measurements should be corrected for differences in measuring depth between tools and the correction noted in the log header. The correction may be automatic, or may be performed by manually shifting the responses of the accessory logs to align with the primary log (usually an electrical log).
2.3 Presentation of Geophysical Logs

2.3.1 Header Format

The header information outlined in Table 1 should be presented in a uniform fashion. The API developed guidelines RP 31 and RP 33 that contain standardized headers for electrical and nuclear logs (API, 1967 and 1974). The API headers originally developed for oil well logging may not be entirely applicable to environmental logging, but provide acceptable standard header formats. An acceptable alternative to the API formats is the abbreviated version presented in Figure 1.

Where more than one data element exist, such as casing or bit size changes, these elements should be recorded on the same header line. The names of all probes and modules used during the same logging run should be recorded on the header.
Table 1 - Log Header Information

<table>
<thead>
<tr>
<th>WELL INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Well Name/Number</td>
</tr>
<tr>
<td>• Location/Site Name</td>
</tr>
<tr>
<td>• Surface Elevation</td>
</tr>
<tr>
<td>• Casing Height (above surface)</td>
</tr>
<tr>
<td>• Depth Reference (description)</td>
</tr>
<tr>
<td>• Borehole Diameter</td>
</tr>
<tr>
<td>• Casing Information (type, diameter, location)</td>
</tr>
<tr>
<td>• Drilling Fluid Description (type, resistivity, temperature)</td>
</tr>
<tr>
<td>• Level of Fluid in Borehole or Well at Time of Logging</td>
</tr>
<tr>
<td>• Construction Information (locations and composition of annular seals, filter pack and screen)</td>
</tr>
<tr>
<td>• Drilling Information (date drilled, name of driller, drilling method, drilled depth)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LOG INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Type of Log</td>
</tr>
<tr>
<td>• Run Number</td>
</tr>
<tr>
<td>• Name(s) of Operators, Observers</td>
</tr>
<tr>
<td>• Date Logged</td>
</tr>
<tr>
<td>• Probe Description (name, serial number)</td>
</tr>
<tr>
<td>• Logging Speed</td>
</tr>
<tr>
<td>• Recorder Scale</td>
</tr>
<tr>
<td>• Module/Panel Settings</td>
</tr>
<tr>
<td>• Listing of all other logs run on same date</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MISCELLANEOUS INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Additional comments (e.g., adverse weather, logging conditions, any irregularities in calibration, logging procedure)</td>
</tr>
</tbody>
</table>

Notes: Log header information recommended for all borehole geophysical logs. Header Information should be as complete as possible. Missing information should be so noted on the header form. After Keys (1989).
Figure 1 - Schematic Diagram for Log Header Format

2.3.2 Log Format

Final copies of geophysical logs should be presented using the three-track or two-track API format, as presented in API RP 31 and API RP 33 (API, 1967 and 1974). Figure 2 is provided for illustration of the API track formats.

Figure 2 - API Track Formats for Borehole Logs

Example of API two-and three-track formats.
A) three-track format, linear scales.
B) two-track format, logarithmic scale for Track 2.
C) three-track format, split grid (combined log and linear scales).
From Schlumberger (1974).
In the three-track format, Track 1 is separated from Tracks 2 and 3 by a depth track. In the two-track format, Track 1 remains the same, but Tracks 2 and 3 are replaced by a single 5-inch wide track. All tracks should have linear scales whenever possible. Logarithmic scales to show the range of signal variation are also acceptable.

In RP 31 and RP 33 (API, 1967 and 1974), the API recommends that electrical logs be segregated from nuclear logs, with each being presented on a separate log record. However, for environmental studies, an accepted and common practice is to combine these types of geophysical logs into a composite log in which nuclear and electrical measurements are combined. In the composite log, Track 1 is reserved for three logs: caliper, spontaneous potential (SP) and gamma. Short- and long-normal resistivity, or their equivalents, are presented in Track 2. Additional correlation logs are assigned to Tracks 2 and 3 as space permits. This format is acceptable with the following caveat: with the exception of Track 1, no more than two logs should be overlaid on the same track. For Track 1, SP, gamma and caliper logs may be overlaid simultaneously, as long as the logs are still legible. If not, then the API guidelines should be followed, and electrical and nuclear logs should be separated, although caliper logs may still be recorded in Track 1. When logs are overlaid, different line patterns should be used to distinguish between log types.

Repeat sections and calibration records may be presented either below the main log or on separate records. If presented separately, headers should be attached for each record.

2.3.3 Scale

The choice of scales is an important factor in assuring that the data show adequate resolution without excessively amplifying noise. To present subsurface information without undue distortion, the vertical log scale should be the same for each log at a site. The vertical scale should be chosen based on site-specific resolution requirements, but should not be greater than API’s 5-inch log (5 inches = 100 feet [1 inch = 20 feet]) for English units, or 1:200 log (1 meter = 200 meters) for metric units (API, 1967 and 1974). Note that this recommendation does not apply to logs reproduced for the purposes of constructing cross-sections or other illustrations. Logs may be reduced for this purpose, so long as copies of the original logs are also provided.

The horizontal scale for each log should be chosen to accommodate the expected range of signal variation. For both analog and digital logging systems, the signal range can usually be measured and selected as the probe is descending the borehole (in digital systems, this process is often automatic). In the event that signal variation exceeds the expected range, or when accommodating the expected variation would degrade resolution, the log should be presented at two scales: one scale must span the entire range of variation, the other should show the necessary resolution for either the entire log or for specific zones of interest, as appropriate to the objectives of the study. Analog systems usually require logging the borehole twice with the same probe; in this case the repeat log may also serve as the second run. With digital systems, the initial
run usually contains all the necessary data so the log, or portions thereof, can be reprinted at the expanded scale.

2.3.4 Digital Formats

The storage of geophysical log data and header information as digital data is universal. DTSC recommends all digital copies of geophysical logs follow the API Digital Log Interchange Standard (RP 66; API, 1991).

2.4 Selection of Logging Techniques

Each borehole geophysical technique measures a different physical property; therefore, the choice of techniques is dependent upon the site-specific geology and hydrology (see Table 2). In addition, several borehole techniques are needed to adequately correlate stratigraphic and hydrostratigraphic units. The selection of borehole logging techniques for use at any site is the responsibility of the qualified geologist or geophysicist.

DTSC has developed a recommended list for the selection of a basic suite of borehole techniques for use in hazardous waste site investigations based on years of successful logging in a variety of hydrogeologic environments (Table 3). This table does not list every type of probe that may be used to delineate borehole lithology or aquifer properties. This list represents the minimal logging suite that the DTSC judges to be adequate for effective geological and hydrogeological interpretation. Additional techniques should be used as warranted by site-specific conditions and data needs, based on the targets of interest, borehole conditions, and data requirements. Additionally, the rationale for selecting additional techniques should be documented in an appropriate site characterization work plan and report.
<table>
<thead>
<tr>
<th>Geophysical Log</th>
<th>Description</th>
<th>Primary Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous Potential (SP)</td>
<td>Used in fluid-filled, uncased borehole only.</td>
<td>Characterize permeability; evaluate formation water salinity.</td>
</tr>
<tr>
<td>Electrical Resistivity (E-Log)</td>
<td>Used in fluid-filled, uncased borehole only.</td>
<td>Characterize permeability; determine stratigraphic correlations. Estimate formation porosity.</td>
</tr>
<tr>
<td>Electromagnetic Induction (IL) Log</td>
<td>Used in air- or fluid-filled, uncased or PVC-cased boreholes, 2 to 10 inches in diameter. Measures formation electrical conductivity between two coils, 20 inches apart by using electromagnetic induction.</td>
<td>Characterize permeability; determine stratigraphic correlations. Estimate formation porosity.</td>
</tr>
<tr>
<td>Three-Arm Caliper Log (CL)</td>
<td>Used in air- or fluid-filled, cased or uncased borehole. Measures borehole diameter using 3 or 4 radially spaced arms.</td>
<td>Determine borehole rugosity in open hole or damaged casing in cased hole</td>
</tr>
<tr>
<td>Borehole Video Log (BVL)</td>
<td>Used in air- or clean water, clean borehole wall. Produces a video tape of the borehole (or casing) in axial or radial (side view) using a downhole camera &amp; light source.</td>
<td>Characterize lithology and evaluate fractures in open hole; can also be used in a cased well to evaluate casing and well screen.</td>
</tr>
<tr>
<td>Acoustic Borehole Televiewer (BHTV) Log</td>
<td>Used in fluid-filled, uncased boreholes. Produces an acoustical image of the borehole and acoustical measurement of borehole diameter.</td>
<td>Characterize lithology; determine lithologic contacts and orientation; stratigraphic correlations; evaluate fracture characteristics; identify borehole breakout or unstable areas.</td>
</tr>
<tr>
<td>Borehole Compensated Acoustic (BHC) Log</td>
<td>Used in fluid-filled, uncased boreholes. Measures compressional wave velocity or transit time (interval transit time) or compressional wave amplitude.</td>
<td>Characterize permeability; provide velocity information for seismic interpretation; estimate formation porosity.</td>
</tr>
<tr>
<td>Natural Gamma Log (NGL)</td>
<td>Used in air- or fluid-filled, cased or uncased borehole, less than 14 inches in diameter. Measures natural gamma radiation emitted by the formation.</td>
<td>Characterize permeability; determine relative volumetric moisture content of the formation.</td>
</tr>
<tr>
<td>Neutron Log (NL)</td>
<td>Used in air or fluid PVC- or steel-cased boreholes only.</td>
<td>Characterize permeability; determine relative volumetric moisture content of the formation.</td>
</tr>
</tbody>
</table>
Table 3 - Minimum Techniques for a Borehole Logging Suite

<table>
<thead>
<tr>
<th>Wet Suite</th>
<th>Dry Suite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caliper</td>
<td>Caliper</td>
</tr>
<tr>
<td>Gamma</td>
<td>Gamma</td>
</tr>
<tr>
<td>Spontaneous Potential (SP)</td>
<td>Induction(^3)</td>
</tr>
<tr>
<td>Point Resistance</td>
<td></td>
</tr>
<tr>
<td>Shallow Electrical(^1)</td>
<td></td>
</tr>
<tr>
<td>Deep Electrical(^2)</td>
<td></td>
</tr>
</tbody>
</table>

B. OPTIONAL LOGGING SUITES

<table>
<thead>
<tr>
<th>Wet Methods</th>
<th>Dry Methods</th>
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<tbody>
<tr>
<td>Borehole Video</td>
<td>Air Rotary</td>
</tr>
<tr>
<td>Acoustic Borehole Televiewer</td>
<td>Percussion(^4)</td>
</tr>
<tr>
<td>Borehole Compensated Acoustic Log</td>
<td>Auger</td>
</tr>
<tr>
<td>Borehole Deviation Logs</td>
<td>Direct Push</td>
</tr>
</tbody>
</table>

C. DRILLING METHODS

<table>
<thead>
<tr>
<th>Wet Methods</th>
<th>Dry Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud Rotary</td>
<td>Air Rotary</td>
</tr>
<tr>
<td>Reverse Circulation</td>
<td>Percussion(^4)</td>
</tr>
<tr>
<td>Cable Tool</td>
<td>Auger</td>
</tr>
<tr>
<td></td>
<td>Direct Push</td>
</tr>
<tr>
<td></td>
<td>Sonic</td>
</tr>
</tbody>
</table>

Notes:
\(^1\) includes short normal, shallow focused or shallow induction probes
\(^2\) includes long normal, deep focused or deep induction probes
\(^3\) includes shallow and deep induction probes
\(^4\) includes down-hole hammer and casing-driver methods

2.4.1 Wet and Dry Suites

The selection of a basic logging suite is dependent upon the presence of fluid in the borehole, primarily because almost all electrical logs require a conducting medium to channel current into the formation. For the purpose of this document, the borehole geophysical techniques that make up the basic logging suites are separated into "wet" and "dry" suites, as shown in Table 3. The wet suite should be used in fluid-filled holes, whereas the dry suite is intended for air-filled holes.

The selection of the wet or dry suite for a particular borehole is primarily based upon the drilling method used to create the hole. Consequently, it is necessary to distinguish between "wet" and "dry" drilling methods. Wet methods use water or mud as a drilling fluid, whereas dry methods utilize either air (with or without liquid additives) or no drilling fluid. Examples of wet and dry drilling methods are also shown in Table 3.
The basic borehole logging suite selection process in this document does not account for the presence of natural ground water in a borehole drilled with dry methods. This is an important factor, since a significant thickness of ground water would enable the use of additional wet methods in an otherwise "dry" borehole. However, the presence or amount of ground water in a borehole is site-specific, and it is not practical to develop selection criteria for this situation. The qualified geologist or geophysicist on-site should document borehole conditions and recommend additional borehole geophysical techniques when necessary.

2.4.2 Casing

Under certain conditions conductor casing must be placed in the hole as drilling proceeds to maintain hole stability, or in the case of hollow-stem auguring, is inherent to the drilling technique. Casing can also include material used to construct the well. Therefore, it is necessary to modify the selection process to include conductor casing/well casing material as a secondary criterion (see Figure 3).

Figure 3 - Selection Process for the Basic Logging Suite

Flow chart outlining the selection process for the basic borehole logging suite. Of primary importance to the selection of borehole geophysical techniques is whether casing is present in the hole at the time of logging. For the purpose of this document, "casing" includes drill pipe, conductor casing, hollow-stem auger pipe, and well casing.
2.5 Borehole Logging Techniques

This section describes the recommended practices and specifications for borehole logging techniques. The following guidelines have been developed for borehole geophysical methods used in environmental investigations or have a demonstrated potential for use in environmental site investigations. Due to the large number of instruments available, it is not practical to develop guidelines for every borehole logging technique. However, as the use of other techniques increases and new techniques are developed, the guidelines will be updated to meet the state of the science.

2.5.1 Electrical Logs

Electrical logs include all logs that measure differences in electrical potential in and adjacent to the borehole due to the flow of electric current (Keys, 1989). Such logs include spontaneous potential (SP), single-point resistance, resistivity and induction techniques. These logs are used to determine bulk and formation-water resistivity, and determine the invasion profile (Figure 4) of the drilling fluid (often an indicator of permeability). Electrical logs may also be used to determine the porosity of clean sand beds (Archie, 1942; Schlumberger Limited, 1989).

Electrical logs (excluding induction logs) can only be used in liquid-filled, uncased holes. Quantitative interpretation of electrical logs requires knowledge of effects of the drilling fluid, necessitating resistivity measurements of the drilling mud and mud filtrate. Measurement of both the mud and the mud filtrate is preferred, but if mud filtrate values are not available, they may be calculated from the drilling mud resistivity, using the formulas presented by Schlumberger (1984, after Overton and Lipson, 1958). Since resistivity is dependent upon temperature, the temperature of the sample should also be recorded at the time of measurement. Resistivity measurements are usually taken from a circulated sample of the drilling fluid; however, when there is groundwater flow within the borehole, measurement of the entire fluid column may be needed, requiring a separate fluid-conductivity/fluid-resistivity log (refer to [Keys, 1989] for a discussion of fluid-conductivity logs).

With the exception of induction logging, electrical techniques are seldom used with auger drilling. Auger drilling is does not use drilling fluids; therefore, the use of electrical logs in augered holes would require filling the borehole with liquid, assuming data are needed above the water table. However, situations may arise where it would be advantageous to run electrical logs in augered holes. In this case, only potable water should be introduced into the hole. If electrical logs are run in augered holes, the resistivity and temperature of the borehole fluid needs to be measured, either by sampling or through a fluid-conductivity log. If sampled, the sample should be taken from the borehole immediately after logging, to minimize potential errors associated with a stratified fluid column and fluid temperature fluctuations.
Diagrammatic representation of the invasion profile. Invasion results from infiltration of drilling fluid from the borehole into the surrounding formation. Invasion occurs with the use of "wet" drilling methods. For a definition of abbreviations, see Abbreviations and Symbols. From Schlumberger (1984).
2.5.1.1 Spontaneous Potential (SP) Logs

SP logs detect changes in electrical potential caused by lithologic or water chemistry contrasts within a borehole. SP measurements are commonly used in the oil industry to determine formation water resistivity ($R_w$) (Schlumberger Limited, 1989). However, the empirical formulas used to determine $R_w$ are unreliable for shallow aquifers due to highly variable formation-water salinity, the general absence of massive clean sands, and the presence of cations other than sodium in significant amounts. Guyod (1966) has discussed the problem of $R_w$ determination in fresh water from the SP log and Collier and Alger (1988) state that the SP log is quantitatively useful only in thick, clean sands. Therefore, SP logs should be used solely for qualitative analysis. A possible exception to this rule would be the case of a flat SP curve, where $R_w$ would be equal to the resistivity of the drilling fluid assuming no malfunction.

A common problem with SP logs is caused by adjusting the shale (or clay) baseline during the logging procedure (Collier and Alger, 1988). This situation can generally be avoided by observing SP response while the probe is lowered in the borehole, and adjusting the baseline accordingly prior to recording; however, circumstances may arise where the baseline may need to be shifted during recording. If this occurs, the baseline shift must be clearly marked on the log record, and a new scale should be inserted above the shift.

2.5.1.2 Resistivity Logs

Many different borehole logging probes are currently available to measure resistivity. Of these tools, point-resistance and normal resistivity probes are most commonly used for groundwater studies. Less frequently used tools, focused or guard logs focus current into the formation.

Both normal and focused resistivity logs are sensitive to borehole mud conditions, bed thicknesses, and the thickness of the invaded zone adjacent to the borehole (Schlumberger Limited, 1989). Normal logs may be severely affected, whereas focused logs are influenced to a lesser degree. In any case, every resistivity log requires corrective processing when used for quantitative analyses (Collier and Alger, 1988).

Focused and normal resistivity logs are generally recorded at short- and long-electrode spacings, to determine the invasion profile of the drilling fluid. Typical short spacings vary from 8 to 16 inches; long spacings vary from 32 to 84 inches. For the purpose of defining standard spacings of normal logs for use in environmental release site investigations, short-normal spacings should be no greater than 16 inches. Long-normal spacing should be no greater than 64 inches.

Lateral logs are similar to normal logs, but with an extremely long (up to 18 feet) electrode spacing and a correspondingly deep formation measurement. Lateral logs exhibit an asymmetrical log response that is difficult to interpret, even for relatively thick beds. Where beds are thin, the difficulty of interpretation becomes difficult; therefore,
use of lateral logs is not recommended. If deep information is needed, an appropriate focused log should be used.

2.5.1.3 Induction Logs

Induction logging techniques are often used in place of resistivity techniques where borehole conditions do not permit standard resistivity logging. Like normal and focused resistivity techniques, induction logs are influenced by lithology, borehole, and invasion effects, and therefore, must be corrected when quantitative analyses are desired. As with normal and focused resistivity logs, when induction logs are chosen as part of the logging suite, both shallow- and deep-sounding induction probes should be included in the suite.

2.5.1.4 Caliper Logs

Caliper logs are used to measure changes in borehole diameter or borehole rugosity. They are generally run in uncased boreholes, although they can be run in cased wells to evaluate well casing collapse. The utility of these logs and their theoretical and practical basis are discussed by Hilchie (1968) and Keys and MacCary (1983). Since virtually every borehole logging technique is affected by borehole diameter changes, caliper logs are an essential part of any logging suite (Collier and Alger, 1988).

**Recommended Specifications.** Many caliper tool configurations exist; the primary differences lie in the number of measuring arms and arm type. Multiple arms provide a better indicator of borehole washouts and/or elliptical shape. Because of this advantage, caliper probes used for environmental site investigations should possess at least three mechanical measuring arms of sufficient length to span the expected range of borehole diameter changes.

The three basic type of caliper arms are pads, bow springs, and fingers. The type of arm that is used can significantly affect the resolution of the caliper log. Since fingers provide better resolution than pads or bow springs, caliper arms for use in environmental site investigations should be of the finger type.

**Supplementary Caliper Measurements.** For nuclear logging techniques, borehole diameter effects are automatically compensated by a built-in caliper. When compensating calipers are part of any borehole technique, a log from the compensation caliper should be recorded in addition to the regular caliper log.

2.5.2 Optional Logs

2.5.2.1 Borehole Video Logs (BVL)

A video camera views uncased boreholes and cased wells using borehole video logs (BVL). BVL evaluates fractured bedrock, inspects borehole “washouts,” and inspects casing conditions using both color and black and white cameras.
Air-filled or clear fluid-filled conditions provide the best results, and the camera should be centralized in the borehole. Runs should be repeated as determined by the project geophysicist. The camera should be allowed to equilibrate with downhole temperature and humidity conditions to ensure that the camera lens does not fog up. If necessary, distilled water can be poured into the borehole to clear fogged camera lenses. Image clarity can be improved with adjustment of brightness, contrast, and other controls.

In recently drilled boreholes, groundwater or drilling water should be of low enough turbidity to ensure clear video data is collected. Boreholes may require surging and/or purging several borehole volumes to reach low enough turbidity for adequate video display records. The final video should display the depth and well identification on the video log and videotape.

### 2.5.2.2 Borehole Televiewer (BHTV) Logs

Acoustic borehole televiewer (BHTV) logs provide high-resolution acoustic images of the borehole wall. These logs provide data on the location, orientation and character of planar subsurface features such as fractures, bedding planes, and solution openings. They can show the location and orientation of lithologic contacts, as well as identifying borehole breakout and unstable areas within the borehole. These tools are run centralized with bow springs in fluid-filled uncased boreholes. The image is produced by reflecting high frequency acoustic energy (at direct incidence) off the borehole wall.

BHTV products are borehole wall acoustic reflectance and acoustic caliper images of the entire 360° degree borehole wall. The received acoustic signals can be recorded in analog format on standard VHS tape or digitized which then can be enhanced, analyzed, and displayed in various color formats using a computer program. These programs produce three-dimensional plots, calculate the aperture and orientation of fractures, the fracture orientation, borehole diameter, provide a digital display of the borehole core, etc. The BHTV display log is similar to a cylinder that has been opened along the north side and flattened. These images can then be enhanced and interpreted on an interactive workstation to provide detailed structural and stratigraphic information about the material penetrated by the borehole.

BHTV logs should be run at a rate of 10 feet per minute or slower and should be located in the center of the borehole. As a check, BHTV logs can be run into the interval with surface casing.

### 2.5.2.3 Borehole Compensated Acoustic (BHC) Logs

Compensated acoustic logs measure the acoustic inverse velocity (interval transit time) of the material penetrated by the borehole. This log is produced by conducting multiple miniature seismic refraction shots as the sonde, containing one or two acoustic transmitter(s) and two receivers, is retrieved from the bottom of a fluid-filled uncased borehole.
BHC tools should be run with centralizers at a rate of 10 to 15 feet per minute. While running, monitor the signals at both receivers to ensure that the automated picking algorithm does not skip cycles. If possible, record full acoustic wave forms for both receivers and enhance with post processing before running the picking algorithm. Magnetostrictive sources should be polarized prior to the logging job, whereas piezometric sources do not need to be polarized prior to logging. Interval transit time (ITT) should be displayed at microseconds per foot (RTL) in API Tracks 2 and 3.

### 2.5.3 Nuclear Logs

Nuclear logs measure radioactivity within the borehole, either due to natural radioisotopes within the formation or from a transient response to radioactive sources contained within the probe. Four nuclear logging tools are widely used:

- gamma (or natural gamma log [NGL]),
- gamma spectrometry
- gamma-gamma, and
- neutron (NL)

Of these, the gamma-gamma and neutron techniques contain radioactive sources. Gamma-gamma is also called a density log—but this log does not directly measure density, so the term gamma-gamma is preferred for discussion purposes.

**Regulatory Requirements.** There are currently no specific state regulations governing the use of radioisotopes in borehole logging. Within California, use of radioisotopes is enforced under the California Code of Regulations (CCR), Title 17, Division 1, Chapter 5, Subchapters 4.0, 4.5 and 4.6. The Radiologic Health Branch (RHB) within the Food, Drug, and Radiation Safety Division of the Department of Public Health, which is responsible for licensing the use of radioisotopes within the state. Under the guidelines of the RHB, the use of nuclear logs containing radioactive sources is prohibited in potable aquifers. In environmental investigations involving contamination of potable aquifers, the RHB may grant one-time exemptions to this prohibition at their discretion, depending on borehole/well condition, construction details, and other pertinent site information. Any nuclear logging using active sources for environmental investigation sites must be licensed by and comply with the guidelines of the RHB, or have the appropriate exemption.

**Order in the Logging Sequence.** Of prime concern in the use of radioactive sources for logging is the possibility of losing the source within the borehole. To avoid this, active nuclear logs should always be run last, after all other logs have been run and the resulting data used to assess borehole conditions for the possibility of borehole collapse and/or lodging of the probe in the borehole.

**Time Constants/Count Intervals.** When analog equipment is used to obtain nuclear logs, the repeatability of the measurement is dependent upon the measurement interval (time constant) and the logging speed. The selection of a time constant that is too short
reduces repeatability and makes the data difficult to interpret. On the other hand, increasing the time constant reduces sensitivity and requires a slower logging speed. The time constant must be chosen appropriately on a site-specific basis, but under most conditions it should not exceed 10 seconds.

The count interval is the time interval over which neutron or gamma events are counted. For digital logging equipment, the count interval replaces the time constant. Unlike the time constant, the count interval for most digital instruments is fixed, usually at 1 second (Hallenburg, 1984). This short interval may occasionally limit repeatability, but this deficiency is offset by increased processing and enhancement capabilities provided by the digital format. In general, any count interval of no more than three seconds provides adequate results, and is considered acceptable.

Logging Speed. Logging speed significantly affects data quality. Faster logging speeds reduce sensitivity and cause lag in the probe response, usually occurring above or below the true location of the bedding surface. Lag is most pronounced on analog systems but also occurs with digital systems where it is generally insignificant; however, depending on the particular configuration of the system in use, lag may become significant at high logging speeds. The appropriate logging speed must be chosen on a site-specific basis, but under most conditions it should not exceed 30 feet per minute (Collier and Alger, 1988). For most environmental site investigations, this maximum speed is not restrictive. The maximum time required for a single logging run would typically be less than 10 minutes. Even at this speed, lag can be significant and should be corrected.

Units of Measurement. Several different units of measurement are used to quantify the response of nuclear probes to radioactivity. The primary unit used for most nuclear logs is the counts per second. The only standardized units of radiation measurement for borehole logging are those developed by the API, hence, these units are called API units. API units exist for gamma and neutron logs, but for neutron and gamma-gamma logs, counts per second are usually directly converted to density or porosity units. This is acceptable for those logs, but DTSC recommends that gamma logs be recorded using API units.

With gamma-gamma and neutron logs, the log response is often directly converted to units of density or porosity, respectively. This is an acceptable technique as long as the original data are presented along with the converted values. This requirement is necessary because the conversions are not absolute. Rather, they are based on sets of assumptions and empirical equations that are dependent on lithologic composition, including interstitial fluid, and may not always be applicable to specific stratigraphic conditions.

Measurement Through Casing. Gamma-gamma logging techniques measure the attenuation of gamma rays as they pass from a source within the probe through the adjacent formations. Gamma logs, on the other hand, measure natural gamma radiation inherent to the formations. Both gamma and gamma-gamma techniques may be
significantly affected by attenuation due to casing material, filter packs, and annular sealants (Keys, 1989). These factors can be corrected to some extent, but the results to date are considered questionable (Collier and Alger, 1988). Quantitative interpretation of gamma and gamma-gamma logs in cased holes is not recommended, with the possible exception of logging through temporary casing (no cement, no filter pack). For this case, appropriate attenuation factors and corrections, if available, must be applied.

Neutron logs are only minimally affected by casing, and quantitative interpretation of neutron logs made through casing are common. However, cement, filter packs, and annular seals adversely affect log response, and quantitative interpretation of neutron logs made through these materials is not recommended.
3.0 SUMMARY OF GUIDELINES

The following outline is presented to summarize the important points presented in this document.

PERSONNEL QUALIFICATIONS
1. Must use a licensed Professional Geologist or a licensed Professional Geophysicist.
2. Provide a summary of specific borehole geophysical experience.

QA/QC PARAMETERS
1. Define study objectives and rationale for tool selection.
2. Ensure header information is as complete as possible.
4. Follow recommended calibration procedures.
5. Use appropriate field standards and perform field checks.
6. Choose appropriate logging speed.
7. Use an accurate surface reference elevation.
8. Provide repeat logs.
9. Correct logs for different depths of measurement.

PRESENTATION OF GEOPHYSICAL LOGS
1. Standardize log and header formats.
2. Overlay no more than two logs on the same track (except for Track 1).
3. Use the same depth scale for every borehole log.
4. Maximum log scale 5 inches = 100 feet.
5. Present logs at coarse and detailed scales when necessary.

SELECTION OF LOGGING TECHNIQUES
1. Use the basic logging suite (Table 3) as a starting point for tool selection.
2. Use other logs beyond the basic logging suite (discussed in Sections 2.4 and 2.5) as appropriate.

BOREHOLE LOGGING TECHNIQUES

ELETRICAL LOGS (ALL)
1. Measure resistivity of drilling mud and, where applicable, mud filtrate.

SPONTANEOUS POTENTIAL (SP) LOGS
1. Use for qualitative analysis only.
2. Avoid artificial baseline shifts.

RESISTIVITY LOGS
1. Use both shallow- and deep-sounding probes to determine invasion profile.
2. Deep-focused logs are strongly preferred over lateral logs.
3. Apply log corrections for quantitative analysis.
INDUCTION LOGS (IL)  
1. Use both shallow- and deep-sounding probes to determine invasion profile.  
2. Apply log corrections for quantitative analysis.

CALIPER LOGS  
1. Use caliper tools that have at least three finger-type feelers.  
2. Include accessory caliper logs as part of the log records.

BOREHOLE VIDEO LOGS (BVL)  
1. Display the depth and well identification on video log and videotape.  
2. Centralize the borehole video camera in the borehole.  
3. Make repeat runs over intervals specified by the project geophysicist.  
4. Allow sufficient time for the BVL camera to equilibrate with downhole temperature and humidity conditions to ensure that the camera lens does not fog up. Distilled water can be poured in the borehole to clear fogged camera lenses.  
5. Adjust brightness, contrast, and other image controls to optimize image clarity.

ACOUSTIC BOREHOLE TELEVIEWER (BHTV) LOGS  
1. BHTV should only be run in fluid filled, uncased boreholes.  
2. Run BHTV at 10 feet per minute or slower.  
3. Run BHTV tool with centralizers.  
4. Run BHTV up into surface casing as a check.  
5. Use interactive workstation enhancement and computer programs for BHTV images.

BOREHOLE COMPENSATED ACOUSTICAL (BHC) LOGS  
1. The BHC interval transit time (ITT) is displayed at microseconds per foot RTL in API Tracks 2 and 3.  
2. BHC tools should be run with centralizers.  
3. Magnetostrictive sources should be polarized prior to the logging job (piezometric sources need not be).  
4. Run BHC at 10 to 15 feet per minute.  
5. Monitor BHC signals at both receivers to ensure that the automated picking algorithm does not skip cycles.  
6. If possible, record full acoustic wave forms for both receivers and enhance with post processing before running the picking algorithm.
NUCLEAR LOGS (NL)

1. Operator must possess a valid DHS permit and exemption for groundwater logging.
2. Run nuclear logs last.
3. Use time constant less than or equal to 10 seconds, or a count interval less than
   or equal to 3 seconds.
4. Use a logging speed less than or equal to 30 feet per minute.
5. Use API units for gamma logs.
6. Provide both raw and converted values from gamma-gamma and neutron logs
   when used to derive density or porosity.
7. When logging through cement and casing, use nuclear logs for qualitative
   analysis only.


4.0 REFERENCES

CITED REFERENCES


Guyod, H. 1966. Interpretation of electric and gamma-ray logs in water wells. Log Analyst, v. 6, no 5, p. 29-44.


**SOURCES OF ADDITIONAL INFORMATION**


