

Review of Borehole Based Geophysical Site Evaluation Tools and Techniques

NWMO TR-2009-25

November 2009

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ABSTRACT

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Report No.: NWMO TR-2009-25

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Date: November 2009

Abstract

This report presents a discussion of borehole geophysical tools and techniques that could be applicable to the characterization of deep geological repository candidate sites. The techniques considered include wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and nuclear magnetic resonance logs), flow logging tools (impeller, heat pulse, electromagnetic, and fluid tracking), seismic methods (sonic and full waveform, tomography, reflection and vertical seismic profiling), borehole radar, borehole time domain electromagnetic surveys and cross-hole electromagnetic imaging. The report provides guidance on the benefits that specific techniques may provide along with some constraints. Borehole geophysical techniques are heavily reliant on technology and as such, techniques will evolve and improve during the life span of a repository investigation.

Typical borehole geophysical applications are presented in this report, including the determination of lithology and stratigraphy, physical properties, rock structure and hydrogeologic properties, as well as in situ stress investigations, and well inspections. Nine case histories are presented and discussed, including crystalline and sedimentary rock environments from project sites in Europe and North America. The project sites presented include nuclear repository sites, underground test sites and heavy civil works.

Borehole geophysics has played an integral part in the characterization of both sedimentary and crystalline rock sites in every nuclear repository program around the world. Borehole geophysical data are one of the primary inputs to the development of the site geosphere model. Virtually all borehole geophysical tools were found to be applicable to both sedimentary and crystalline rocks, although the importance of one tool versus the other does vary with the application.

Canada is very well positioned to apply borehole-based geophysical methods in these types of geoscientific and ground engineering studies. There are a number of well established consulting and service provider companies with the expertise and equipment inventory to complete these types of surveys.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is responsible for implementing Adaptive Phased Management, the approach selected by the Government of Canada for long-term management of used nuclear fuel generated by Canadian nuclear reactors (NWMO 2005). The ultimate objective of this approach is centralized containment and isolation of used nuclear fuel in a deep geological repository in a suitable sedimentary or crystalline formation.

The geoscientific suitability of candidate sites will be assessed over a period of several years, with each step designed to evaluate the site in progressively greater detail. Initial site evaluation stages are conducted in the form of desktop feasibility studies using available geoscientific information and possibly preliminary field investigations that would include non-intrusive remote sensing techniques such as satellite, airborne and ground-based geophysical methods. A review of available non-intrusive methods was conducted by the NWMO in 2008 (Emsley et al, 2008).

In order to develop readiness for the later stages of site evaluation that will involve intrusive work, the NWMO commissioned a review of available borehole-based geophysical tools and techniques for characterizing potential candidate sites. This report discusses these methods focussing on state-of-the-science technologies, applicability, accuracy, limitations and constraints, and best practices in similar investigations undertaken in Canada and elsewhere.

1.1 Borehole Geophysical Investigations

Borehole geophysical methods can provide important in situ information that contributes across a range of disciplines (including geological, hydrogeological, hydrochemistry, geotechnical, and transport models), inputs which together form the geosphere model for the site. For example:

- Borehole geophysical data is essential to developing an understanding of site stratigraphy and rock lithology to support the geological model.
- Important physical properties can be measured using borehole geophysics. For example, sonic and density geophysical data can be used to derive estimates of rock engineering properties.
- Geophysical imaging tools (televiewers and dipmeters) can be used to identify and orient fractures and structures in the rock. This information, together with other data sets, can be used to understand how fracture systems are interconnected.
- Flow testing tools can be used to estimate hydraulic properties of the rock and evaluate interconnections in the rock system.

A site characterization program is comprised of a number of interrelated disciplines, which means that a holistic approach should be adopted in the design and implementation of all investigations. This holistic approach must consider the use of data during all phases of the project and into the post operational phases (post closure monitoring).

Geophysical surveys carried out during site characterization phases should take into account any future survey requirements, recognizing the limitation that technologies will improve over time.

1.2 Objectives

The general objective of the study was to develop a state-of-the-science review of borehole-based geophysical site evaluation tools and techniques for characterizing potential nuclear waste repository candidate sites. This study identifies the methods that are available, highlights recent technological developments and provides numerous examples of application. The following techniques are presented and discussed in this report:

Conventional Logs (Chapter 3):

- Borehole Orientation Logs
- Electric Logs
- Induction Logs
- Natural Gamma and Spectral Gamma Logs
- Active Source Nuclear Logs
- Caliper Logs
- Borehole Imaging Logs
- Borehole Gravity
- Borehole Nuclear Magnetic Resonance (NMR)

Flow Testing Logs (Chapter 4):

- Fluid Temperature and Resistivity Logs
- Impeller Flow Meter
- Heat Pulse Flow Meter
- Electromagnetic Flow Meter
- Posiva Flow Log
- Borehole Dilution and Hydrophysical Logging
- Cross-borehole Testing

Borehole Seismic Radar and EM Methods (Chapter 5):

- Borehole Seismic Methods
 - Conventional Sonic Logs
 - Shear Velocity Logging
 - Full Waveform Logging
 - Tube Wave Logging
 - Cement Bond Logging
 - Seismic Tomography
- Vertical Seismic Profile (VSP) and Cross-Hole Seismic Reflection
- Borehole Radar
- Borehole TDEM
- Cross-Hole EM

A discussion of geophysical log applications is presented in Chapter 6, which includes the following general categories:

- Lithology and Stratigraphy
- Physical Properties
- Rock Structure

- Fluid Parameters
- Casing Evaluation
- Borehole Parameters

The following nine case studies are presented in Chapter 7:

- Crystalline Rock Environments
 - Forsmark Site, Sweden
 - Granitic Rock, Czech Republic
 - Üveghuta Site, Hungary
 - Water Tunnel No. 3, New York, USA
 - Sellafield Site, UK
 - AECL Underground Research Laboratory, Manitoba, Canada
- Sedimentary Rock Environments
 - Zürcher Weinland Site, Switzerland
 - Michigan Technological University (MTU) Test Site, Michigan, USA
 - Detroit River International Crossing (DRIC), Ontario, Canada

Conclusions in this report provide a summary of the borehole geophysical techniques their applications, and their relevance to the future site characterization studies that will take place under Adaptive Phased Management.

2. SURVEY DESIGN

First and foremost, borehole geophysical investigations must be designed to answer specific questions about geological, hydrogeological and geotechnical conditions on the site, and help to construct and refine the geosphere model. The geophysical data will be used to help assess the performance, as well as the constructability of the facility.

The survey design also needs to consider possible uses of the data through the operation of any facility and into the post closure phase, as reviews of various programmes worldwide conducted by independent panels see this as an essential component in the development of confidence that the process is well managed and understood.

Key questions to ask when designing the borehole geophysical investigations are:

- What borehole or geophysical data is already available for the site?
- What is already known about the geological setting?
- What needs to be known about the geologic, hydrogeologic and geotechnical conditions at the site?
- What QA/QC procedures are required?
- What is the data management plan?

These are important questions which need to be considered in the early design stages of the investigation and should be revisited continually throughout the implementation stages of site characterization.

2.1 Desktop Level Studies

It is assumed that desktop level studies have already taken place prior to initiating the design of the borehole geophysical investigations. This would have included a review of available geological mapping, geophysical data and remote sensing data, and may have also included the acquisition of site specific airborne or surface-based geophysical surveys. Any available deep borehole data, such as oil and gas drilling records, would also have been examined.

From these data, a conceptual geosphere model of the site would have been developed at the screening stage, with the level of detail of that model being commensurate with the type and quality of data that are available. This conceptualization will obviously need to be incorporated into the design of the characterization study, including the borehole geophysics component, as the primary purpose of the characterization studies will be to refine and validate the geosphere model.

2.2 Geological Setting

It is understood that the site selected for a deep geological repository in Canada could be in either a sedimentary or crystalline rock formation. Design of the borehole geophysics investigations will need to take into consideration the unique characteristics of these two geologic environments.

For example, sedimentary rocks are typically sub-horizontally stratified shales, sandstones, mudstones, limestones and dolomites; the boundaries between these strata act as marker horizons which are readily correlated between boreholes.

By contrast, crystalline rocks cover a wide range of types from volcanics to massive intrusive rocks of various chemical compositions. Owing to their great age and often complex geologic history, Precambrian crystalline rocks can be very structurally complex (i.e. faulted and folded) and can be fractured. Fractures generally play the major role in fluid movement and fracture interconnectivity is critical to understanding that fluid movement.

So while there may be some similarities between sedimentary and crystalline rocks, there are also important differences that can and will influence the design of a site characterization programme and specifically, the borehole geophysics component of that programme. These considerations are discussed in the methodologies sections of this report, and further punctuated in the case studies, which encompass examples from both geological settings.

2.3 Data Uses

Development of a borehole geophysical investigation programme must consider the planned and potential future use(s) of the data. Ideally, only information that is required should be obtained from the characterization activities, such that all information obtained contributes to the overall geoscientific understanding of the site and will ultimately form part of the safety case. However, not all of the information that provides the overall geoscientific understanding of the site is used directly for Performance Assessment (in the context of undertaking the numerical risk calculations). As such, subsets of the acquired data may have different end uses including Performance Assessment, engineering design and post closure monitoring. Consequently, the requirements of the overlapping subsets of data will need to be considered at the survey design stage.

It may also be necessary to consider other end uses for the data, such as forming the baseline or reference data for future periodic surveys. Another consideration may be that high resolution monitoring of any facility could be required during operation, which needs to be considered at an early stage of the programme.

Looking further ahead, it is likely that once in the underground environment, the precise nature of the geologic structures should become apparent, which in turn may create a requirement for additional borehole geophysical survey work to be performed. A site model may include geologic structures represented by simple planar features to which some attribute(s) may be attached. However, on a small scale, geologic features are likely to be complex, potentially requiring additional geophysical survey work to locate and define them in a more detailed manner.

2.4 Quality Assurance

An effective quality assurance (QA) programme for borehole geophysical data is essential for the completion of a successful site characterization programme. All data collected should have an appropriate quality assurance pedigree so it can ultimately be used in a demonstration of repository safety within a regulatory framework. As such, a robust and effective quality assurance programme must be established prior to initiating characterization activities that may gather data that could ultimately be used in a compliance demonstration.

In the context of borehole geophysics, quality assurance means that there are documented procedures in place to calibrate instruments and ensure they are functioning properly, and that the data are acquired, processed and interpreted correctly. Quality control (QC) means that these procedures have been followed throughout the process, and that this has been documented. This will include:

- Pre-logging calibration trials;
- Calibration checks during data collection;
- Depth error calculations and tolerances;
- Post processing requirements; and
- Integration with other data and programs.

An example of this last point would be the value of integrating geophysical logs with other core logging practices – there is a great deal of value to be had in using geophysical log data during the geological and geotechnical core logging programme – for depth control, quantitative assessment of in situ conditions versus disturbed samples, oriented core, etc.

An effective QA/QC programme would result in a compliance demonstration based on the geophysical data and interpretations having a strong quality pedigree. This would increase both regulators' and the public's confidence in the ultimate compliance demonstration.

2.5 Data Management

Hand-in-hand with quality assurance is the need for a strong geophysical data management system. A robust data management system helps to ensure that project participants involved in site characterization will have access to the most current data and can clearly identify the pedigree of that data.

Borehole geophysics can generate large volumes of data very quickly; good data management practices begin with ensuring that the raw data is backed up in the field, and that additional backups are created throughout subsequent processing steps. Another key issue will be that all borehole geophysical data will need to be geospatially referenced and time stamped.

For data users, access is likely to be through the internet using tools such as a secure collaboration workspace (CWS), like SharePoint™. For archival purposes, consideration will need to be given to storing the data in a format that will allow it to be retrieved and used in the current software tools of the day, potentially many years after the data was originally collected, given the timescale of Adaptive Phased Management.

3. BOREHOLE GEOPHYSICAL METHODS I – CONVENTIONAL LOGS

This chapter presents what might best be described as conventional geophysical logging tools and techniques that can be used for subsurface investigations to characterize potential deep geological repository candidate sites. The techniques described in this chapter include:

- Borehole Orientation Logs
- Electric Logs
- Induction Logs
- Natural Gamma and Spectral Gamma Logs
- Active Source Nuclear Logs
- Caliper Logs
- Borehole Imaging Logs
- Borehole Gravity
- Borehole Nuclear Magnetic Resonance (NMR)

While borehole gravity and borehole NMR techniques are emerging technologies, the other logging techniques are generally widely applied in hydrocarbon and mineral exploration, as well as engineering and environmental studies.

Flow testing log techniques are presented in Chapter 4 and seismic and radar borehole techniques are presented in Chapter 5.

The general format for each section in this chapter is as follows:

- Method Description (theory, methodology, equipment, calibration, borehole/casing/fluid requirements, acquisition speed, resolution of the data)
- Applicability to Programme
- Processing and QA/QC
- Strengths and Weaknesses
- Potential to Combine Methods
- Commercial Availability

3.1 Borehole Orientation Logs

Borehole orientation surveys are sometimes referred to as borehole directional surveys and the tools span a broad range of technologies, from single reading devices that can be lowered on a cable or drill stem, to continuous recording devices run on modern wireline systems.

Borehole orientation surveys are applicable to all rock types – sedimentary and crystalline. The borehole deviation data, inclination and azimuth, are used to compute true vertical depth (TVD), northing and easting logs. The TVD and northing and easting logs allow the computation of the borehole closure angle and the closure distance. The TVD log is used to construct depth corrected stratigraphic sections from other geophysical logs and from drill or core logs.

Borehole orientation data can be presented as referenced to magnetic north, or corrected to true north by the correct magnetic declination value for the borehole location. Processed orientation data can be presented as a “bull’s eye” view of the borehole path, a 3D cylinder view of the borehole path, closure plot, or as profile plots at selected orientations (Figure 3.1-1).

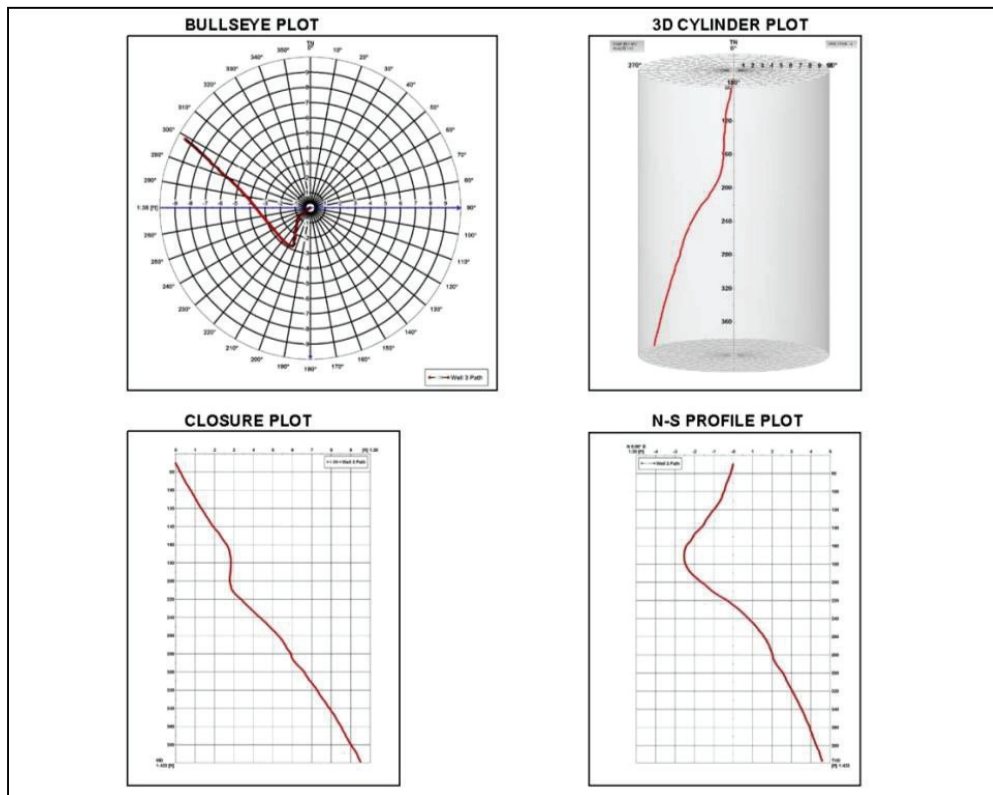


Figure 3.1-1: Displaying borehole orientation survey results. (Golder Associates)

3.1.1 Magnetic / Mechanical Tools

The Tropari is an example of a micro-mechanical single measurement borehole orientation tool (Figure 3.1-2) that has been in use for many years. The device uses a timer that is preset at the surface to trigger a lock that freezes the onboard compass and inclinometer to provide a magnetic azimuth and inclination reading. This device can be used in boreholes 36 mm or larger, and can be lowered by cable, by hand via lightweight rods or rope, or by drill rod.



Figure 3.1-2: A Tropari borehole orientation device. (Pajari Instruments Ltd.)

They can be run in open or plastic cased boreholes with air, water or mud as the fluid. More advanced designs, such as those by Sperry-Sun, utilize a timer and photographic film to capture multiple measurements in a single trip down the borehole.

Measurements should be made at least 10 m from the end of the drill bit, or the base of steel casing. The devices will provide an erroneous result for azimuth if influenced by magnetic minerals in the rock. The device should be stationary for at least 10 minutes prior to taking the measurement. It typically takes on the order of 30 minutes to 1 hour to make a single measurement, depending on several factors including the depth of the borehole. The instrument has a measurement accuracy of $\pm 0.5^\circ$ (inclination and azimuth).

3.1.2 Optical Tools

Reflex Instruments manufactures an optical borehole deviation tool called the Reflex Maxibor II. This tool is equipped with silicon accelerometers and an optical CMOS image sensor. The accelerometers measure tool orientation and provide inclination and roll information. The optical sensor allows the tool to function similar to the operation of a surveyor's theodolite, measuring angles and distances. This tool is 1.2 m in length and 44 mm in diameter. The tool bends as it travels down the borehole causing the reflector rings seen by the camera to shift, corresponding to the curvature of the borehole (Figure 3.1-3). The Maxibor II typically takes a measurement every 1.5 m or 3.0 m (operator selectable).

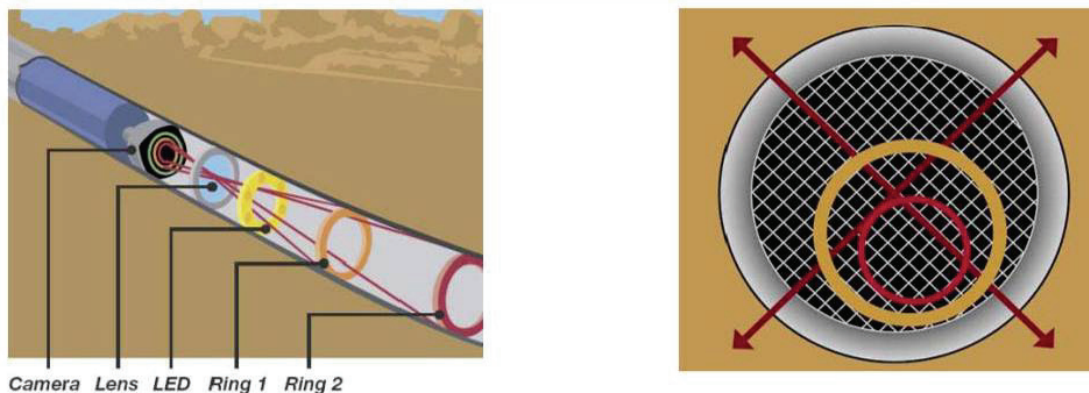


Figure 3.1-3: Measuring the curvature of the borehole with an optical surveying technique and camera view of reflector rings. (Reflex Instruments)

The Maxibor II can be run in open or cased boreholes with air, water or mud as the fluid, and is pressure-rated to operate safely to at least 3,500 m water depth. The ability to acquire orientation data in steel cased boreholes or through drill rods is a significant advantage over orientation systems which employ magnetometers. The tool is also not adversely affected by magnetic minerals in the rock. The tool is initially oriented to the surveyed measurements (dip and azimuth) of the borehole surface casing. Typically, a 100 m section of a borehole can be surveyed in about 20 minutes. Instrument position accuracy is reported as being better than 0.1% of the hole depth.

3.1.3 Gyroscope Tools

Gyroscope borehole orientation tools use various types of gyro sensors; tri-axial gyroscope, digital micro-gyro, and gimbal-mounted directional gyroscope, to name a few. Gyroscopic probes are designed to be run stand alone, as single or multi-shot instruments, and record at operator selectable intervals. Gyroscopes can be run in open or cased (plastic or steel) boreholes with air, water or mud as the fluid, and are not adversely affected by magnetic minerals in the rock.

Gyroscopic borehole orientation tools have traditionally been expensive, delicate, and technically challenging to operate. Some systems require that the operator, prior to the start of the survey, mount the probe in a stand and orient a reference mark to magnetic north using a conventional compass. To begin the logging run, the operator issues an unlocking command from the surface unit, the gyroscope then maintains this direction reference regardless of subsequent rotation of the probe while logging.

Recent advancements in gyroscope tool design, like the Reflex Gyro, have resulted in rugged slim-hole devices that are easy to operate. This instrument is 40 mm in diameter and about 80 cm long. Its maximum pressure rating is not reported. It has a tested accuracy of $\pm 0.5^\circ$ when surveying an 800 m section of borehole at 5 m stations in a time of 40 minutes.

3.1.4 Magnetometer / Accelerometer Tools

Magnetometer / accelerometer based instruments are the most common borehole orientation tools available today and were developed from satellite and missile guidance technology. All borehole imaging tools, such as acoustic and optical televiwers, are equipped with orientation instrumentation consisting of a 3-axis magnetometer / accelerometer. These systems are also available as stand-alone tools.

The 3-axis (fluxgate) magnetometer measures the magnitude and direction of the earth's magnetic field by measuring one component parallel to the borehole axis and two orthogonal components. Most accelerometers used in borehole applications are a piezoelectric design, and help determine orientation by sensing the downward acceleration due to gravity. An accelerometer is oriented parallel to each magnetometer axis. The sensors are rugged and come in many sizes and configurations.

Magnetometer / accelerometer based borehole orientation tools can be run in open or plastic cased boreholes with air, water or mud as the fluid, and are affected by magnetic minerals in the rock.

These types of orientation systems are easy to run and can record continuous data or stationary measurements. Typical logging speeds are 2 to 4 m/min taking readings at a user selectable interval of 1 cm or better. An example system is the ALT OBI40 optical televiwer that has magnetometer / accelerometer electronics with a reported accuracy of $\pm 0.5^\circ$ (inclination) and $\pm 1^\circ$ (azimuth) and can be operated in up to 2,000 m of water.

Most stand-alone probes are designed as slim-hole tools and can be run in boreholes with a minimum diameter of 50 mm. The tools are typically centralized in larger boreholes so the recorded orientation of the probe matches the orientation of the borehole.

3.1.5 Summary

Applicability to Programme

Borehole orientation is critical to site characterization studies in both sedimentary and crystalline rock. Borehole orientation data is used to determine the orientation of structures in the borehole, such as fractures and geologic units. Accurate borehole orientation data is also necessary for cross-hole and surface to borehole geophysical methods. It is probable that at least one type of orientation survey will be run in each borehole, including any deep vertical boreholes. In some cases, more than one type of orientation survey may be required to validate accuracy.

Processing and QA/QC

Device specific processing software is provided with most borehole orientation instruments, and does not require the operator to perform the detailed calculations. Instrument calibration and QA/QC is device-specific.

The process of converting raw dip, azimuth and depth data into a plot of the path of the hole in three-dimensional space by interpolating between survey points is called “desurveying” (Killeen and Elliot, 1997). A number of different algorithms can be used for the interpolation (Howson and Sides, 1986). Reviews of the various methods of computing borehole position, and their possible errors have been presented by several authors including Wolff and deWardt (1981), Balch and Blohm (1991) and Killeen et al (1996).

Strengths and Weaknesses

Optical and gyroscopic tools, such as the Reflex Maxibor II and Reflex Gyro, offer the advantage of being insensitive to ferrous metal and magnetic mineralization in the rock. They are however relatively expensive and cannot easily be combined with other technologies. They are relatively easy to use and can survey rapidly.

Magnetometer / accelerometer based tools are less expensive, more readily available and are more readily combined with other technologies. Magnetometers and magnetic compasses are affected by ferrous metal and magnetic mineralization, so these devices cannot acquire accurate orientation data inside steel casings and through such mineralization zones.

Potential to Combine Methods

Magnetometer / accelerometer based systems are commonly integrated into other types of probes, particularly borehole imaging tools.

Commercial Availability

The best known manufacturer of borehole orientation devices is Reflex Instruments, which manufactures a range of slim-hole borehole orientation logging devices based on all three of the common designs (i.e. optical, gyroscopic and magnetometer / accelerometer). Other suppliers of magnetometer / accelerometer orientation systems, both stand alone and integrated with other devices, include: Century Geophysical Corp., Mount Sopris Instruments Co. Ltd. and Robertson Geologging Limited. Most geophysical logging service companies provide at least one type of borehole orientation service.

3.2 Electric Logs

Electric logs are the oldest geophysical logging techniques, introduced by the Schlumberger brothers in 1927 in oil and gas exploration (Telford, 1990). These logs were developed to identify sedimentary rock stratigraphy in boreholes drilled using mud rotary methods and were an extension of the surface based electrical methods for oil and gas exploration.

The electric log (or e-log) suite generally consists of spontaneous potential (SP), single point resistance (SPR), short and long normal and/or guard (or lateral) logs, and are generally recorded and presented together. These logs measure the formation electrical properties in the vicinity of the borehole with varying depths of investigation and are variably affected by fluid invasion in porous zones, borehole diameter and the electrical conductivity of the fluid (water or mud) in the borehole. These logs can only be acquired in open fluid-filled boreholes.

3.2.1 SP and SPR

SP

The SP log records the potential difference between an electrode in the borehole and an electrode at surface (Figure 3.2-1a). Spontaneous potential is a function of the chemical activity of fluid in the borehole and adjacent materials, the temperature and type and amount of clay present with the main sources of SP being electrochemical, electrokinetic, or streaming potentials and redox effects.

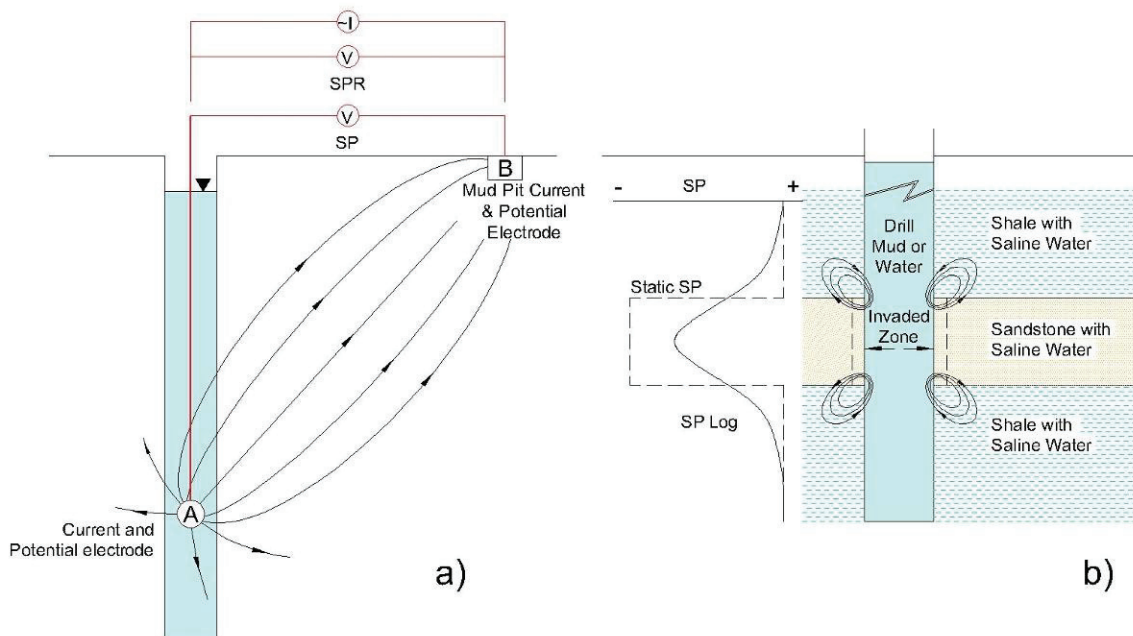


Figure 3.2-1: SP and SPR Logs - a) electrode arrangement of the SP and SPR logs in the borehole and b) the SP effect. (after Telford, 1990)

The usual model for the SP log is that it is a record of the potentials that develop at the contacts between shale and sandstone (or clay beds and a sand aquifer) in a borehole where the salinity of the borehole fluid is different from the formation water (Figure 3.2-1b). Also, streaming potentials (generated by the movement of an electrolyte through permeable media where there is a net charge difference between the fluid and the solid phases) may be significant where

formation water is moving into or out of a borehole such as at a fracture or other discrete permeable zone and may show as sharp oscillations on an otherwise smooth curve.

The main use of the SP log is for differentiating stratigraphy in sedimentary rock environments, although there may be situations where the log could be of use in crystalline rock environments – such as highlighting weathered or altered zones or identification of flowing fractures due to streaming potentials. Lithologic contacts are identified as the inflection point on the SP log and in general, if the borehole fluid is fresher than the formation, the SP log deflections in shale are positive and in sandstone are negative.

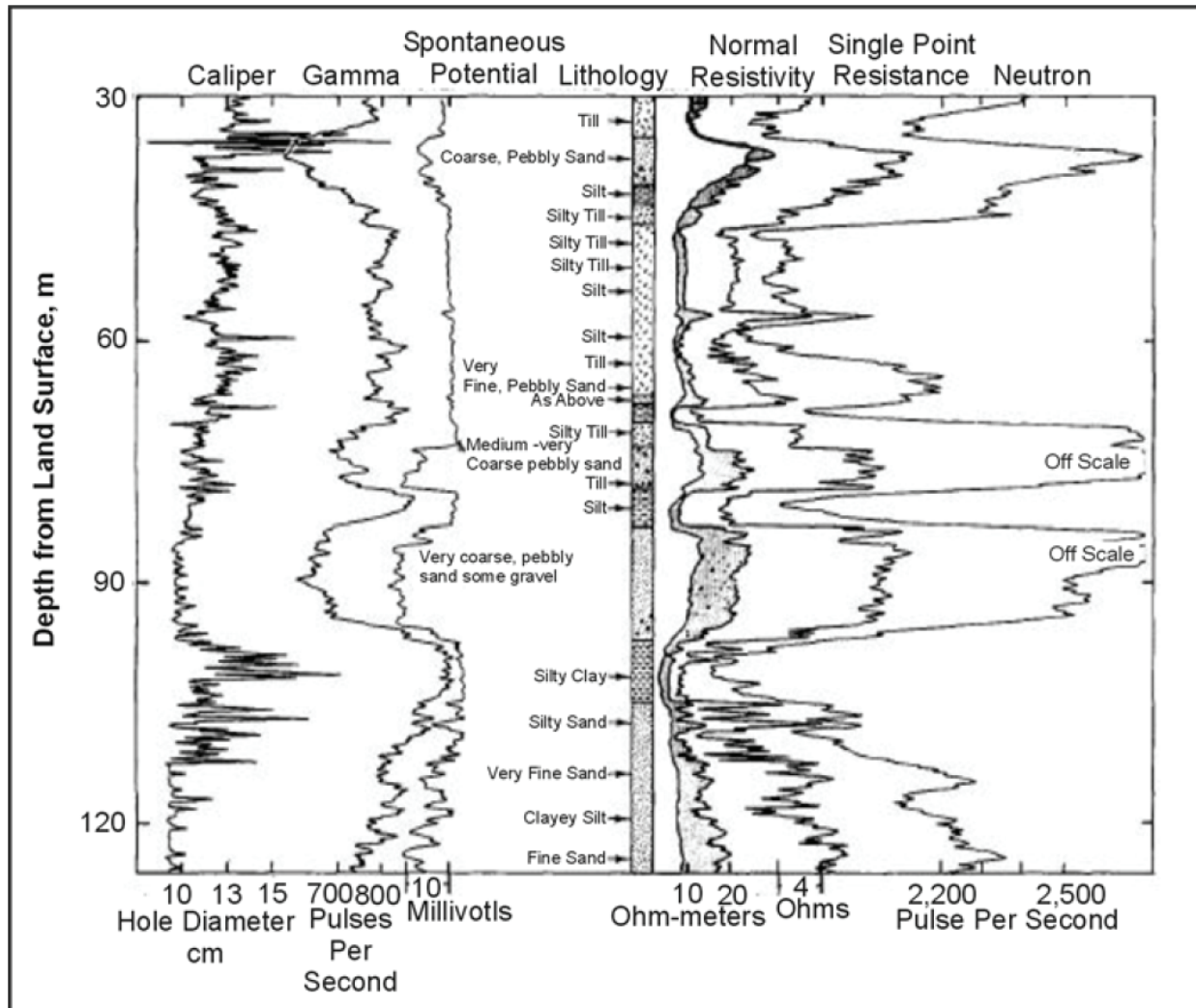


Figure 3.2-2: SP, SPR and normal logs compared to other logs and stratigraphy, Kipling SK. (<http://www.cflhd.gov/geotechnical/>)

Figure 3.2-2 is an example showing e-logs collected in a mud rotary borehole drilled in overburden; note the same SP response is observed in sand and clay contacts as is seen in sandstone and shale contacts.

The SP curve can be used to estimate formation water resistivity (R_w) as follows:

$$SSP = -K \times \log(R_M/R_W)$$

where R_M is the resistivity of the borehole mud, SSP is the static SP deflection from the shale baseline (mV), K is a temperature dependant correction factor ($K=60+0.133T$), and resistivities are in $\Omega\text{-m}$. Formation water salinity can in turn be estimated from R_W .

The volume of investigation for the SP log is highly variable, as it depends on formation resistivity and the cross-sectional area of layers intersected by the borehole. Additionally, the log is adversely affected by stray electrical currents. Increases in the diameter of the borehole, salinity of the borehole fluid (when fresh to start) and depth of fluid invasion will decrease the magnitude of the SP log response and serve to affect the repeatability of the log if these changes are rapidly occurring in the borehole.

SPR

The SPR log measures the electrical resistance in ohms (Ω) between an electrode in the borehole and an electrode at surface (Figure 3.2-1). The resistance of the intervening earth material is a function of composition, cross-sectional area and length of the travel path. However, as there is no way to measure the length or cross-sectional area of the travel path, the measurement is relative and the logs cannot be related quantitatively to formation resistivity.

The volume of investigation is small (5 to 10 times the diameter of the borehole electrode) and the logs are strongly affected by changes in borehole diameter. As such, the electrode diameter should be as large as possible and if the logs are required, the borehole electrode should be the differential type where the current and potential portions are separated by a thin insulating membrane.

SPR logs deflect according to the changes in bed resistivity adjacent to the borehole electrode, with positive deflections indicating an increase in resistivity. The response is independent of bed thickness resulting in a high vertical resolution of contacts between materials of differing resistivity (Figure 3.2-2). In sedimentary rock, the primary use is for accurately identifying lithologic contacts. Of interest in crystalline rocks is that the SPR log is very sensitive to water bearing fractures.

3.2.2 Short and Long Normal Resistivity

The normal resistivity logs measure the apparent resistivity of the formation (in $\Omega\text{-m}$) at "short" and "long" spacings, typically 16" and 64", or 0.25' and 2.5', respectively (depending on the tool). The current supply circuit consists of a supply electrode A in the borehole and a return electrode B at surface (Figure 3.2-3). The potential circuit is between the M electrode located at a short distance (i.e. 16" or 0.25') or long distance (i.e. 64" or 2.5') from the current supply electrode A, and the logging cable armour N. Both short and long normal responses are typically measured at the same time.

The equipment consists of a current supply capable of producing AC or commutated (switched +/-) DC current between the A and B electrodes and a voltmeter to measure the resultant potential difference between the M and N electrodes. The apparent resistivity (R_a in $\Omega\text{-m}$) for the short and long normal log is calculated as:

$$R_a = 4\pi(\Delta V/I)(AM)$$

where ΔV (volts) is the change in voltage, I is the applied current in amperes, and AM is the electrode spacing in the borehole in metres. The effective volume of investigation for the normal resistivity measurement is a sphere with a radius equal to the separation between the A and M electrodes. The log represents a measurement of the average resistivity within that sphere of investigation. Therefore, the measured resistivity is called an “apparent resistivity”. Normal resistivity logging systems can be calibrated at surface by placing resistors between the electrodes. Modern systems are factory calibrated and should not require calibration other than to check equipment operation.

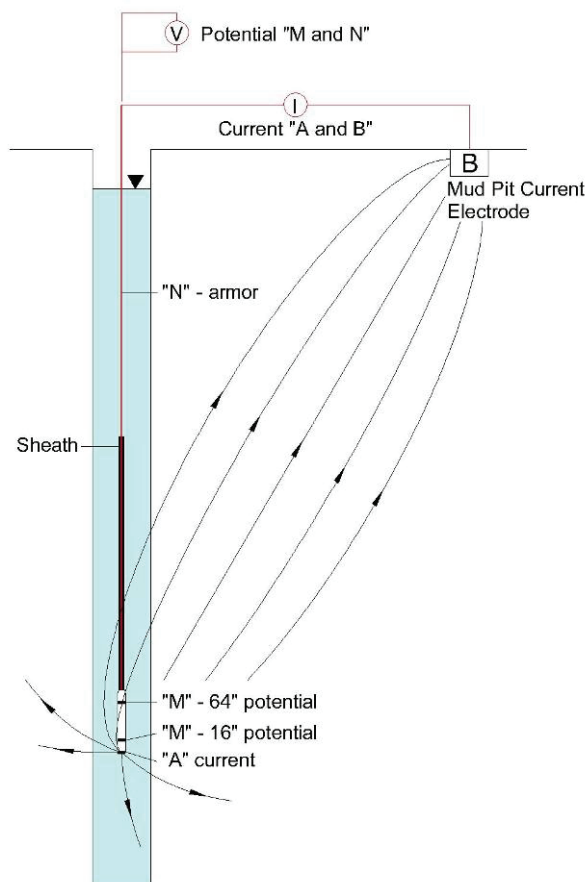


Figure 3.2-3: Schematic of Normal Resistivity Logs. (after Telford, 1990)

An example showing typical electric log responses in a sedimentary rock environment, along with natural gamma and induction logs, is presented on Figure 3.2-4. Typically, there is a negative correlation between natural gamma response and normal resistivity – gamma highs corresponding to resistivity lows. This is because shale is made up of clay minerals, which are both rich in ^{40}K (i.e. gamma high) and electrically conductive (i.e. resistivity low). In this case, the SP log is muted due to using fresh water for drilling in a shallow, fresh water, bedrock formation. The EM Induction log has been plotted for direct comparison to both the natural gamma and normal resistivity logs.

Because of the radius of investigation proportional to spacing, the short normal log is more greatly influenced by the resistivity of the borehole fluid (zone of invasion) and is less likely to be a measure of true formation resistivity. The log response for the long normal log only provides a

true formation resistivity if the bed thickness is significantly greater than the electrode separation.

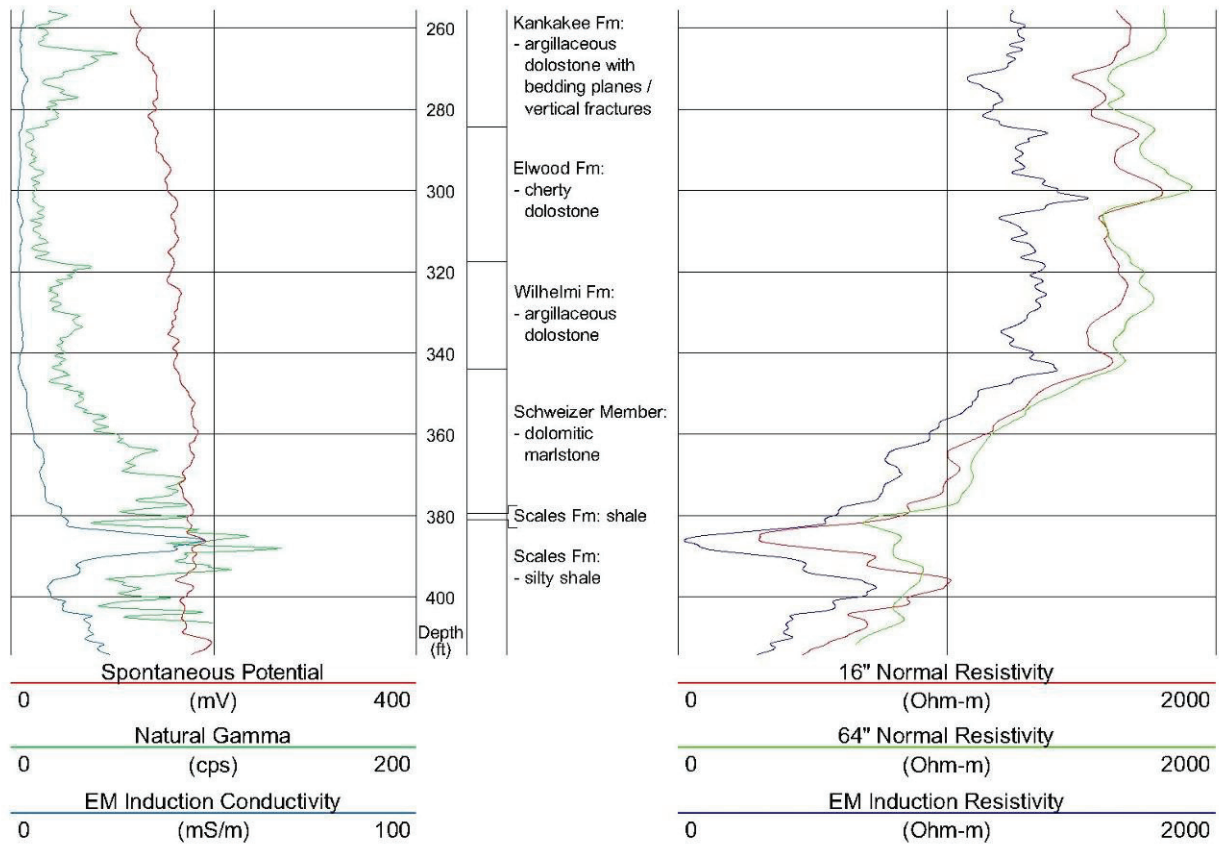


Figure 3.2-4: Electric logs with Natural Gamma and Induction logs. (Golder Associates)

Archie's Law defines the relationship between porosity (Φ), resistivity and formation factor (F), as follows (Telford, 1990):

$$F = 1/\Phi^m = R_o/R_w$$

where m is the cementation exponent, R_o is the bulk water wet resistivity of a rock sample, and R_w is the resistivity of the water in the pores. Following from this, using porosity derived from a neutron, gamma density or acoustic velocity log and an estimate of R_o from a long normal log, the resistivity of the pore water (R_w) can be estimated. This relationship is only valid if porosity and clay content are relatively uniform and does not apply to rocks with high clay content or with randomly distributed solution openings or fractures.

3.2.3 Guard (Focussed Resistivity)

The guard log includes a central current-source electrode mounted between two guard electrodes as shown on Figure 3.2-5. The guard electrodes and the potential electrode (armour) are maintained at the same potential in order to focus the current path to a thin, horizontal disk. The potential of the central current electrode with respect to the cable armour and the measured current are combined to provide a measure of the apparent resistivity. For

some systems, the positions of the armour potential and surface current return electrodes are switched.

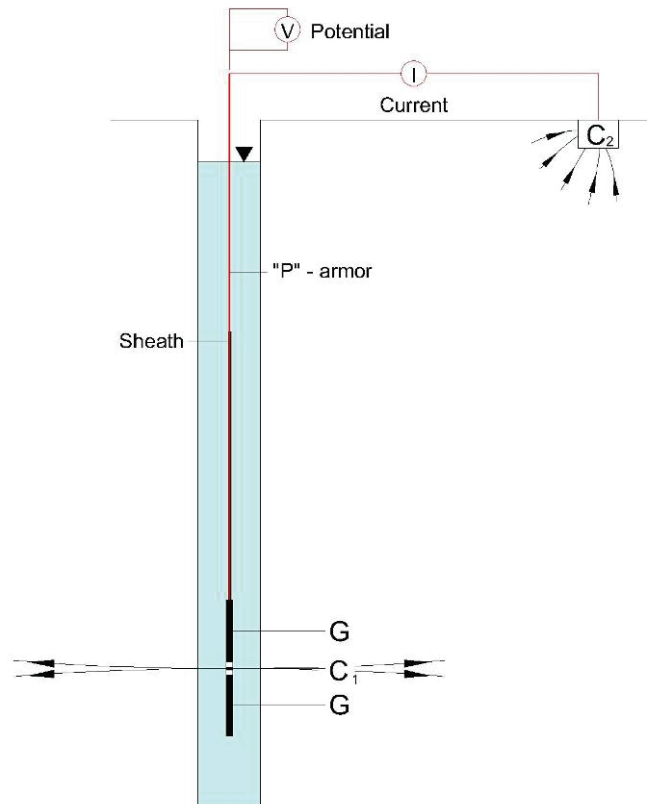


Figure 3.2-5: Schematic of the Guard Log. (modified from Telford, 1990)

The depth of investigation is the distance at which the current begins to defocus appreciably and is estimated at three times the length of the guard electrodes. Longer guard electrodes can be used to improve depth of investigation but this prevents logging to the bottom of the borehole.

The guard log provides superior R_o estimates in environments of high borehole fluid salinity and high formation resistance in comparison to a long normal resistivity log. The length of the insulating sheath on the cable armour above the guard and current electrodes is 10 m, which restricts the logging interval to 10 m below the water level in the borehole.

3.2.4 Summary

Applicability to Programme

The electric logs can be run in open boreholes in both sedimentary and crystalline rock environments. In sedimentary rock, resistivity logs can be used in combination with other logs (i.e. gamma and neutron) to assess stratigraphy, formation resistivity, pore fluid resistivity (i.e. fluid type), porosity, permeability and water saturation. In crystalline rock, resistivity logs can be used to identify fractures or shear zones that may contain water, gouge or conductive minerals (e.g. graphite, massive sulphides, etc.).

Of the electric logs, the normal and guard (lateral) logs are likely to be the most important, as they can be used to estimate rock electrical properties and stratigraphy. The SP and SPR logs are mainly useful to identify contacts, but they don't yield physical property information and they are prone to noise, which potentially makes them more problematic than valuable as an investigative tool.

Processing and QA/QC

The logs can be presented as raw data or can be processed to estimate formation properties including true resistivity (R_T), formation water resistivity (R_W), bed thickness and lithology.

Typically, the probes are calibrated by the manufacturer but are routinely sold with calibration check systems consisting of resistors for attaching to the probes. An additional check is to run the probes in boreholes that have been logged previously and compare results.

Strengths and Weaknesses

Specific strengths and weakness for each of the electric log types are outlined in the previous sub-sections. In general, this suite of logs has been used for many years and there are a wealth of interpretive capabilities including software, results and experience from previous surveys. Weaknesses in the application of these techniques include:

- Most electric logs are affected by changes in borehole diameter (rugosity), borehole fluid salinity and stray currents.
- Electric logs can only be acquired in the fluid filled portion of boreholes and the boreholes must be uncased.
- The probes that use the log cable armour as a current return or potential electrode lose data at the top of the borehole due to a 10 to 15 m insulating sheath above the probe.
- For the guard logs, data may be lost at the bottom of the borehole due to the length of the guard electrode.
- Log repeatability may be an issue if borehole conditions (salinity of water levels) change rapidly at the time of logging as may be the case if a flowing fracture intersects the borehole.
- The logs may lack resolution of layering in low resistivity (< 10 to $20 \Omega\text{-m}$) materials.

Potential to Combine Methods

Electric log arrays are often packaged with other probes such as natural gamma and gamma density. This allows for combined logging runs and reduced time for data acquisition.

Commercial Availability

Most logging companies will include electric logs as part of their service offering and all of the equipment manufacturers produce electric logs in a variety of formats. The suppliers of slim-hole electric logging tools in North America include: Century Geophysical Corp., Mount Sopris Instruments Co. Ltd. and Robertson Geologging Limited.

3.3 Induction Logs

Induction logs measure the electrical conductivity and/or the magnetic susceptibility of the rock formation using electromagnetic induction. Conductivity is measured in milliSiemens/metre (mS/m) and is the mathematical reciprocal of resistivity, which is measured by galvanic methods in the electric logs. Magnetic susceptibility is typically measured relative to the primary field strength, often in units of parts per thousand (ppt).

In an induction log tool, an electromagnetic field produced by a transmitting coil induces eddy currents, which flow in conductive materials surrounding the borehole. These eddy currents in turn generate secondary electromagnetic fields which induce voltages in the receiver coil on the instrument. A schematic showing the principle of operation is presented on Figure 3.3-1a. Within the normal range of operation of the instruments (materials having a low induction number), the quadrature signal (signal 90° out of phase with the primary) is proportional to the electrical conductivity of the material surrounding the borehole, while the in-phase component is proportional to magnetic susceptibility (McNeil, 1980a).

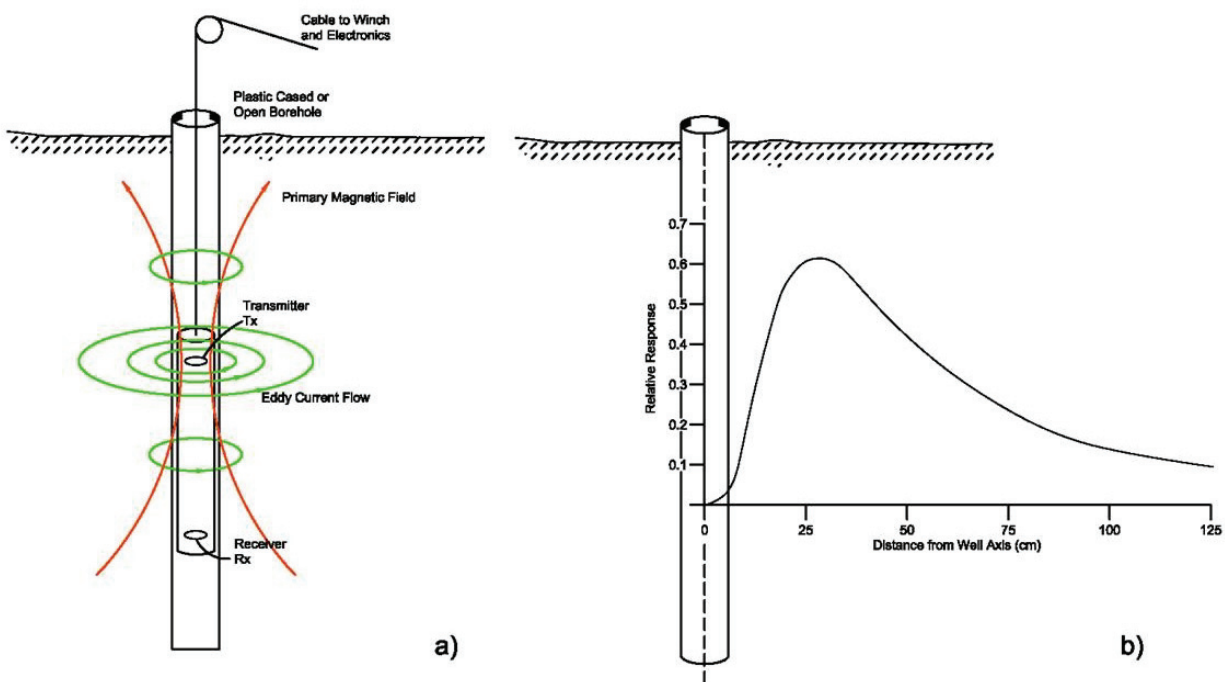


Figure 3.3-1: Principle of Operation and Radial Sensitivity of the Induction Log. (McNeil, 1986)

Most tools have additional coils to obtain a focused depth of investigation while reducing the effect of nearby conducting material and causing the response function to peak at a particular distance from the probe (Figure 3.3-1b). This has the advantage of rendering these tools relatively insensitive to the fluid in the boreholes, thereby reducing borehole effects on measuring formation electrical properties. As in electric logs that measure apparent resistivity, the induction log measures “apparent conductivity” since it is the measure of a bulk volume of material, although the measurement is focussed into the formation. Induction logs can be acquired in open or plastic cased boreholes, with air, water or mud as the borehole fluid. They cannot be acquired in steel cased holes.

A typical induction tool has a claimed measurement accuracy of 5% of full scale and a measurement precision better than 1%. Data is typically acquired at logging speeds from 5 to 15 m/min.

Applicability to Programme

Apparent conductivity logging is most applicable to sedimentary and crystalline rock environments where rock conductivities are greater than 2 mS/m (i.e. resistivity less than 500 Ω -m). In low conductivity rocks, the log may be useful for delineating conductive zones, such as fractures or faults or conductors such as graphitic shear zones and mineralization. Magnetic susceptibility logging is most applicable to crystalline rock environments, where the log can be used to characterize rock type and rock properties.

Processing and QA/QC

Processing and QA/QC steps consist of calibrating the probe (particularly zeroing the probe) prior to logging and a check of the calibration after the logging run. Another critical step in the QA/QC process is acquiring down and up runs in the borehole to assess (thermal) drift. The combination of calibration checks and the down and up logging runs provides a basis for making corrections to the logs, if required.

Strengths and Weaknesses

The induction probe is a “focussed tool” and provides a measurement of formation apparent conductivity and magnetic susceptibility that is minimally affected by borehole rugosity and borehole fluid salinity. The readings in mS/m can easily be converted to units of apparent resistivity (Ω -m). In combination with other tools, it is very useful for delineating stratigraphy for correlation between boreholes. The log response can also provide a qualitative estimate of formation water salinity. A clear strength of the tool is that it can be run in plastic-cased boreholes.

A weakness with induction tools is that they are subject to drift due to temperature changes, and should be calibrated at the temperature in the borehole. At the start of logging, the tool should be allowed to stabilize in the borehole (i.e. reach the borehole temperature). Also, there are limitations on the possible depth of logging for some models due to pressure restrictions.

Potential to Combine Methods

Induction logs can be run in combination with other probes in the boreholes but the general requirement for down and up runs for calibration and single conductor wire-lines used in the majority of slim-hole borehole logging operations generally precludes this. Typically induction log data is processed and presented with other log data such as natural gamma.

Commercial Availability

Where the primary focus is the collection of geophysical data for geological, geotechnical and hydrogeological purposes, a slim-hole induction tool with good vertical resolution, low drift and low noise characteristics is most appropriate. The most widely used tool of this kind is the EM39, manufactured by Geonics Ltd. of Toronto, Canada. The EM39 electronics are also repackaged and sold in North America by Mount Sopris Instruments Inc., Century Geophysical Corp. and Robertson Geologging Limited. This tool can be operated to water depths of up to 1,000 m. Most logging companies will include an induction log as part of their service offering.

Larger diameter, high pressure and temperature induction tools for applications greater than 1,000 m are available from oil field service companies such as Schlumberger, Halliburton and CNLC.

3.4 Natural Gamma and Spectral Gamma Logs

The natural gamma and spectral gamma logs are primary lithology tools, which measure gamma radiation in the borehole naturally emanating from the rocks. The natural gamma tool is sometimes referred to as gamma, gamma ray and total count gamma.

The primary sources of naturally occurring radiation in the geologic environment are the isotopes of the daughter products of the most abundant radionuclides such as ^{40}K , the uranium-radium series and the thorium series. The decay of these isotopes produces alpha and beta particles, and gamma rays. The gamma rays are emitted at discrete energy levels. The spectral gamma tool measures the gamma ray intensity within these discrete energy levels, while the simpler natural gamma tool measures only the total gamma ray energy.

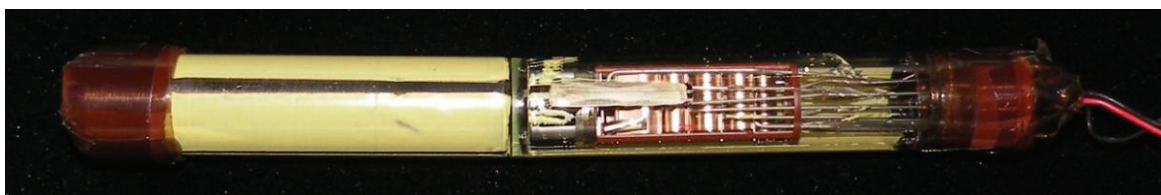


Figure 3.4-1: A gamma scintillation counter and photomultiplier. (Golder Associates)

The most common detector used in modern natural gamma tools is a scintillation counter, although the earliest probe designs employed Geiger tubes. A scintillation counter is basically a scintillator attached to a photomultiplier. The most common scintillator in use today is a sodium iodide (NaI) crystal (Figure 3.4-1). A common size for these NaI crystals is 76.2 mm by 25.4 mm. When the scintillating crystal is struck by a gamma ray, the crystal emits a small amount of light that is proportional to gamma ray energy. The light emitted from the crystal is detected by the photomultiplier which then produces an electrical signal with an amplitude proportional to the gamma ray energy.

Because the spectral gamma tool measures the gamma ray intensity within discrete energy bands that are characteristic of ^{40}K , the uranium-radium series, and the thorium series, it is sometimes referred to as a KUT tool. The most common energy range is from 100 KeV to 3 MeV. Most of the commercially available tools use a scintillation counter with a NaI crystal. Other commonly used scintillator crystals are BGO (Bismuth germanate) and CsI(Tl) (cesium iodide doped with thallium). The major difference between the standard natural gamma detector and the spectral gamma detector is a multichannel analyzer. The multichannel analyzer (256, 512 or 1024 channels) separates the recorded energy into individual packets depending on the number of channels (11.719 keV per channel for 256 channel, 5.859 keV per channel for 512 channels or 2.93 keV per channel for 1024 channels).

The spectral gamma tool can be used in the same manner as the natural gamma tool for lithology and stratigraphic correlation across a site. However, the spectral gamma tool can also be used for advanced sedimentological studies such as characterizing the depositional environments of shales, and to determine clay/shale content and mineral types. In crystalline rock, spectral gamma logging can be used to help determine rock types. Of course, gamma and spectral gamma tools can be used for uranium mineral exploration.

Most gamma or spectral gamma responses are recorded in counts per second (cps) or counts per minute (cpm). The American Petroleum Institute has constructed calibration facilities for natural gamma logging tools, where the tools are calibrated in "API" units (ranges from 0 to 100

API for most sedimentary rocks). A calibration factor can therefore be provided by the tool manufacturer to convert count rates from a gamma tool into API units.

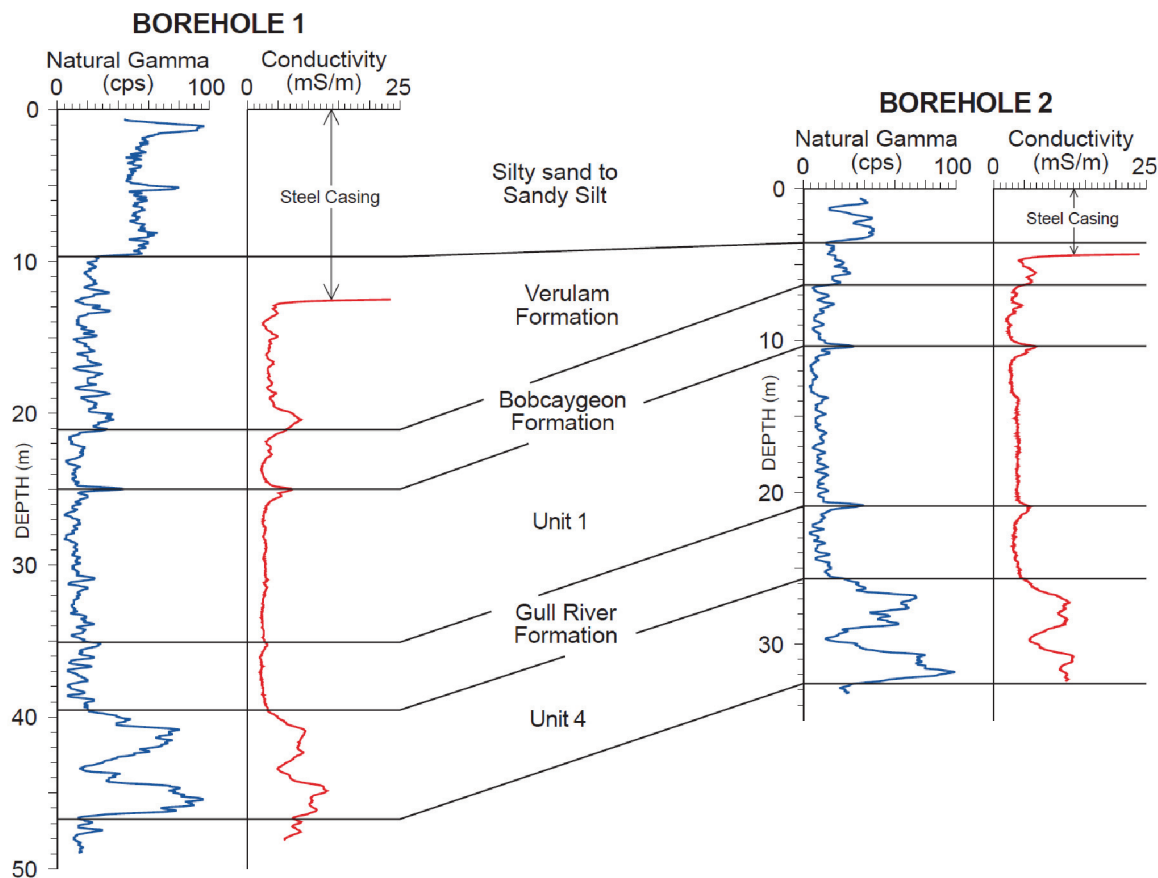


Figure 3.4-2: Stratigraphic correlation with natural gamma and conductivity logs. (Golder Associates)

The emission of natural radiation, such as gamma rays, is made up of individual (random) radiation emission events that follow a Poisson distribution (i.e. the standard deviation of the radiation rate is equal to the square root of the mean radiation rate). This means that at low levels, the recorded rate of radiation is noisy (a.k.a. nuclear statistical error). For example, at 25 cps, the SD=5 cps or +/-20%. Compare this to a rate of 900 cps, with the SD=30 or +/-3.3% (6 times less noisy). This random noise can be overcome by averaging the count rate over a period of several seconds to smooth out the random variations. The averaging period for smoothing radiation count rates is called a time constant (TC) and is measured in seconds. The longer the time constant, the smoother the radiation rate that is recorded. This understanding of radiation statistics is critical to understanding the selection of appropriate time constants and logging speeds for nuclear logging tools. One scheme for estimating logging speed is given by the formula:

$$Sm < 0.15G$$

Where Sm = the logging speed in meters per minute, and G = the average measured gamma activity of the interval. This formula gives the logging speed required to ensure that the nuclear statistical error is less than about 5% (ASTM, D 6274).

The natural gamma log is run moving up the borehole, generally uncanceled. Typical logging speeds for natural gamma logs are 2 to 5 m/min. However, in formations with low gamma count rates, the logging speed should be reduced.

The spectral gamma log is also run moving up the borehole. The logging rate will vary depending on the number of channels recorded and other manufacturer criteria. Optionally, after the continuous run, the tool may be moved back down the borehole to perform stationary measurements at a particular gamma peak, or trough to acquire higher resolution data to better characterize a particular bed or strata of interest. The time of these stationary measurements will depend on the count rate being measured, but because the count rates at different energy levels can be even lower, it is even more important to log slowly, typically 1 m/min or less.

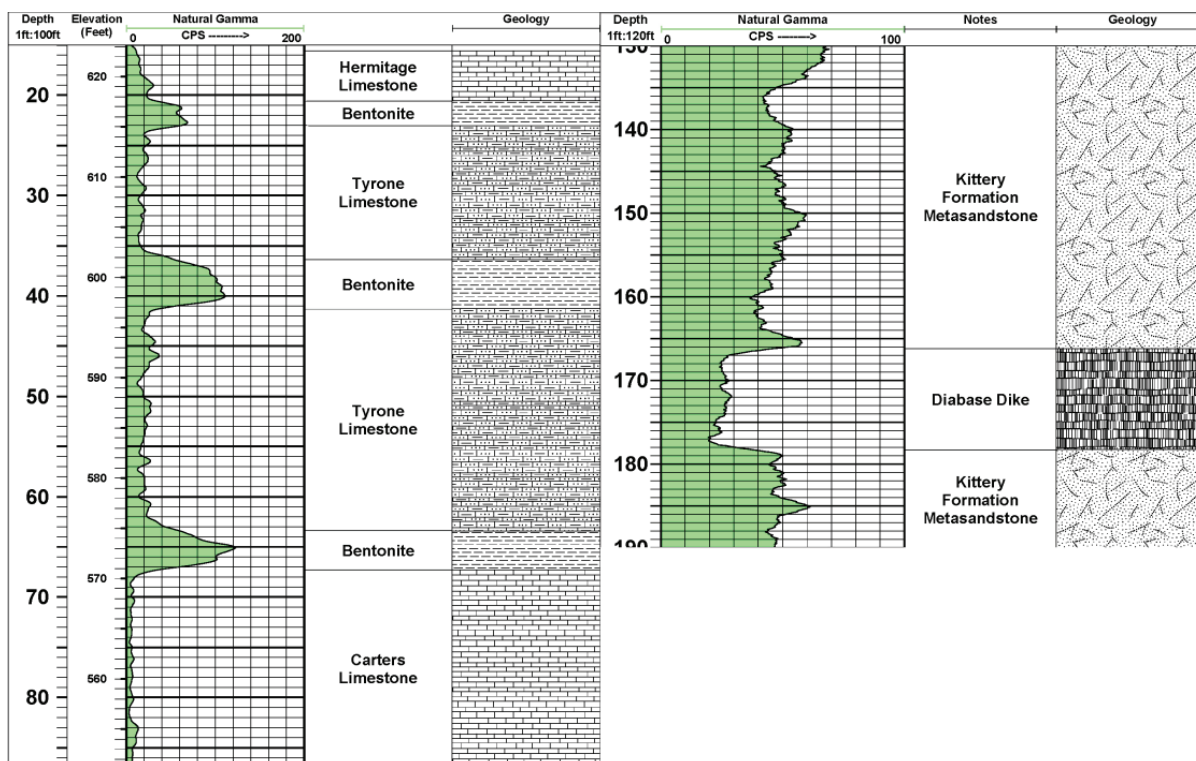


Figure 3.4-3: Natural Gamma Log Response in Sedimentary and Crystalline Rock. (Golder Associates)

Applicability to Programme

The natural gamma and spectral gamma logs are applicable to investigations in both, sedimentary and crystalline rocks, particularly for stratigraphic correlation (see Figure 3.4-3) and to characterize rock properties.

Strengths and Weaknesses

A major strength of the natural gamma and spectral gamma logs is that they can be run in open holes or cased holes (PVC and steel), with air, water or mud as the fluid. It should be noted that gamma response is attenuated by steel casings and by the air gap in a large diameter borehole. This effect can be calibrated and compensated for during processing, although this is seldom done for conventional applications.

The natural gamma tools are manufactured in a large range of sizes. Most of the commercially available natural gamma tools have diameters of approximately 40 mm, and some are as small as 19 mm in diameter. The gamma tools are fragile, such that a blow to the tool can cause a crack in the scintillating crystal (Figure 3.4-4) causing the tool to record dramatically lower count rates.

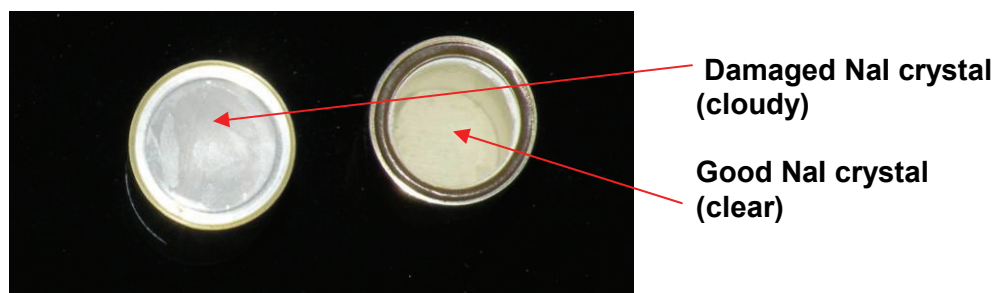


Figure 3.4-4: Photograph of two NaI scintillator crystals. (Golder Associates)

Processing and QA/QC

The natural gamma log can be presented raw, but is normally presented with a weighted or moving average filter applied, in order to further smooth the log response. A gamma log from a cased hole can be corrected for casing effects if data exist from the open hole prior to the well construction. Spectral gamma data is usually presented as a total gamma log and also as a percent of potassium, uranium and thorium (KUT log). Site specific calibration may be required to obtain accurate percentages in the spectrum.



Figure 3.4-5: Photograph of a typical 10 uCi gamma check source. (Golder Associates)

A small gamma check source (Figure 3.4-5) can be used to confirm the proper operation of the natural gamma tool. The use of a repeat run is an important quality assurance step. The repeat gamma log run should be approximately 10% of the total log length and be repeated over a section with a lot of variation.

Potential to Combine Methods

The gamma detector is often packaged in a logging tool with other sensors, such as, SP, SPR, Normal Resistivity, EM induction or caliper. This allows for the collection of multiple log types in a single logging run.

Commercial Availability

Natural gamma is one of the most commonly run logs and accordingly, one of the least expensive and most commercially available. The spectral gamma log is not as common as the

standard natural gamma log, but most major manufacturers of borehole geophysical equipment also produce a spectral gamma tool, including Mount Sopris Instruments Inc., Century Geophysical Corp. and Robertson Geologging Limited. Most logging companies will include a gamma log as part of their service offering, some will offer spectral gamma services.

3.5 Active Source Nuclear Logs

This section discusses the family of borehole geophysical logging tools that employ radioactive sources to measure formation properties, such as density and porosity. Logging sources are most often comprised of radioactive material that is contained within a stainless steel capsule. These capsules are typically cylindrical in shape and doubly encapsulated in 304 or 316 stainless steel designed to withstand 25,000 psia pressure and temperatures from -57 to +595 C. The capsule length varies from 6 mm to 102 mm (Figure 3.5-1).

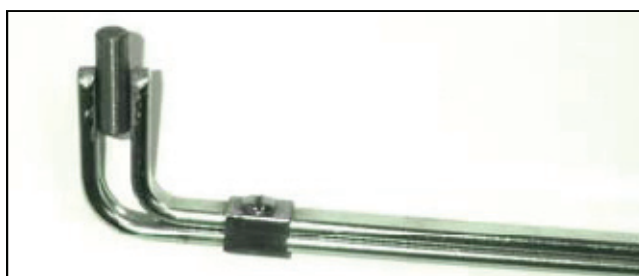


Figure 3.5-1: 100 mCi ^{137}Cs logging source and source handling tool. (Mount Sopris Instrument Co.)

The logging sources are mounted into heavily constructed stainless steel source holders known as “bull plugs”. Using special handling tools, the bull plugs are mounted into shielded storage/transport containers (Figure 3.5-2). At the borehole site, the bull plug is removed from the storage/transport container using a special handling tool and mounted on the borehole logging tool, and the tool is lowered into the borehole.

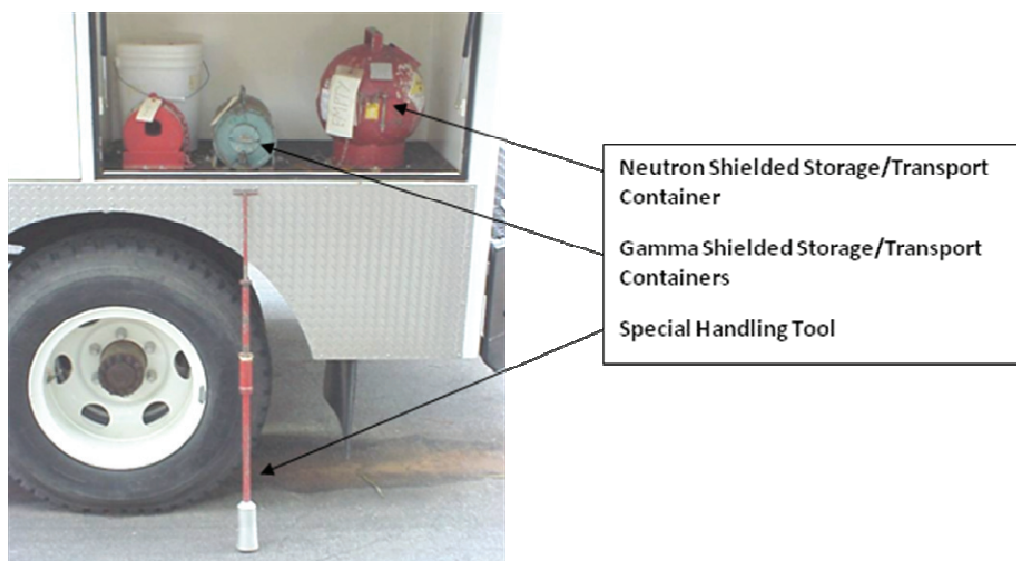


Figure 3.5-2: Logging truck with radioactive logging source shielded storage / transport containers. (Golder Associates)

3.5.1 Neutron Porosity

A neutron log is effectively a measure of the hydrogen content in the pore space of the formation and can be used to estimate formation porosity in sedimentary rocks. The measurement is made by bombarding the formation with high energy neutrons (neutrons in the energy range of 4.5 MeV). The neutrons are approximately the same mass as the nucleus of the hydrogen atoms in the water or oil/gas filled pore space of the formation. Neutrons lose energy through scattering and absorption as they collide with the hydrogen atoms. The slowed neutrons fall into two energy ranges, thermal and epithermal neutrons.

Thermal neutrons have slowed to a state of thermal equilibrium with their surroundings (below 0.1 eV). Epithermal neutrons have slowed to near thermal equilibrium, but are still energetic enough to avoid capture (0.1 eV to 1keV). Borehole geophysical logging tools fall into two basic categories, ones with thermal neutron detectors and ones with epithermal neutron detectors (Bassiouni, 1994 and Hearst et al, 2000).

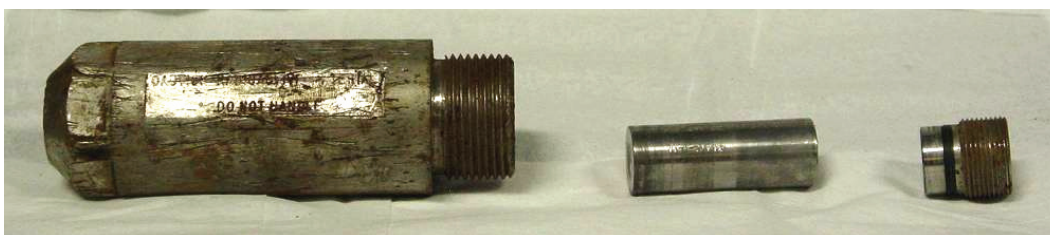


Figure 3.5-3: Photograph of a 3 Ci neutron source. (Mount Sopris Instrument Co.)

Most neutron tools employ a chemical radioactive source to bombard the formation with high energy neutrons. The most common source in use for neutron logging is an alpha emitter, $^{241}\text{Am}/\text{Be}$ source. The size ranges from 2 to 20 Curies and has a half life of 433 years. The source is loaded into a bull plug (centre object in Figure 3.5-3) which is in turn mounted onto the logging tool (Dresser Atlas, 1982 and IAEA, 2007).

Neutron tools are manufactured in many different designs; single detector, dual detector compensated, sidewalled, and some with articulated arms that force a pod containing the source and detector(s) against the borehole wall. Neutron logs can be run in cased and open boreholes, with air, mud or water as the fluid.

Gamma detectors used in the gamma and density logging tools do not work for neutron detection since neutrons are non-ionizing. Logging tools usually use neutron capture devices as detectors – either Geiger or proportional counters. Two common neutron detectors seen in the logging industry are BF_3 counters and ^3He counters. To convert these to epithermal detectors they can be wrapped in a shielding material such as cadmium to block the slower thermal neutrons. Single detector tools are typically epithermal neutron tools, while dual detector compensated tools are usually thermal neutron tools (thermal to increase the count rate seen at the far/long detector).

In the absence of shale, porosity is inversely proportional to neutron count rate in sedimentary rocks. Shale is a low porosity rock, but due to the large amount of bound water in the clay minerals, low count rates are recorded and incorrectly high porosity is indicated by the neutron log. A shale correction must be made for logs collected through formations that contain shale. Figure 3.5-4 shows an uncorrected neutron log in cps; areas in the log affected by shale are

circled in red. Gas in the pore space of a formation will result in higher count rates than if the pore space was water or oil filled, thus incorrectly indicating a lower porosity for that formation.

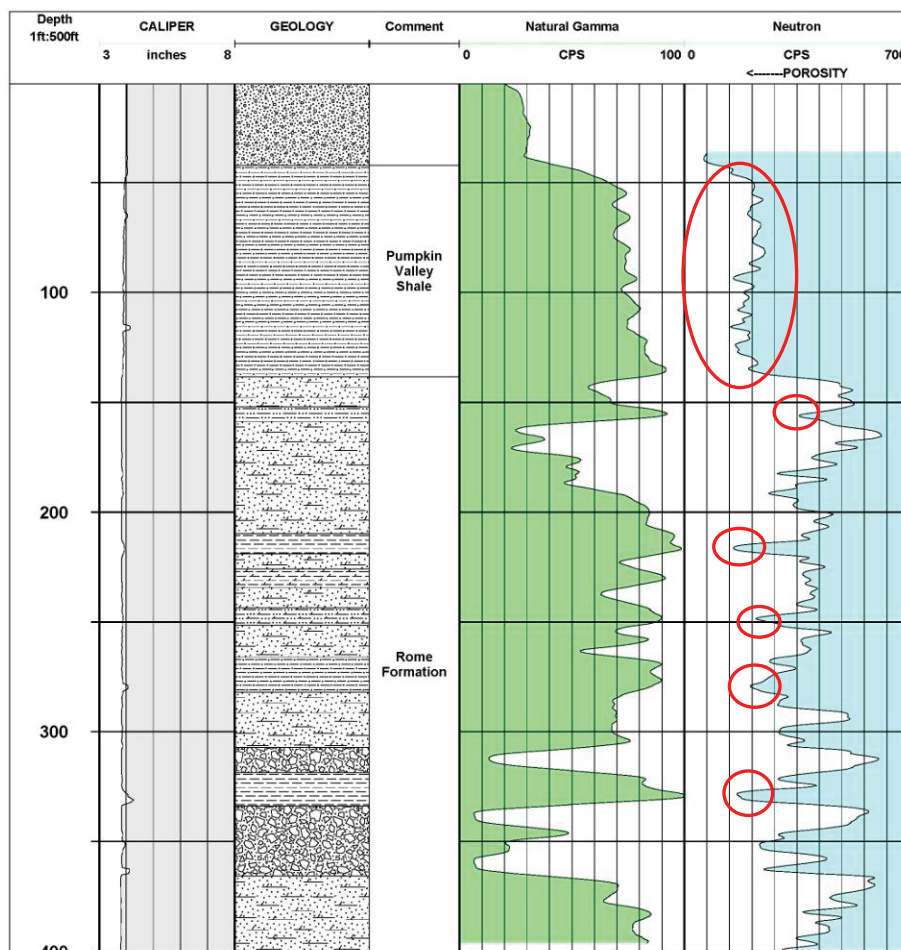


Figure 3.5-4: Uncalibrated neutron log illustrating "shale effect" areas circled in red. (Golder Associates)

The chlorine atom has a very high capture cross section for neutrons in comparison to most other atoms, so chlorine can significantly attenuate neutron log response. Accordingly, a correction must be applied to neutron logs for pore water salinity. In environmental applications, the high capture cross section of the chlorine atom enables neutron logs to detect free phase chlorinated solvents in aquifers (Schneider and Greenhouse, 1992).

Neutron tools can be calibrated for porosity in limestone rocks in the API's calibration pits in Houston and Austin, Texas. These pits are constructed of limestone of known porosity (2% to 26%). Also, the major oil and gas instrument companies have their own calibration pits. A crystalline rock calibration pit facility was constructed at the Denver Federal Centre in Colorado in the 1980's using blocks of granite and granodiorite, which has been used in the past for neutron porosity experiments by USGS researchers (Mathews, 1983).

Neutron logs are typically run at logging speeds of 3 to 10 m/min. A compensated neutron tool measures neutron response in the formation with a depth of investigation on the order of 30 to 50 cm. Neutron responses are typically repeatable within +/-2% of full scale.

Applicability to Programme

Neutron porosity logging can be used to estimate porosity in a sedimentary rock environment and potentially in a crystalline rock environment. Some researchers have noted that because neutron log response is affected by minerals having a high atomic density, neutron logs often over predict porosity for crystalline rocks (Bartetzko et al, 2005). Neutron logs can also be used to help identify the pore fluid type: oil, gas or water and to identify lithology.

Strengths and Weaknesses

The neutron tool is unique in its ability to estimate porosity in rocks via the detection of hydrogen. A great strength of the neutron tool is the ability to be operated through a casing.

The greatest weakness of the neutron log is that it typically requires an active radioactive source, which requires special licensing, special safety handling protocols and is at some risk of being lost in an open borehole.

Processing and QA/QC

Processing the neutron log data from raw cps to porosity is commonly done for sedimentary rock environments, and can be quite involved. There are many factors that can affect the neutron log including; borehole diameter, borehole fluid, mudcake, borehole fluid and formation salinity, shale, tool standoff, and gas in the formation pore space.

Some logging systems are designed with pre-determined calibration values that allow the neutron log to be reported in "percent porosity" for sedimentary environments. Most tool manufacturers provide calibration curves for their tools for specific lithologies and borehole sizes. It is probable that in a repository characterization program, neutron logs will require site-specific calibration if they are to be used to estimate porosity. Neutron porosity data is often cross-plotted with gamma density log data.

Commercial Availability

Neutron logging tools are produced by most tool manufacturers. Health and safety concerns, liability concerns and increased government regulation are among the issues that have led some logging service companies that rely on active neutron sources to cease providing neutron porosity services.

The large oil and gas instrument companies now manufacture tools that are based on a neutron generator technology, so no active sources are used. Neutron generators use deuterium-deuterium reactions to produce a high neutron yield. They can also be designed to use tritium-tritium reactions to generate neutrons across a broad energy spectrum or deuterium - tritium reactions to produce higher energy neutrons. Producers of neutron generator tools are: Baker Hughes, Halliburton, Schlumberger, Sandia National Laboratories and Lawrence Berkeley National Laboratory.

3.5.2 Gamma Density

A gamma density log (or gamma-gamma log) is the measure of the formation electron density, which is directly related to bulk density (Dresser Atlas, 1982). The relationship between gamma ray penetration and electron density of the formation is an exponentially inverse one; the greater the electron density, the less the gamma ray penetration.

Gamma rays interact with matter in three primary ways; photoelectric absorption, Compton scattering, and pair production. For tools using sources within the energy range of 0.1 MeV to 2 MeV, Compton scattering is the primary mode (Dresser Atlas, 1982 and Labo, 1987).



Figure 3.5-5: Photograph showing the end of a compensated density tool with the source holder "bull plug". (Mount Sopris Instrument Co.)

Most gamma density tools employ a radioactive source to bombard the formation with medium energy gamma rays. The most common sources in use for gamma density logging are ^{137}Cs and ^{60}Co . The size ranges from 100 microCuries to 3 Curies. Cesium-137 emits gamma rays at 0.66 MeV and has a half life of 30 years, which makes it a very stable and preferred source. Cobalt 60 emits gamma rays at 1.17 MeV and 1.33 MeV, and has a half life of 5.2 years, which makes it a less stable source. The source is loaded into a bull plug (Figure 3.5-5) which is in turn mounted onto the logging tool (Bassiouni, 1994 and IAEA, 2007).

The detectors used in the density tools are the same type of scintillation counters that are found in natural gamma tools. Single detector tools are usually non-collimated and these logs are referred to as 4Pi density. These tools usually have spacers that allow the operator to change the source to detector spacing. These tools are run decentralized, typically using a bow spring to press against the borehole or casing wall. An improvement on this design is the dual detector, or compensated density tool. The density tool can be run in cased and open boreholes, with air, water or mud as the fluid.

The compensated density tool has a near or short spaced detector, and a far or long spaced detector. These detectors are collimated, and on the opposite side of the tool is a mechanical caliper arm that when open will press the collimated detector windows against the formation. This design minimizes borehole mudcake, rugosity and tool standoff errors.

Gamma density logs are typically run at logging speeds of 3 to 10 m/min. A compensated tool measures response in the formation with a depth of investigation on the order of 5 to 15 cm. Gamma density responses are typically repeatable within +/-5% of full scale.

Applicability to Programme

The gamma density log is applicable to both sedimentary and crystalline rock environments, and can be used to estimate rock density and lithology. It is particularly useful in identifying coal and evaporites.

Strengths and Weaknesses

The gamma density log is unique in that it can be used to directly estimate rock density. Another strength is that it can be used in cased boreholes. When used in a cased borehole, the

casing construction will strongly affect the response. Calibration data should be collected for the formation behind the casing, and if possible for the material used in the well construction.

The greatest weakness of the gamma density log is that it typically requires an active radioactive source, which requires special licensing, special safety handling protocols and is at some risk of being lost in an open borehole.

If logging in formations with high natural gamma rates (such as uranium deposits) it may be necessary to log the borehole without the source and with the source, in order to remove the natural gamma effects.

Processing and QA/QC

Calibration data can be recorded from test pits designed with materials of known density, with various borehole diameters, or from sets of test blocks. Calibration data from at least two or three different densities is necessary to generate a calibration curve for the gamma density tool. Common materials used for calibration blocks are acrylic (1.2 g/cm^3), magnesium (1.8 g/cm^3), and aluminium (2.62 g/cm^3). Figure 3.5-6 is a photograph of a compensated density tool placed in a magnesium block during calibration.

For the compensated density tool it is necessary to build a set of curves for different standoff distances. Borehole corrections may be required, especially when logging in large, air-filled boreholes. This correction requires a caliper log.

The gamma density log can be used to calculate density porosity for the formation. As with the neutron log, in the presence of shale, the density porosity will need a shale correction. The gamma density log is often used to generate a cross-plot with the neutron porosity log.



Figure 3.5-6: Gamma Density probe in aluminium calibration block. (Golder Associates)

Commercial Availability

Gamma density logging tools are produced by all of the smaller geophysical logging instrument companies, and by all of the large oil and gas instrument and service companies such as Baker Hughes, Halliburton, and Schlumberger. Health and safety concerns, liability concerns and increased government regulation are among the issues that have led some logging service companies to cease providing gamma density services.

3.5.3 Litho-density

The litho-density tool is used to estimate material density and photoelectric absorption index P_e (Bassiouni, 1994 and Hearst et al, 2000). The tool is configured similarly to the standard compensated gamma density tool. It uses a ^{137}Cs source with two, more closely-spaced and high resolution detectors.

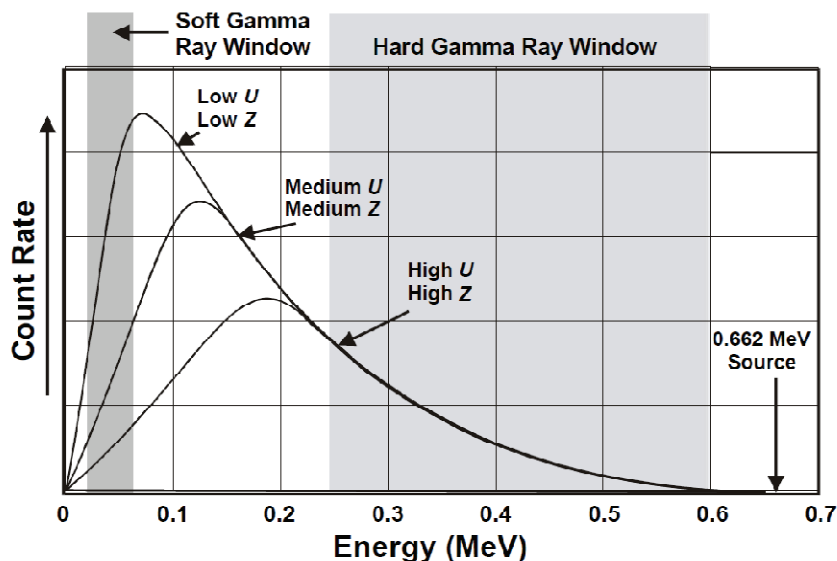


Figure 3.5-7: Gamma Ray Energy Spectra and Measurement Window (Glover, 2009)

With reference to Figure 3.5-7 (Glover, 2009), these detectors separately count gamma rays from Compton scattering (the “hard gamma window”) as well as gamma rays from photoelectric absorption (the “soft gamma window”). Photoelectric absorption is dependent on the atomic number (Z), which reflects the chemical composition of the atom, which is why these logs are referred to as litho-density logs (Labo, 1987). The photoelectric absorption index P_e (barns/electron) for a material can be approximated by:

$$P_e = (Z/10)^{3.6}$$

where: Z = atomic number (Glover, 2009). Photoelectric data for common minerals and fluids are provided in Table 3.5-1 below, where U is the volumetric photoelectric absorption index. As can be seen from the table, rocks, minerals and fluids have a characteristic P_e (and U) value. Most minerals found in crystalline rocks have a high P_e while limestone, dolomite and evaporites have a moderate P_e and sandstone, shale and coal have a low P_e .

The values of P_e for the fluids commonly found in rocks are so low compared with the values for the rock matrix, that influence of the fluid on P_e is negligible, with the possible exception of highly saturated brines. The litho-density log is therefore sensitive to differences in the mean atomic number of a formation without being sensitive to changes in the porosity and fluid saturation of that lithology. This combination makes the log a very good indicator of lithology (Glover, 2009).

These tools are run decentralized, typically using a bow spring to press against the borehole or casing wall. The litho-density tool can be run in cased and open boreholes, with air, water or mud as the fluid. Litho-density logs are typically run at logging speeds of 3 to 10 m/min. The

tool measures response in the formation with a depth of investigation on the order of 5 to 15 cm. Litho-density responses are typically repeatable within +/-5% of full scale.

Table 3.5-1: Photoelectric data for common minerals and fluids. (Glover, 2009)

	Formula	MW	P_e	Z (equiv.)	U
Anhydrite	CaSO ₄	136.15	5.06	15.69	14.93
Barite	BaSO ₄	233.37	267	47.2	1070
Biotite	-	-	6.30	-	21.0
Calcite	CaCO ₃	100.09	5.08	15.71	13.8
Dolomite	CaCO ₃ .MgCO ₃	184.42	3.14	3.74	9.00
K Feldspar	-	-	2.86	-	7.51
Glauconite	-	-	5.32	-	21.0
Gypsum	CaSO ₄ .2H ₂ O	172.18	3.42	14.07	9.37
Halite	NaCl	58.45	4.17	15.3	9.68
Hematite	Fe ₂ O ₃	159.70	21.5	23.45	107
Limonite	-	-	13.0	-	46.7
Magnetite	MgCO ₃	231.55	22.2	23.65	113
Muscovite	-	-	2.40	-	7.90
Pyrite	FeS ₂	119.98	17.0	21.96	82.1
Quartz	SiO ₂	60.09	1.81	11.78	4.79
Siderite	FeCO ₃	115.86	1.69	21.09	55.9
Sylvite	KCl	74.60	8.51	18.13	15.8
Zircon	ZrSiO ₄	183.31	69.1	32.45	311
Shale	-	-	3.42	14.07	-
Shaly Sand	-	-	2.70	-	6.52
Anthracite	-	-	0.161	6.02	-
Bituminous Coal	-	-	0.180	6.21	-
Fresh Water	H ₂ O	18.02	0.358	7.52	0.398
Salt Water	120,000 ppm NaCl	-	0.807	9.42	0.850
Oil	(CH ₂) _n	-	0.119	5.53	-
Methane	CH ₄	16.04	0.095	5.21	-

Applicability to Programme

The litho-density log is applicable to both sedimentary and crystalline rocks and can be used to measure bulk density and help identify lithology by means of photoelectric absorption index P_e .

Strengths and Weaknesses

The litho-density tool has many of the same strengths and weaknesses as the gamma density tool. An additional strength is that the litho-density tool's measurement of photoelectric absorption index is generally insensitive to pore fluid type and porosity.

Processing and QA/QC

The soft gamma ray data is processed to yield density estimates in a manner similar to gamma density log data. The bulk density log can be used with the Wylie time-average equation to calculate density porosity (Labo, 1987).

Photoelectric absorption index data processing can be quite involved, but typically employs cross-plotting techniques with other logs (such as neutron and natural gamma) for lithology characterization.

Commercial Availability

Photoelectric, litho-density services are available from most of the major oil and gas instrument and service companies such as Baker Hughes, Halliburton, and Schlumberger. The smaller geophysical logging instrument and service companies typically do not offer this service.

3.6 Caliper Logs

Caliper logs provide a continuous record of borehole diameter as a function of depth. The tools work by using spring loaded arms, which are pressed against the borehole wall as the tool is raised from the bottom of the borehole. The arms interact with a variable potentiometer within a circuit which produces a calibrated voltage proportional to the deflection of the arms. The arms of the caliper tool are opened (and closed) by a motor that tensions a spring. This allows the probe to be run into the borehole with the arms retracted. Once opened, at the start of logging, the spring-loaded arms respond to borehole diameter variations as the probe is run up the borehole.

The caliper is a useful first log to determine the borehole condition before running more costly probes and it is also important for the processing of other logs. If there is loose material on the borehole walls, it is likely that caliper arms will dislodge it before other tools are run in the borehole.

Calibration of the caliper is performed using two rings with known diameters before and after a logging run. The precision of the measurements are on the order of 1 mm. The probe is usually run at 2 to 4 m/min with a sampling interval 1 cm or less for geotechnical logging applications. Logs can be acquired in dry or fluid-filled boreholes. Many different types of caliper probes exist but two of the most commonly used are the three-arm and the four-arm types, as discussed below.

3.6.1 Three-arm Caliper

The three-arm caliper provides a single continuous log of borehole diameter as determined by three mechanically coupled arms in contact with the borehole walls (Figure 3.6-1).

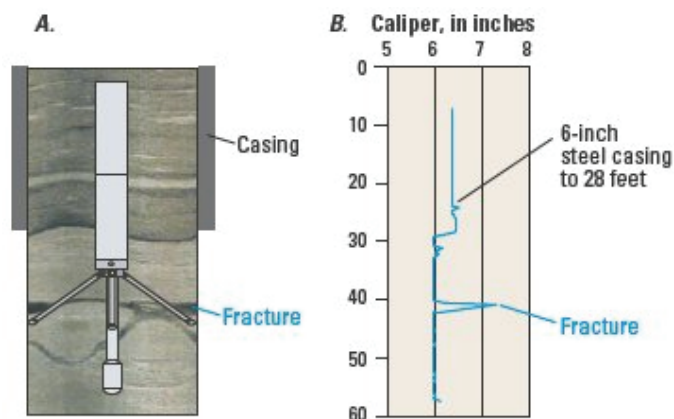


Figure 3.6-1: Three-arm caliper example. (USGS)

The standard caliper range can be increased by using extension arms. The three-arm caliper is used to locate collapsed zones within the borehole, calculate cement volumes for grouting, locating cracks, fractures and casing breaks, to provide data for correcting other logs affected by borehole diameter variations.

3.6.2 Four-arm Caliper

The four-arm caliper provides continuous measurements of borehole diameter in two orthogonal directions. Two independent, perpendicular (XY) pairs of caliper arms are held against the borehole wall by the action of a spring-loaded rack and gear system. The probe's orientation system provides the borehole azimuth and inclination and the directions of the X and Y caliper measurements.

Arms of differing lengths can be fitted to the probe in order to maximize the resolution of the measurement for a specific diameter range. This probe can also be combined with other tools (e.g. natural gamma). The four-arm caliper is used to determine hole and casing diameter, trajectory measurement, detection of borehole ovalisation (in-situ stress measurement), cement volume calculation and location of fracture zones or cavities.

Applicability to Programme

Caliper logs are applicable to both sedimentary and crystalline rock environments. The logs provide a direct measure of borehole diameter, which can be important to calibrate and make corrections to other acquired and calculated logs. The caliper log response indicates borehole rugosity, which is a subtle indicator of lithology when viewed in conjunction with other log data. The caliper log can also indicate the presence of mud cake in the borehole and thereby help identify zones of different permeability.

Strengths and Weaknesses

Using the caliper tool as the first logging run helps identify unstable borehole conditions, so that more expensive probes are not lost. It can only be run upwards because of the contacting caliper arms. If run without centralization in shallow inclined boreholes, the caliper log can produce erroneous readings.

Processing and QA/QC

Processing caliper log data is straightforward. Subsequent to correcting for depth offsets against the depth of known features in the borehole (drilled depth, casing depth and stickup), the calibration data from the field records are reviewed to determine if an adjustment to the log is required. Any required corrections are made and the log is plotted to show diameter in the borehole. For logs with telemetry (4-arm calipers), the recorded dip and azimuth data are compared when possible against known values for the borehole. Caliper log data is also quite important in the interpretation and correction of other types of log data, including electric and active source nuclear logs, for example.

Potential to Combine Methods

Caliper logs are often run in combination with other logging tools, as caliper log data is used to make corrections to logs and calculate many types of derived logs.

Commercial Availability

Virtually all manufacturers produce a caliper device either as a stand-alone tool or in combination with other probes and all geophysical log service companies include it as a standard tool.

3.7 Borehole Imaging Logs

Borehole imaging involves acquiring a radial scan of a borehole wall that is oriented in space such that depth and direction of features can be determined. The images can be optical (optical televiewer, borehole video), acoustic (acoustic televiewer) or electrical (dip meters and formation micro-imagers/scanners). With the exception of borehole video, these logs are oriented so that careful analysis of structure and geology intersecting the borehole is possible. Typically these data are exported for additional analysis to produce stereonet for structure or are used to generate additional calculated logs (e.g. fracture frequency).

During logging, the data recorded includes tilt and azimuth (dip and dip direction) of the tool attitude in the borehole with a 3-component fluxgate magnetometer and a 3-component tiltmeter. As the tools are run centralized, the borehole tilt and azimuth are also acquired. The probes also typically acquire other telemetry data for tool orientation (roll and magnetic roll, magnetic field) as well as speed, temperature and a number of parameters for diagnosing instrument operation.

3.7.1 Optical and Acoustic Televiewers

The optical televiewer generates a scanned image of the borehole wall with detail for resolving fractures as narrow as 0.1 millimetre (mm) and with a radial resolution of 1 degree or better. Applications for these logs include casing defect inspections, characterization of fractures in either air or water-filled boreholes and, in combination with traditional core logging, can be used for mineralogy and foliation studies. The tool generates a continuous oriented 360° image of the borehole wall using an optical imaging system.

The acoustic televiewer, which requires a fluid-filled borehole, produces an image of the borehole wall based on the amplitude and travel time of acoustic beams reflected from the formation wall. When an acoustic beam is transmitted, part of the energy is lost in voids or fractures, producing dark bands on the amplitude log. Travel time measurements allow a reconstruction of the borehole shape, essentially producing a three-dimensional caliper representation of the borehole.

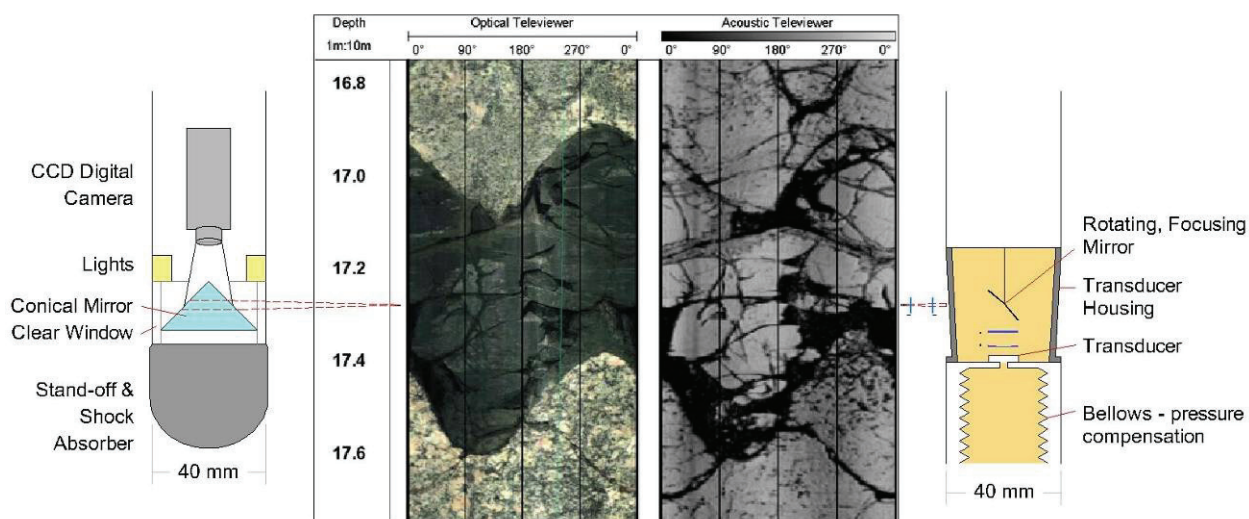


Figure 3.7-1: Optical and Acoustic Televiewer images. (Golder Associates and ALT)

The problem of data acquisition in holes with murky drill fluid (or for holes in poor ground where mud has been used for drill support) can be overcome by use of an acoustic televiewer in place of an optical televiewer, as the fluid does not need to be clear to log the borehole.

Optical and acoustic televiewer image examples are shown on Figure 3.7-1. Image resolution is a function of borehole radius and user definable settings such as scan interval and samples per scan. The data example was acquired with 1 mm/360 pts/turn and 2 mm/144 pts/turn for the optical and acoustic televiewers, respectively, in an HQ-sized borehole.

Optical and acoustic televiewer data are complimentary tools especially when the purpose of the survey is structural analysis. The independently acquired and oriented images should align precisely, which is valuable as a QA/QC check and features observed in the optical image may not be present in the acoustic image and vice versa. A common data display option is the projection on a virtual core that can be rotated and viewed from any orientation. Televiewer images can complement and even replace coring surveys and the associated problems of core recovery and orientation.

Image Orientation

Images acquired by televiewers are oriented by collecting simultaneous data from a 3-component fluxgate magnetometer and a 3-component tiltmeter incorporated into the tool (Section 3.1). Prior to interpretation, the image is rotated to a common reference direction, either true or magnetic north or the high-side of the borehole. Planar features which intersect the borehole wall produce sinusoidal traces in the “unwrapped” televiewer image. Using the reference direction recorded during logging, sinusoids can be analyzed to produce dip and dip direction of structural features, are shown on Figure 3.7-2.

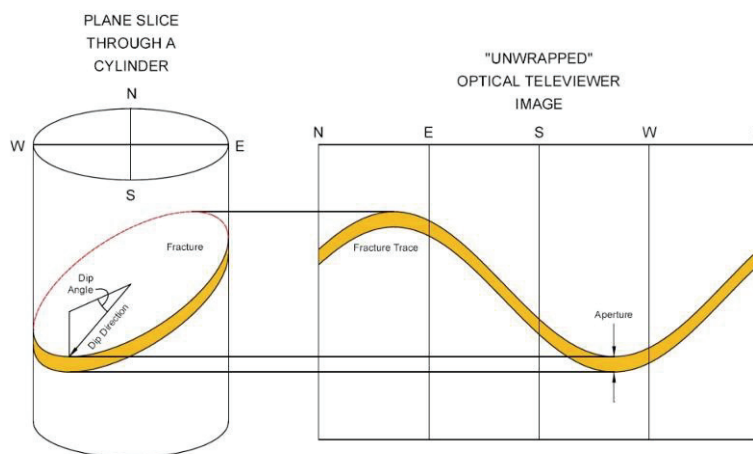


Figure 3.7-2: Plane structures as televiewer images. (Golder Associates)

Applicability to Programme

Televiewer data is of use in both sedimentary and crystalline rock environments to provide detailed measurements of structures intersection the borehole. The televiewer data may also be ancillary to, or even replace data from oriented core.

Strengths and Weaknesses

The fine-scale detail of these logs integrated with other log data can provide enhanced level of interpretation for lithology, structure and studies related to fluid migration. The value of the logs

increases significantly if it is possible to acquire both the optical and acoustic televewers, as the independently acquired and oriented images should align precisely (which is valuable as a QA/QC check) and features observed in the optical image may not be present in the acoustic image and vice versa.

The perceived value of televewer logs are the high-resolution, high-quality and oriented images of the borehole wall that are obtained. It is important to note that these are images of the borehole wall and represent the formation affected by drilling damage and contact with borehole fluids. The orientation of planar features is local and may not represent the overall trend of structure in the rock. This is overcome to a degree if a number of boreholes at a site can be logged such that there is a statistical sampling of the structure.

Key advantages to using OTV/ATV logging methods and observations include:

- Potential for reduced core collection effort;
- OTV and ATV logging allows the investigator to clearly see zones of poor core recovery and intense fracturing *in-situ* - the equivalent of 100% recovery can be achieved;
- Borehole televewer logging is relatively inexpensive to run and is highly portable allowing the technique to be used in difficult terrain;
- Conventional coring requires multiple core runs that often end up being logged as a series of segments between blockages or runs, while borehole televewer logging provides a continuous record of the borehole with more accurate depth references; and
- Recorded borehole data can be imported directly into software applications such as DIPS or ROCKPACK for kinematic analysis;

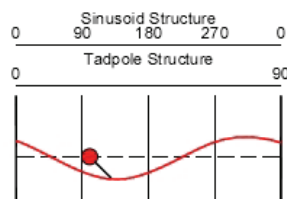
Televewer operation requires specialized training to ensure that appropriate calibrations to reference orientations and zero reading measurement protocols are followed to collect accurate data. Some environments containing magnetic minerals or materials may require additional calibration, data reduction or tools to ensure that accurate data are collected.

Processing and QA/QC

Processing steps for televewer log data generally include the following:

- Importing the raw data into a software package designed for manipulation and presentation of geophysical log data.
- Applying depth corrections as needed to account for casing stickup and cable stretch if appropriate – typically, a check is completed to ensure that features common to all logs in the same borehole match for depth.
- The televewer log images are aligned with either high side in the borehole or magnetic north. At this point, the televewer telemetry data can be corrected over portions of the borehole clearly affected by magnetic interference – specifically the casing.
- Features on the televewer logs are then identified and analyzed for azimuth and dip.
- Sinusoidal features on the amplitude and travel time logs are interpreted according to a system of classification (for example).

- 1 - Major Open Joint / Fracture
- 2 - Minor Open Joint / Fracture
- 3 - Partially Open Joint Fracture
- 4 - Filled Fracture / Joint
- 5 - Bedding / Banding / Foliation
- 6 - Geological Contact



- The sinusoid shows the trace of the feature from the image (optical or acoustic televiewer).
- The centre of the tadpole shows the dip measured from horizontal (0 to 90 degrees) and the tail shows the dip direction (0 to 360 degrees).
- The dashed line is the depth.

1. Major Open Joint / Fracture: Continuous televiewer sinusoids with aperture greater than 1 cm and associated caliper or travel time anomalies.
2. Minor Open Joint / Fracture: Continuous televiewer sinusoids with less than 1 cm of aperture but with associated caliper or travel time anomalies.
3. Partially Open Joint / Fracture: Continuous televiewer sinusoid with dis-continuous aperture.
4. Filled Fracture / Joint: Continuous or discontinuous sinusoids with no aperture that are parallel or at an angle to the foliation.
5. Bedding / Banding / Foliation: Generally appear as a series of parallel or sub-parallel sinusoids. These can be misinterpreted as Filled Fractures / Joints and vice-versa.
6. Geological Contact: These are interpreted from review of the televiewer data together with the stratigraphic logs (natural gamma and apparent conductivity) and marked if there is no obvious associated mechanical structure.

Other processing steps may include combining televiewer data with other logs. An example is combining acoustic televiewer and full wave form sonic logs to generate apparent density and apparent rock hardness logs. This type of processing is site specific but has been successfully applied at a number of sites.

The key for quality control is ensuring the accuracy of the orientation system within the televiewer, which should be checked with a calibration device prior to logging. In the presence of magnetic materials (minerals, metal) in the borehole, the tool's azimuth readings will be influenced. This can be overcome by applying a correction to the magnetometer data over affected portions of the log – either by:

- Orienting the image to high side in inclined holes using the inclinometer data collected by the televiewer and then using ancillary information from a borehole deviation tool (gyroscope or maxibore), which is unaffected by magnetic materials to rotate the image to north; or
- Using the roll data acquired by the inclinometers to correct the magnetic roll data. The magnetic roll data can then be used to orient the image to north. Typically, this technique can be usefully applied if short sections of the borehole are affected by magnetic materials.

Commercial Availability

Slim-hole versions of the televiewer tools are available in North America from: Century Geophysical Corp., Mount Sopris Instruments (ALT) and Robertson Geologging Ltd. Typically, the slim-hole tools are limited to operating depths of 2,000 m (< 20 MPa) but there are versions of the acoustic televiewer with extended pressure and temperature capability. Most logging contractors will offer televiewer logs in their service package.

3.7.2 Dipmeter

Dipmeters are borehole tools that are used to determine the dip angle and dip direction of planar features intersecting the borehole. To accomplish this task a dipmeter must be capable of detecting features that intersect the borehole, be able to measure the borehole diameter (caliper measurement), and be capable of measuring tool orientation.

The dipmeter's primary sensors are multiple articulated arms (as few as three, but usually four and sometimes six or more) that are used to press sensor pads against the borehole wall (Figure 3.7-3). The most common sensors are electrodes for measuring resistivity or conductivity. The dipmeter's arms provide the borehole caliper measurement and the sensor pads provide the measurement that is used to detect planar features. To provide tool orientation data, dipmeters are equipped with orientation packages (usually 3-axis magnetometer and 3 accelerometers).

Dipmeters are logged moving up the borehole. The logging speed should follow the manufacturer's recommendation and be adjusted to meet project specific requirements; high resolution surveys may require two to four samples per cm (Hearst et al, 2000 p. 326).

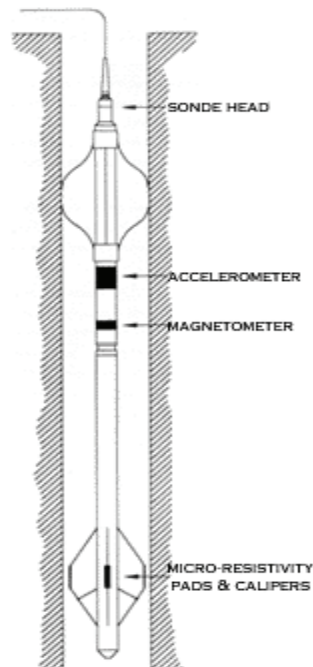


Figure 3.7-3: Schematic of a dipmeter. (Robertson Geologging Limited)

Applicability to Programme

Dipmeter tools are applicable to both sedimentary and crystalline rock environments, although in slim-hole applications, dipmeter tools have largely been replaced by televIEWER tools.

Processing and QA/QC

Dipmeter data is usually processed by software from the tool manufacturer, or from a third party provider. Borehole orientation data can be presented referenced to magnetic north, or corrected to true north by the correct magnetic declination value for the borehole location. Processed orientation data can be presented as a “bull’s eye” view of the borehole path, a 3D cylinder view of the borehole path, closure plot, or as profile plots at selected orientations

The structure data measured from the dipmeter are azimuth and dip, which are commonly presented as tadpole plots, rosette plots, or stereonet plots, similar to that described in Section 3.7.1. The caliper function should be calibrated, or verified prior to the logging run. The function of the tools orientation package should be verified with a conventional compass prior to the logging run.

Strengths and Weaknesses

The dipmeter is run in open holes only, water-filled, mud-filled and air-filled. Dipmeters are more rugged than imaging tools such as acoustic and optical televIEWERS and cost much less. Mud cake on the borehole wall can interfere with the operation of the sensor pads. Analysis of the individual electrical traces to correctly identify responses that correlate to a planar feature can be difficult, and is a fundamental problem. The accuracy of the azimuth from older models can be as high as $\pm 20^\circ$, and $\pm 5^\circ$ in the newer tools. The accuracy of the inclination from older models can be as high as $\pm 10^\circ$, and $\pm 1^\circ$ in the newer tools (Hearst et al, 2000, pp. 326-330).

Potential to Combine Methods

The dipmeter may include other sensors, such as, gamma, SP and SPR. This allows for the collection of multiple log types in a single logging run. The caliper log can be used for borehole correction of other geophysical log data. The borehole orientation data can be used to correct other logs to true vertical depth.

Commercial Availability

Slim-hole versions of the dipmeter tools are available in North America from: Century Geophysical Corp., Mount Sopris Instruments (ALT) and Robertson Geologging Ltd. Dipmeter tools are available from the major oil and gas instrument and service companies such as Baker Hughes, Halliburton, and Schlumberger.

3.7.3 Electrical Resistivity Formation Scanner

Electrical resistivity formation scanners evolved from the simpler dipmeter. Formation scanners are advanced borehole imaging tools designed to generate a high resolution 360° image of the borehole wall and to determine the dip angle and dip direction of planar features intersecting the borehole. Formation scanners rely on 3-axis magnetometers and accelerometers for tool orientation.

Formation scanners have built on the dipmeter concept of multiple articulated arms (four to six arms) pressing sensor pads against the borehole wall by adding many sensor buttons (commonly 24 buttons) to each pad. This modification changes a 6-arm dipmeter recording six resistivity traces into a formation scanner recording 144 resistivity traces. Formation scanners can typically record data at high vertical resolutions with samples every 3 mm (Figure 3.7-4).

Formation scanners typically produce images of from 60% to 80% of the borehole wall; the coverage depends on the number of pads, size of the pads, the number of buttons on each pad, and the borehole diameter. For example:

- Schlumberger Formation MicroImager (FMI™): four arms, eight pads, 24 measuring electrodes per pad, for a total of 192 measurements per sample.
- Halliburton Electrical Micro Imaging (EMI™): six arms, six pads, 25 measuring electrodes per pad, for a total of 150 measurements per sample.
- Weatherford High-Resolution micro-imager (HMI®): six arms, six pads, 25 measuring electrodes per pad, for a total of 150 measurements per sample.
- Baker Atlas STAR ImagerSM Service: six arms, six pads, 24 measuring electrodes per pad, for a total of 144 measurements per sample.

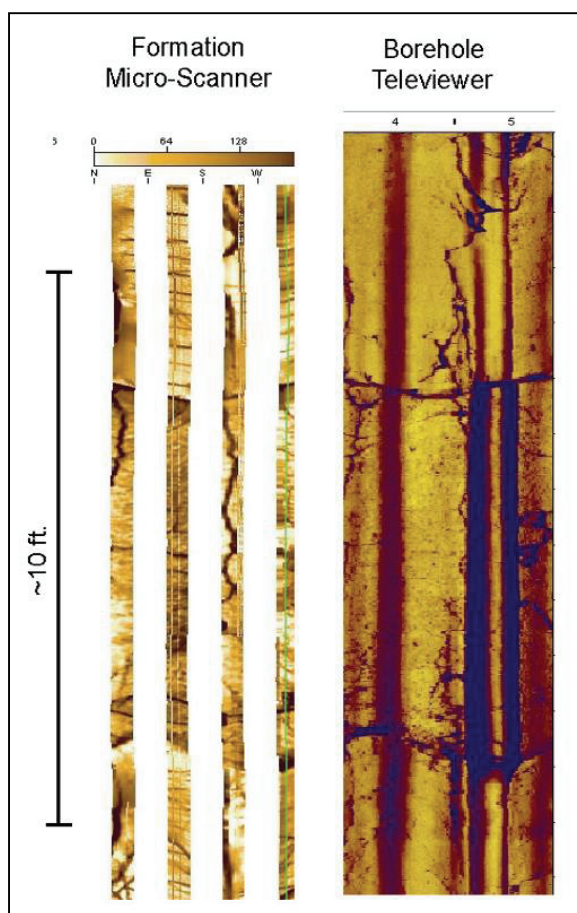


Figure 3.7-4: Example of data from a formation scanner. (USGS)

Processing and QA/QC

Formation scanner data is usually processed by software from the tool manufacturer, or from a third party provider. Borehole orientation data can be presented referenced to magnetic north, or corrected to true north by the correct magnetic declination value for the borehole location. Processed orientation data can be presented as a “bull’s eye” view of the borehole path, a 3D cylinder view of the borehole path, closure plot, or as profile plots at selected orientations. The

structure data measured from formation scanners is commonly presented as tadpole plots, rosette plots, or stereonet plots.

Strengths and Weaknesses

Formation scanners are run in open holes only, water-filled, mud-filled and air-filled. The minimum borehole diameter for most formation scanners is 152 mm. Mud cake on the borehole wall can interfere with the operation of the sensor pads and with the image quality (Hearst et al, 2000, pp. 330-333).

Potential to Combine Methods

Electrical resistivity formation scanners typically run as stand-alone tools.

Commercial Availability

Electrical resistivity formation scanners are commercially available from a handful of manufacturers/service providers. Schlumberger offers their version called a Formation MicroImager (FMI™). Halliburton offers their version called Electrical Micro Imaging (EMI™). Weatherford offers their version called high-resolution micro-imager (HMI®). Baker Atlas offers their version as STAR ImagerSM service.

3.7.4 Borehole Video Log

Video cameras are available for borehole applications in a number of formats (Figures 3.7-5 and 3.7-6) including black and white and colour, slim-hole design and larger, downward looking with side-view or pan capability digital recording with depth and borehole identifier overlay. Virtually all models have integrated lighting systems. Some systems can also track and display depth on screen by passing the cable over an odometer wheel.

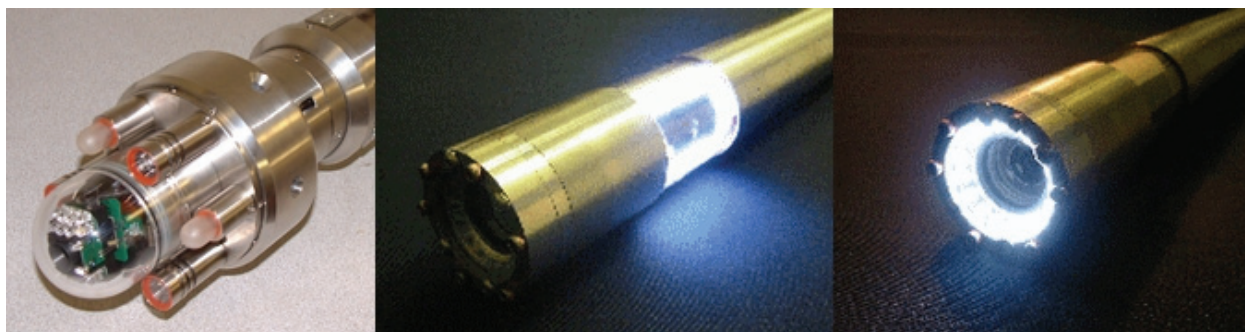


Figure 3.7-5: Borehole camera options including panning (left) and side and downward looking (middle and right) (Robertson Geologging Limited)

Camera or video logs require clear fluid or air-filled boreholes and are mostly used for well inspections (casing, screen and obstructions or for locating lost parts and tools). They can also be used to identify flowing fractures. Figure 3.7-7 shows examples of flowing fractures above the water level in the borehole (left) and below the water level (right). Particle movement on the video of the borehole in the image on the right indicated water flow from the fracture into the borehole. Video logs can also be used to semi-quantitatively map fractures in the borehole wall with orientation accuracy limited to about $\pm 10^\circ$ azimuth and dip.



Figure 3.7-6: A borehole camera system including winch and recording equipment (top-right) and the camera head with down and side view capability (Laval Underground Surveys)

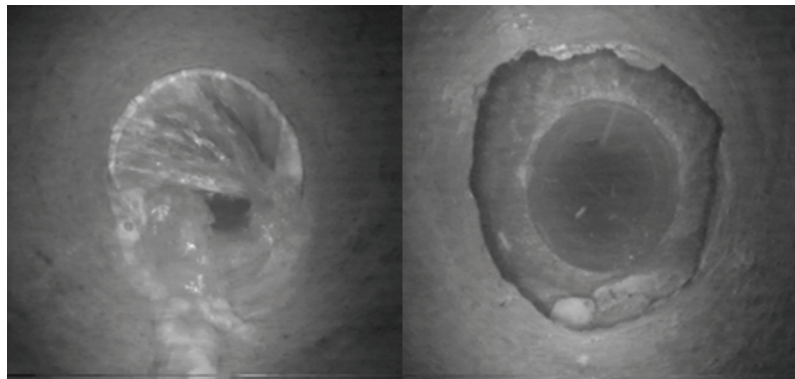


Figure 3.7-7: Flowing fracture examples (Golder Associates)

Applicability to Programme

Camera systems are typically rated to pressures of 15 to 20 MPa and can be run to depth in boreholes in excess of 1,000 metres deep. The data are qualitative rather than quantitative, but the images can be compelling to a wide audience for identifying and explaining key results from a borehole investigation.

Strengths and Weaknesses

A main strength of a video log is that the results are viewed real-time and the examination of a borehole can be modified during logging – spending more time on features of interest and acquiring video coverage from a number of angles. However, as the data is qualitative, it is difficult to obtain precise measurements of these features. Visibility can be a key challenge below the water table. The borehole needs to be flushed prior to logging and the camera itself can disturb settled materials, particularly in inclined boreholes, such that the operator needs to keep advancing the camera forward to maintain good visibility.

Processing and QA/QC

Processing is generally limited to observing the video coverage and taking notes of observations relevant to the purpose of the logging program. The images have been used to measure dip, aperture and azimuth (if there is a north reference in the image) by overlaying an acetate reference diagram on video images. This can yield useful data in lieu of acquiring televiwer or formation scanner logs but accuracy is limited to ± 10 degrees for the dip and azimuth estimates. QA/QC is limited to ensuring that depth encoding for the logs is accurate.

Commercial Availability

Camera systems are available from a number of manufacturers: Robertson Geologging Limited, Geovista, Laval Underground Surveys, Geovision/Marks Products, Inc. and Well Vu/Nature Vision, Inc. Other suppliers include camera systems such as the SeeSnake® which has been developed for pipe inspections but can be reconfigured for use in deep boreholes. Most borehole geophysical service providers have this capability.

3.8 Borehole Gravity

The borehole gravity meter (BHGM) is a deep-investigating, logging tool that measures vertical variations of the Earth's gravity field (measured in milligals or microgals). These variations depend on the changes in the formation density not only above and below the sensor, but also laterally away from the borehole. Gravity measurements are made at regular depth intervals, with readings averaged over a 10 to 15 minute period at each location. The log is not continuous and BHGM measurements are taken at discrete depths usually at intervals of 3 to 10 m, depending on the vertical and density resolution required.

The gravity meter is a delicate spring balance which measures changes in weight of a small proof mass (see Figure 3.8-1). The lever arm mass pivots and stretches the spring under the influence of the local gravity field.

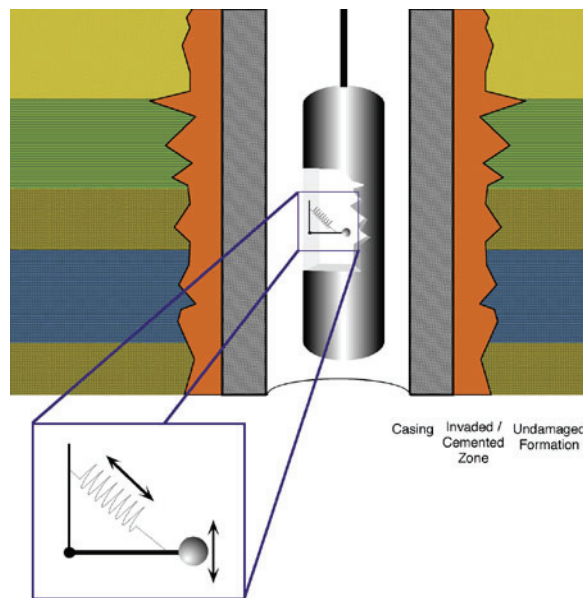


Figure 3.8-1: Borehole gravity sensor. (Chapin and Ander, 1999)

The BHGM measurement samples a large volume of rock which provides a density-porosity value that is more representative of the formation. Density information obtained from borehole gravity measurements are both highly accurate and not affected by borehole conditions or casing which can render other density tools either useless or prone to significant error.

Borehole gravity is a bulk density method, so when coupled with a near-borehole imaging nuclear density method such as a gamma-gamma log, the formation porosity can be computed with great accuracy. In a sense, borehole gravity samples tens to a hundred metres into the formation whereas measurements from traditional logging tools sample only a short distance from the well (less than 40 cm). The tool can be run in open and cased boreholes that are air, water or mud filled.

In the example below from the east Texas Cotton Valley Trend, the observed density variations between the near-borehole detecting gamma-gamma log and the far-imaging borehole gravity log (in yellow) suggested that the well was about 100 m away from a low density porous reef (Figure 3.8-2). This information helped to make an oil discovery (Chapin and Ander, 1999).

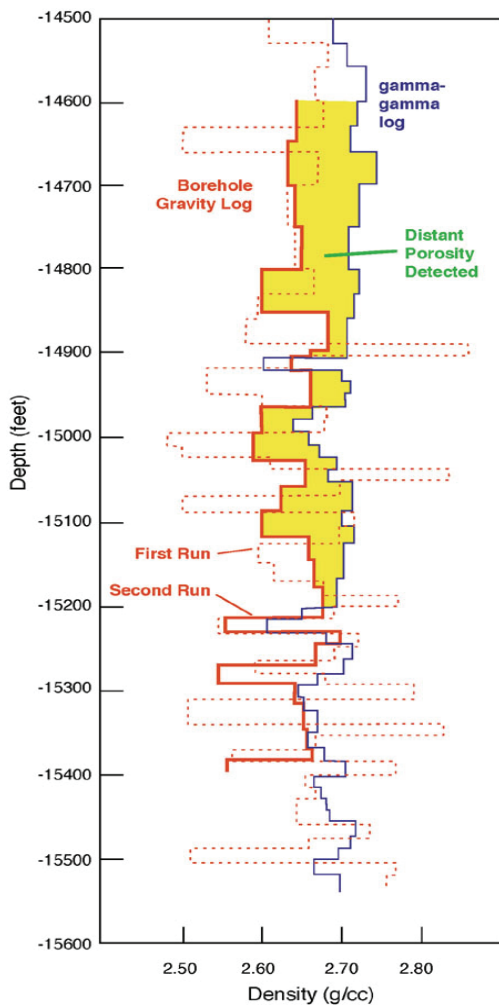


Figure 3.8-2: Density and borehole gravity log data acquired in 1996. (Chapin and Ander, 1999)

Complex geology can be modelled in gravity so that the response of a range of hypothetical models can be studied and understood before undertaking a survey. Modelling is particularly effective where seismic data can be integrated into the modelling process; a model is sought that is consistent with both gravity and seismic data sets.

On surveys where the depth increment is small, gravity readings are repeated a minimum of 3 times to reduce the depth and gravity uncertainties. In borehole gravity, the distance resolution is a tradeoff with vertical resolution. As the object gets more distant, its signal becomes broader in wavelength. Thus, the readings can be processed for more distant objects but this will decrease the vertical resolution.

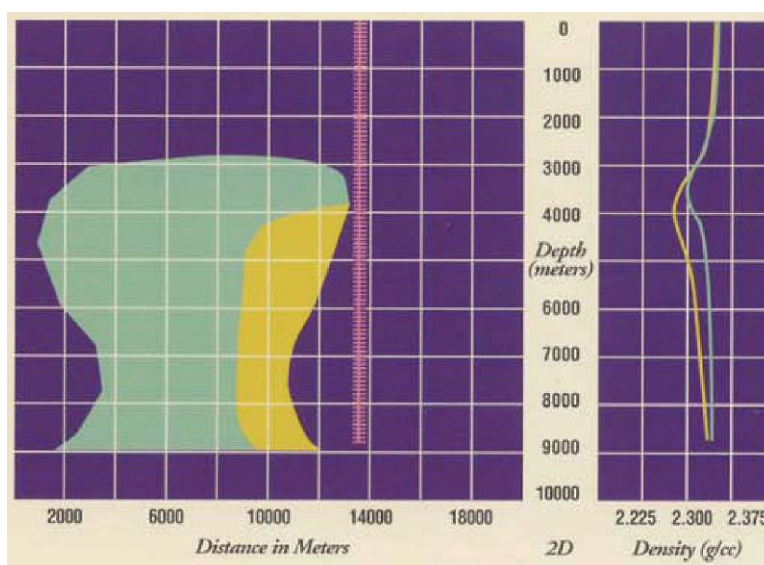


Figure 3.8-3: Gravity low due to structural effect of a salt overhang.

Borehole gravity has a large set of applications and is especially beneficial in carbonate and fractured reservoirs. BHGM surveys have been used to find hydrocarbon-filled porosity missed by other logs in both open and cased holes. Gas-saturated sands are a particularly detectable target. Other uses of the borehole gravity method include formation evaluation and reservoir monitoring. It can detect lateral variations in density arising from porosity changes away from the borehole (e.g., fracture), and lateral proximity to lithology changes such as major faults or salt intrusions. Figure 3.8-3 shows the large differences in density between the BHGM and gamma density measurements in the vicinity of the salt flanks.

Applicability to Programme

The current uses of the borehole gravity method include formation evaluation, reservoir monitoring, determining behind-the-casing bypassed gas and exploration for distant structures. There is a clear potential to use borehole gravity data to survey for discontinuities, including faults and voids, in the near proximity of boreholes and more distant, in both sedimentary and crystalline rock environments.

Strengths and Weaknesses

The main strength of BHGM as a density logging tool is that it is practically unaffected by near-hole influences that strongly affect nuclear tools. These include the casing, poor cement bonding, rugosity, washouts and fluid invasion.

The greatest current drawback for the tool is that it can only be used in boreholes deviated less than 14° from vertical and the length of time required for an individual reading, typically 10 to 15 minutes.

Processing and QA/QC

Measurements of gravity differences repeatable to about 3 microgals have been achieved using a LaCoste and Romberg borehole gravity meter. In borehole gravity measurements, highly accurate formation density measurements, averaged over a large volume, may be made by comparing changes of gravity between measurement stations. The vertical gradient of gravity in a uniform medium is proportional to the medium's density and the BHGM apparent density is given approximately by the following equation (there are small corrections for latitude and elevation):

$$\rho = 3.6824 - 0.1283 \Delta g / \Delta z$$

where: ρ is in g/cm³, Δz is in metres, and Δg is in microgals. The constant density term compensates for the earth's normal vertical gravity gradient (the free air gradient).

The meter must be levelled at each station, and it is accurately calibrated at a temperature of about 126° C. For higher temperatures up to 260° C, the meter is operated inside a Dewar flask. The instrument will not operate in a well bore deviated from vertical by more than 14°.

Potential to Combine Methods

Although the BHGM is run as a standalone tool, the results are often combined with those from a gamma-density log because density differences are a good indicator for structures away from the well. Deep density BHGM and down hole seismic surveys (VSP) are a good combination because they are both stationary recordings. BHGM complements VSP, surface seismic and gravity information in modelling the subsurface.

Commercial Availability

The only commercially available borehole gravity sensors are manufactured by LaCoste & Romberg of Austin, Texas.

3.9 Nuclear Magnetic Resonance (NMR) Log

The principle behind the NMR method is that many nuclei are electrically charged spinning protons that create weak magnetic fields and have magnetic moments (behaving like spinning bar magnets). The interaction of these spinning magnetic nuclei with an applied external magnetic field will produce a measurable signal. These signals are small for most elements, but hydrogen has a relatively large magnetic moment. NMR tools are tuned to the magnetic resonant frequency of hydrogen to maximize the measured signal (Allen et al, 2000; Kenyon et al 1995; and Romero et al, 2008).

From the 1960's to the 1990's, NMR tools were designed using the earth's magnetic field for proton alignment. Modern NMR tools are designed with large permanent magnets (550 gauss), which are approximately 1,000 times larger than the earth's magnetic field. As the NMR tool moves along the borehole, the hydrogen protons in the formation adjacent to the tool align with the magnetic field of the large permanent magnet(s) in the tool (Allen et al, 2000; Kenyon et al 1995; and Romero et al, 2008).

The quantities measured are signal amplitude and decay. The NMR measurement begins with the hydrogen protons aligning with the static magnetic field of the NMR tool, referred to as polarization. The exposure time is referred to as the wait time (WT) during which the nuclei polarize at an exponential rate known as T_1 . After a set WT the tool's antenna emits a series of radio frequency (RF) pulses known as Carr-Purcell-Meiboom-Gill (CPMG sequence) that tip the spinning hydrogen nuclei 90° from the tool's magnetic field, causing them to precess about the permanent magnetic field. Between successive RF bursts, the formation fluid generates RF echoes that are received by the tool's antenna. This time between the RF bursts is known as the echo spacing (TE). The amplitude of the initial echo is proportional to the number of hydrogen nuclei, and this is calibrated to provide a measure of porosity. The amplitude of the subsequent echoes decreases exponentially (relaxation rate, T_2) over the measurement cycle. Small pore size allows for short T_2 times, while large pore size allows for large T_2 times. Thus, T_2 distribution is a measure of the pore size distribution (Kenyon et al 1995).

A few of the important NMR measurements for site characterization include:

- total porosity, independent of lithology;
- pore size distribution;
- grain size
- permeability;
- bound and free fluid volumes;
- T_1 , T_2 and diffusion distributions; and
- shale volume and distribution.

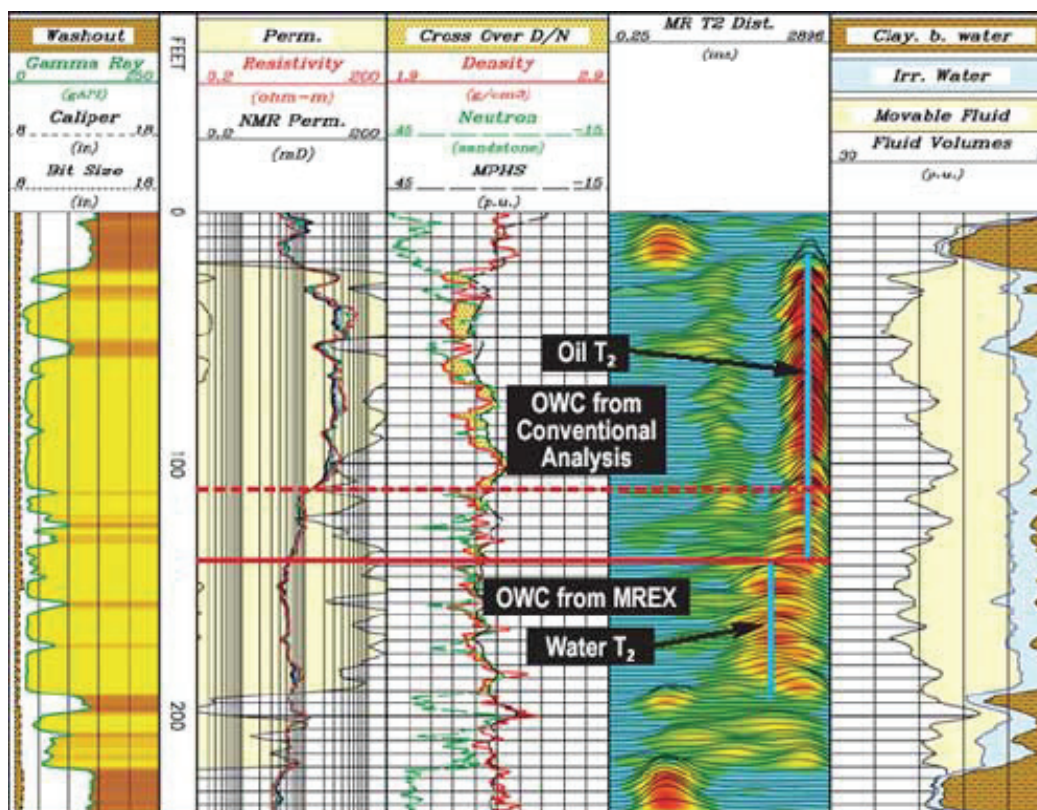


Figure 3.9-1: Log example from MX ExplorerSM. (<http://www.bakerhughes.com>)

Figure 3.9-1 shows conventional log data with NMR log data from the Baker Hughes MX ExplorerSM (MREXSM) NMR service. Note how the tool can be used to better identify the oil/water contact (OWC) in the formation compared to conventional log analyses

Applicability to Programme

NMR is most applicable in sedimentary rock environments, but can also be deployed in a crystalline rock environment.

Strengths and Weaknesses

The NMR method does not measure fracture permeability because the NMR signal responds predominantly to the pore space of the formation. The NMR tools are large tools; generally, over 10 m in length, 11.4 cm to 15.5 cm in diameter, and weigh from 200 kg to 540 kg.

NMR tools have, in the past, fallen into two categories; the centralized concentric-shell tools and the pad contact tools. The lateral depth of investigation for these tools was typically 2 cm to 3 cm, so the measurement was from the flushed or invaded zone around the borehole.

The new generation of NMR tools, like Schlumberger's MR scanner, provide fixed depths of investigation at multiple shells, for depths of investigation from 3.8 cm to 10.2 cm. These are still shallow reading tools, with the measurements coming from the flushed zone around the borehole.

Processing and QA/QC

NMR tools should be calibrated in the service company shop prior to each logging job. The shop calibration process will determine:

- The pulse strength $B1$ needed to produce the maximum $A0$, where $A0$ is the amplitude of echo train at time zero. (Both 90° and 180° pulses have the same amplitude but different lengths).
- The relationship between $B1$ and $A0$ that is required to perform a "power correction."
- The correction to Echoes 1 and 2, resulting from the so-called stimulated echo effect.
- The relationship between $A0$ and porosity. (The maximum $A0$ is calibrated to 100% porosity in the calibration tank (Coates et al, 1999)).

Schlumberger, Halliburton and Baker Hughes all have various advanced proprietary software for inversion of the NMR data. Halliburton has developed specialized models, such as MRILAN and StiMRILTM for combining the data from their MRIL tool with neutron, density, sonic and resistivity log data to generate information about rock properties, formation lithology and permeability (Coates et al, 1999).

Commercial Availability

Most of the major oil and gas service companies provide NMR services. Some of the most known NMR borehole service providers are Halliburton's MRIL services, Schlumberger's CMR Combinable Magnetic Resonance services and MR Scanner services, the Baker Hughes MR Explorer (MREX) service, and Weatherford's NMRT sensor.

The smaller mineral logging instrument and service companies do not offer this service. However, there has been interest expressed in the last year for the manufacture of a smaller slimhole NMR tool that could be available to the smaller mineral logging service companies. The development of this tool is still several years away.

4. BOREHOLE GEOPHYSICAL METHODS II - FLOW TESTING LOGS

This chapter presents the geophysical methods that can be used for flow testing in boreholes as part of investigations to characterize potential deep geological repository candidate sites. The tools and techniques described in this chapter include:

- Fluid Temperature and Resistivity Logs
- Impeller Flow Meter
- Heat Pulse Flow Meter
- Electromagnetic Flow Meter
- Posiva Flow Meter
- Borehole Dilution and Hydrophysical Logging
- Cross-borehole Testing

Methods of analysis and interpretation of flow logging data are presented and discussed, as well as the comparison (verification) of flow log results with packer testing. Key aspects of flow logging techniques are then summarized including:

- Applicability to Programme
- Processing and QA/QC
- Accuracy and Resolution
- Limits and Constraints
- Strengths and Weaknesses
- Potential to Combine Methods
- Commercial Availability

4.1 Fundamental Principles

Borehole flow testing is the process of measuring the distribution of flow in boreholes to determine the intervals where flow enters or exits under a given hydraulic condition. Many borehole geophysical measurements are made to infer the porosity and permeability of the rock surrounding the borehole. Flow logging methods have the advantage that they involve direct measurement of the hydraulic response of the rocks around the borehole and do not require an assumed relation between geophysical quantities and the hydraulic properties of the formation.

In crystalline or massive sedimentary rocks (assumed to be of negligible porosity and matrix permeability), flow in a borehole is assumed to be laminar with an approximately parabolic velocity distribution in the borehole cross-section. This laminar distribution of flow along the borehole axis is assumed to apply to within one borehole diameter of inflow and outflow points which correspond with fractures, sets of fractures, or bedding planes enlarged by dissolution.

Turbulent flow is uncommon because the standard threshold for the onset of turbulence (Reynolds number > 2000) requires greater discharge rates than can usually be sustained in fractured rock boreholes (Paillet et al, 1998). The amount of inflow from each such zone is given by the difference between the flow measured above and below that depth interval, with outflow expressed as negative inflow.

In the analysis of borehole flow logs, the integrated permeability (product of permeability and thickness) for each inflow or outflow interval is expressed as transmissivity, T (Dewiest, 1969).

The actual thickness of a fracture or set of fractures is difficult to define, and may include the fluid-filled openings between asperities in contact at the fracture face, layers of infilling minerals deposited within fracture passages, and an alteration halo surrounding the fracture. However, the hydraulic aperture (a) is expressed as the width of a perfectly plane opening between two uniform blocks that conducts an equivalent amount of flow for a given pressure gradient (Snow, 1965)

$$T = 12\mu a^3 / \rho g \text{ or } a = (\rho g T / 12\mu)^{1/3}$$

where μ is the viscosity of groundwater, ρ is the density of groundwater and g is the acceleration due to gravity. The amount of inflow or outflow under any specific hydraulic condition cannot be assumed proportional to T because the flow rate depends on the product of T and the local pressure gradient driving the flow. Under laminar flow conditions, the pressure at the borehole wall can be taken as equal to the hydraulic head in the open borehole, but the far field pressure can be different for each producing zone since they may be isolated from each other in the surrounding rock.

This requires that two sets of data be collected under two different hydraulic conditions (usually ambient and steady pumping) to simultaneously estimate both zone transmissivity and far-field hydraulic head (Paillet et al, 2000). This approach can be expanded to include measurements under several different conditions as in a stepped pumping test, producing an over-determined inversion. Because the data sets are generally analyzed by fitting a flow model to the data set, the minimization of the error between each profile and the model can be expanded to a global minimization of the error between all predicted flows and all data sets.

The importance of comparing inflow under two different hydraulic conditions when there is ambient flow between zones cannot be over emphasized. The hydraulics of the open borehole act to effectively disguise the most transmissive zones under any one condition. This can be demonstrated by noting that the water level in an open borehole connected to several zones of permeability connected to reservoirs of differing hydraulic head will be the T -weighted averages of those hydraulic heads (Paillet et al, 2000). In the case of three such zones:

$$WL_0 = (WL_1 * T_1 + WL_2 * T_2 + WL_3 * T_3) / (T_1 + T_2 + T_3)$$

where T is the transmissivity and WL is the water level. The subscripts 1, 2 and 3 refer to the water levels and transmissivities of the three zones and the subscript 0 references the water level in the open borehole. The water level therefore adjusts so that the head difference driving flow out of the most transmissive zone is minimized.

There are borehole logging systems available to measure both vertical and horizontal flow in boreholes. Complex distributions of horizontal flow have been measured in fractured bedrock aquifers, but there have been questions about the reliability and repeatability of these methods, which are based on particle or chemical tracer methods (Wilson et al, 2001). They have been most effectively applied to more homogeneous flow regimes in porous sedimentary rocks (Pitrak et al, 2007). The horizontal flow interpretation in heterogeneous fractured rocks is a poorly defined inversion problem because the measurement is sensitive to the local flow regime in the immediate vicinity of the borehole and does not provide a representative measurement of either the direction or magnitude of the larger scale flow in the rock mass. Horizontal flow measurement methods will therefore not be considered further in this document.

4.2 Fluid Temperature and Resistivity Logs

Measurements of fluid column temperature and electrical resistivity are routinely obtained in boreholes. If there is no significant permeability in the formation around the borehole, the temperature of the fluid column will reflect the local geothermal gradient and the fluid column resistivity will represent the distribution of solutes in the borehole water.

Since the geothermal gradient is determined by the steady upward flow of heat from within the earth, any variations in the fluid temperature profile will reflect changes in thermal conductivity in the surrounding rock as long as there is no flow in the borehole (Keys, 1997; Hearst et al, 2000). The fluid resistivity profile will reflect any stratification of the water within the stagnant column. In many open boreholes there can be natural (ambient) flow along the borehole between permeable zones, and fluid column logs can be run during steady pumping or injection in boreholes that do not have flow under ambient conditions. The fluid column logs will then reflect the properties of the inflowing water, and there may be discontinuities in the profiles where water enters or exits from the column.

If no other data is provided, fluid column logs can be very ambiguous to interpret in terms of borehole flow (Keys, 1997). For example, there may be no detectable change in fluid column properties where a major proportion of ambient flow exits the borehole because the much-reduced flow beyond the exit point is characterized by the same temperature and resistivity. Fluid column logs can be useful in identifying the exact exit point within intervals known to have significant flow. Fluid column logs obtained under ambient and pumped conditions can be compared to provide a preliminary characterization of borehole flow regimes or to corroborate flow measurements in other ways.

The most effective use of fluid column logs results when high-resolution flow meters are used to characterize the rate of flow at discrete points, and then fluid column logs are used to identify the precise depth at which inflow or outflow occurs in the intervals between flow measurement stations (Paillet and Ellefsen, 2004; LeBorgne et al, 2006). This approach is especially useful in situations where borehole conditions (such as washouts and slotted liners in unstable zones) provide intervals where flow measurements cannot be taken effectively and the inflow points cannot be bracketed with closely spaced measurements.

The Mount Sopris 2PFA-1000 is probably the most widely used fluid temperature and resistivity tool in North America for this type of testing. It uses a seven electrode mirrored Wenner array for measuring borehole fluid resistivity and a temperature sensor based on a fast response semiconductor device whose output voltage changes linearly with temperature. It has a fluid resistivity measurement range of 0 to 100 ohm-m and a temperature range of -20 to 80 °C. The probe has a reported accuracy of 1% of full scale or better, with a resolution of 0.05 ohm-m and 0.1 °C, respectively for resistivity and temperature.

4.3 Impeller Flow Meter

The impeller flow meter is designed to rotate on a bearing and be aligned transverse to the borehole axis. Electronic sensors record the rate of rotation of the impeller under the influence of flow past the impeller blades. The impeller is usually housed within a protective cage at the bottom of the logging probe, and the probe body is usually centralized within the borehole. Impeller output in counts per second is calibrated in flow units by regressing output against known flow rates in flow tubes of a known diameter (Keys, 1997; Hill, 1990). Calibration for upward and downward flow may differ slightly because of the fluid dynamic effects of the probe

body located above the impeller. There will also be a “stall zone” (flow less than about 10 cm/s) at low flow where there is not enough flow to turn the impeller (Hearst et al, 2000).

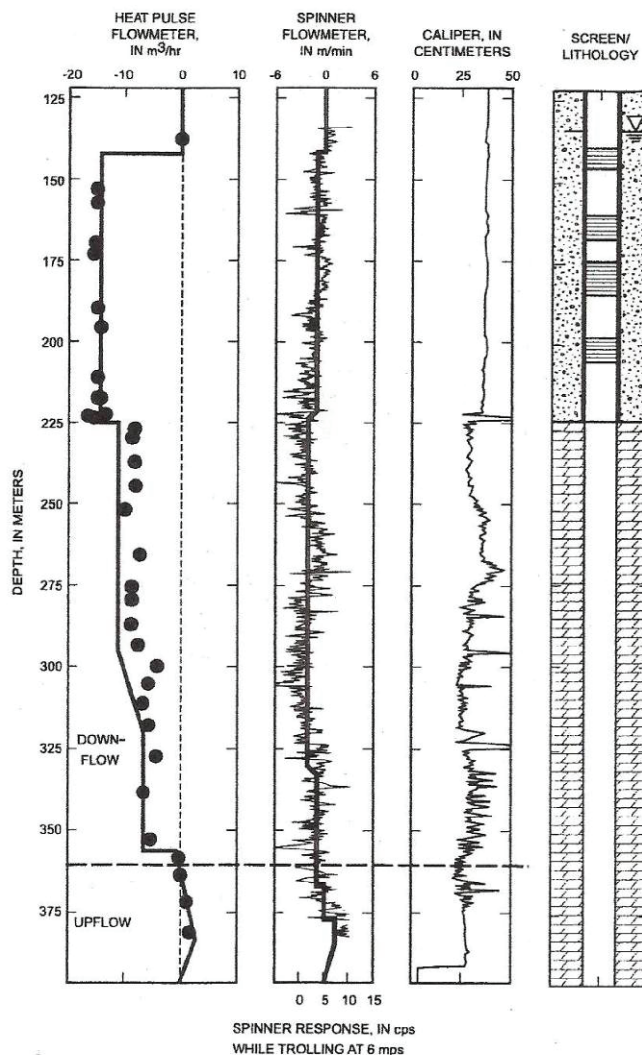


Figure 4.3-1: Example of impeller flow meter data compared to HPFM data.

The impeller log is most often used in the trolling mode where there is enough movement of the probe to turn the impeller blades even when there is no flow in the borehole. Some impeller probes can distinguish between upward and downward flow, whereas others simply provide a pulse output rate that is proportional to blade rotation rate and not indicative of rotation (and therefore flow) direction. Most effective results are obtained when data are collected by trolling upwards and downwards, and then comparing the results (Keys, 1997). One of the major complications in impeller logging is the “dither” in the data. The rotation rate will typically be only a few cps, so that the log has a “stair-step” oscillation between discrete counts in measurement periods. This can be suppressed by increasing the trolling rate, but with the disadvantage that relatively small inflow or outflow “steps” in the log will be hard to recognize within the much larger effects of the trolling. This is illustrated by the example of an impeller log in a 15 cm diameter borehole shown on Figure 4.3-1. A typical trolling speed of 5 m/min corresponds to almost 100 l/min moving by the probe. Recognition of a few l/min inflow against

this background can be difficult in the presence of other noise such as provided by minor variations in borehole diameter.

In many applications it will be difficult to obtain flow rates large enough to provide effective flow profiling with an impeller flow meter (Keys, 1997). When impeller logging is performed under marginal conditions, it is best to plan logging so as to maximize impeller performance. For example, pumping at 20 l/min might provide enough flow in a 7.5 cm diameter borehole for impeller logging, and a borehole might be able to sustain that pumping rate with a drawdown of a few tens of metres. Logs would be obtained by trolling downward so that probe movement adds to the effective flow through the impeller.

Impeller flow meter logs are recorded in counts per second (cps). The cps values are converted to flow rate by identifying the no flow interval below all inflow depths at the bottom of the log. A second calibration point is given by comparing the probe output to the known pumping rate at the top of the log. The no-flow baseline output in cps is then subtracted from the log, and the remaining values calibrated using the response at the known pumping rate.

A number of different manufacturers make impeller tools, including Mount Sopris Instrument Co. (Model FLP-2492), as well as a number of smaller logging equipment manufacturers, such as Comprobe Inc.

4.4 Heat Pulse Flow Meter

The heat pulse flow meter (HPFM) is a device designed to measure relatively low flow in boreholes and has the advantage of being used in well tests where the pumping rate is less than 5 l/min. The probe has a cylindrical measurement section consisting of thermistors situated a short distance above and below a wire grid (Hess, 1986).

A slight electrical discharge on the grid heats a small parcel of water. The movement of that heated parcel past one of the thermistors registers an electronic pulse by allowing current to flow through an unbalanced bridge circuit. Volumetric flow through the measurement section is closely correlated with the inverse of the elapsed time between grid discharge and pulse detection. The HPFM tool is equipped with flexible disks (or sometimes a wireline operated packer) to block the annulus between measurement section and borehole wall. The Mount Sopris model HFP-2293 heat pulse flow meter, based on a prototype developed by the USGS, is shown on Figure 4.4-1

Effective flow measurements can be made over a range of from 0.1 to 5.0 l/min. Almost all boreholes intersect one or more permeable zones capable of sustaining this amount of flow, and drawdown quickly stabilizes at such low rates. In situations where permeability is so low that even 0.1 l/min of steady flow cannot be maintained, logging is performed under the recovery mode where the water level is quickly drawn down by tens of meters and flow is measured under effectively steady drawdown rather than during steady pumping (Paillet and Ellefsen, 2004). In situations where ambient flow is greater than 5 l/m occurs, flow diverters can be modified to allow a known fraction of flow to bypass the measurement section. The HPFM has been successfully used to log boreholes under ambient flow rates greater than 100 l/min in several studies in the literature (Paillet et al, 2000). An example of HPFM data modified to work in a high flow environment and compared to the impeller flow meter is shown in Figure 4.3-1.



Figure 4.4-1: Mount Sopris heat pulse flow meter model HFP-2293. (USGS)

In almost all situations and applications, heat pulse (HP) flow measurements are made with the probe stationed at specific depth levels. It is theoretically possible to make measurements while trolling the probe, but the trolling rate has to be kept low (less than 0.5 m/min) in order to keep the movement of water through the moving probe from exceeding probe sensitivity (Paillet and Ellefsen, 2004). Sensitivity can be reduced to extend the measurement range to larger flows by using an under-sized diverter, but this greatly reduces the ability of the probe to resolve inflow.

Stationary measurements are made by firing the grid discharge and recording the pulse travel time. Most HPFM probe software provide automatic picks of pulse arrival, but these need to be checked to insure a genuine pick is made based on a real pulse and not random noise in the probe response. Movement of the probe may have disturbed the water column so that repeat measurements are made until a repeatable travel time is recorded (Hess, 1986). Care should be taken to insure that probe is stationed in a depth interval where the caliper log indicates a smooth borehole wall so that the diverter properly seals the annulus. Experience has shown that the direction of movement of the probe before it is stationed influences the flow measurements. This happens because the amount of leakage by the diverter depends on whether the diverter is curved up or down given that the shape of the diverter favours leakage in one direction over leakage in the other direction. All measurements should be made with the diverter in the same configuration to insure consistency. One simple way to do this is to visit each measurement station while moving from the bottom of the borehole to the top. Making all measurements in sequence from bottom to top also minimizes the number of times that the probe is moved up and down, which can cause the accumulation of depth errors.

Although probe response (in pulse travel time) comes with a calibration relating response to volumetric discharge, this calibration applies only to the flow passing through the measurement section. In rough-walled boreholes, there is always some leakage of flow around the diverters (Paillet and Ellefsen, 2004). HPFM data should be checked against known flow rates in the borehole whenever possible, and the flow adjusted by a bypass factor:

$$K_b = Q_p / Q_0$$

where Q_p is a known flow rate (usually borehole injection rate or pump discharge) and Q_0 is the calibrated flow through the probe measurement section. These measurements are usually made at an upper depth station in the open borehole below a pump and above the uppermost inflow zone. If there is not enough room to make a measurement in that interval, the pump can be removed and the up-flow measured and then compared to the measured rate of water level recovery. Bypass factors of from 1.5 to 3.0 have been reported in the literature for typical bedrock boreholes drilled by air-hammer percussion methods (Paillet et al, 2000; Paillet and Ellefsen, 2004).

Figure 4.4-2 presents an example of HP and EM flow meter profiles in a bedrock borehole on the University of Connecticut campus, where flow profiles have been obtained under ambient conditions and pumping at a steady rate of 10 l/min, and flow model analysis was used to estimate transmissivity and hydraulic head of individual fracture zones.

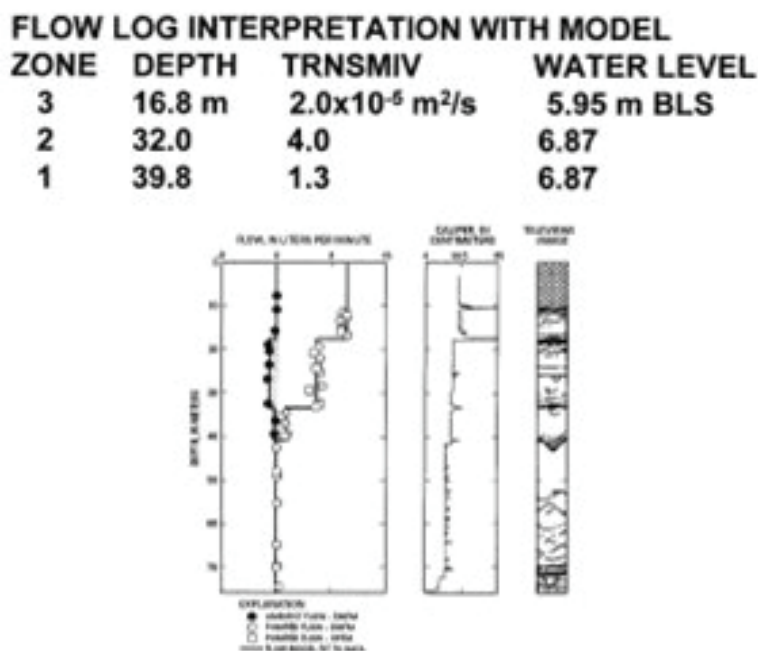


Figure 4.4-2: Examples of HP and EM flow meter profiles.

It is also important to make measurements at several different stations within each interval where flow is assumed to be constant (that is, in intervals between inflow/outflow zones). This is important because the object of flow logging is to identify permeable zones. The identification is based on differences in flow measurements made above and below each such zone. Local borehole conditions introduce some scatter in the flow measurements. If several measurements are taken in zones where the flow is assumed to be constant, then this provides an estimate of the scatter in the data. This, in turn, allows identification of depth intervals where changes in flow measured above and below suspected permeable zones are definitely greater than the scatter within constant flow zones (Figure 4.4-2).

4.5 Electromagnetic Flow Meter

The electromagnetic (EM) flow meter measures flow in a cylindrical section by sensing the electromotive force (emf) induced by the movement of electrically conducting ground water through a magnetic field (Molz et al, 1994). The induced emf is found to be proportional to the rate of flow as long as the solute content of the water exceeds a minimum of about 40 mg/l. As with the HPFM, flexible disks (diverters) are used to seal the annulus between measurement section and borehole wall. The low-flow detection limit is about 0.1 l/min. However, the zero-point for the measurement is known to drift as a function of borehole conditions (Paillet, 2004). The probe should be allowed about 15 minutes after first being immersed in groundwater to come to thermal equilibrium in order to minimize this drift. Even then, data should be collected repeatedly in sections of the borehole (casing under no flow, and in a stagnant zone below all flow) to verify that drift has been minimal, and to produce a record to allow drift to be removed during data processing.

The EM flow meter collects data continuously, and does not have an upper measurement limit. This means that EM flow meter logs can be obtained in the trolling mode. Even so, the continuous data stream is subject to noise, so that most reliable measurements are made with the probe held stationary, and output averaged for 30 seconds or more. Probe software includes calibration values provided from the manufacturer's calibration facility, giving flow through the measurement section in discharge units. The same issues related to diverter configuration apply to the EM flow meter. The direction of diverter curvature needs to be kept consistent for stationary measurements, and such measurements need to be made where the caliper log indicates a smooth borehole wall.

The EM flow meter is equipped with flexible disk diverters and has all of the leakage issues that occur in the case of the HP flow meter. Measured flow rates can be substantially less than actual flow in rough-walled boreholes. Because the EM flow meter can make measurements at high flow rates, trolling measurements in a stagnant column can be used to compare the known volumetric rate of water movement through the probe and diverter (product of trolling rate and casing volume) with the flow being measured by the probe. This method of bypass factor calibration can be used when there is no way to directly compare flow measurements given by the stationary probe to a known flow rate at a specified measurement station. EM flow meter data collected in the stationary mode compared to HPFM measurements in the same borehole are shown in Figure 4.4-2.

4.6 Posiva Flow Log

The Posiva Flow Log (PFL) is a highly specialized version of the HPFM where a pair of flexible diverters are used to isolate a section of borehole. The probe is designed to allow flow from below the lower diverter to move through the probe, while only the inflow or outflow in the zone between the two diverters is shunted through the HP measurement section. This probe is used in essentially the same way as the conventional HPFM, except that the output gives a direct indication of inflow and outflow at each measurement station. This has a distinct advantage over the conventional HP where the analysis has to identify inflow or outflow zones within the scatter of the distribution of flow measurements.

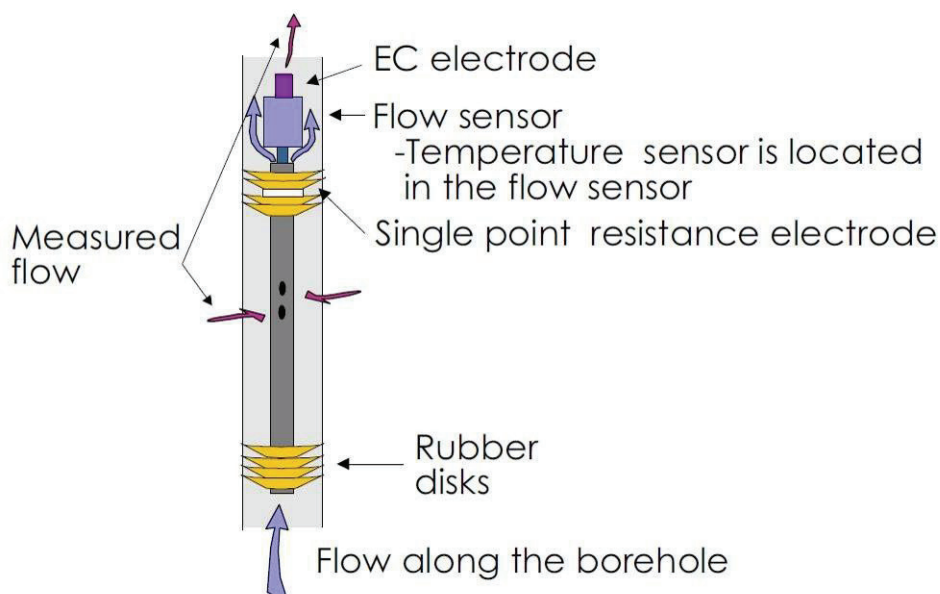


Figure 4.6-1: Schematic of the Posiva “difference” flow meter. (Posiva, 2008)

The PFL is stated to have a flow rate measurement range of 6 to 300,000 ml/hr, with an accuracy of $\pm 10\%$ of the measured value (Posiva, 2008).

4.7 Borehole Dilution and Hydrophysical Logging

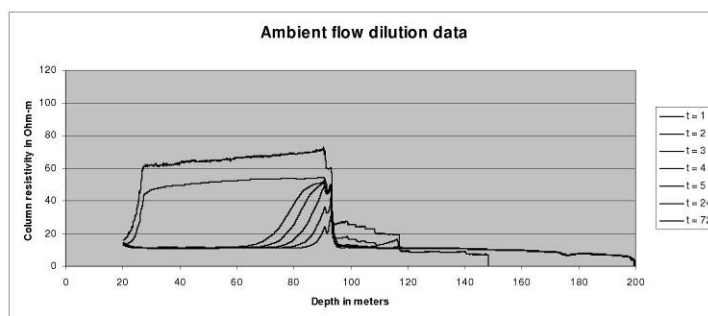
Dilution logging consists of repeat (time lapse) fluid column logging to characterize the changes over time in the distribution of column fluid electrical conductivity (fec) after establishment of an initial condition where the fluid column contains water of a distinctly different fec than the natural groundwater (Tsang et al, 1990; West and Odling, 2007). This can be done by adding solutes to the fluid column, or replacing the column with de-ionized (distilled) water. The latter process is sometimes denoted as hydrophysical logging. A slightly different version of dilution logging is performed by staining the column with a dye, and then detecting dye concentration as attenuation of light from a LED source precisely tuned to the absorption spectrum of the dye (Pitrak et al, 2007).

One critical step in dilution logging is to establish the initial condition without disturbing the hydraulics of the borehole. This is not a problem when there is little or no ambient flow, but becomes an issue when there is significant ongoing flow to disrupt the column replacement while it is occurring. Dilution logging is obviously suitable for extreme low flow situations, where water movement can be monitored over periods of several hours to several days. Dilution logging is much more difficult in higher flow situations because these flow rates produce a large length scale for longitudinal dispersion, limiting the ability to detect the movement of water interfaces (Paillet and Pedler, 1996). The requirement to minimize disturbance of the column by passage of the logging probe also requires logging at a rate of 3 m/min or less. This requires several tens of minutes to log a section of borehole of 100 m or more. Dilution log interpretation becomes difficult when the character of the solute column is varying over time scales shorter than the time required to profile the column.

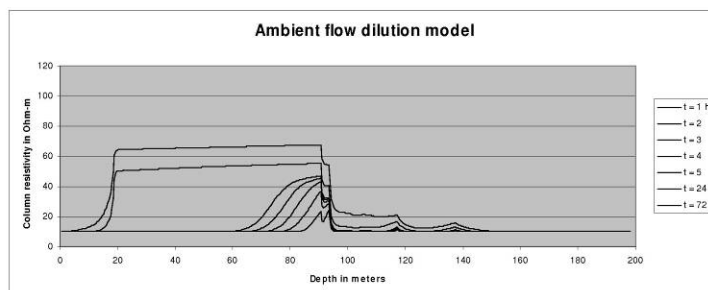
Dilution log interpretation has the advantage that the method gives a direct measurement of flow in the fluid column without concern for leakage around a diverter, scatter related to local borehole conditions or fluid column disturbance by probe movement. Flow values are given by

modelling the convection and diffusion of the solute in the column over time. Discrete inflow zones are identified where inflowing water dilutes the column, or adds conductivity to an initially de-ionized column. The movement of the interface in the intervals between such zones gives the flow profile for the borehole under the given hydraulic conditions. The net displacement of fluid column interfaces over the time between successive logs provides a simple and effective average of the rate of flow in the given interval, as long as the flow rate is low enough that the interface movement can be effectively captured over several successive profiles (Figure 4.7-1).

(a) Ambient dilution data



(b) Ambient dilution model fit



(c) Ambient flow from model

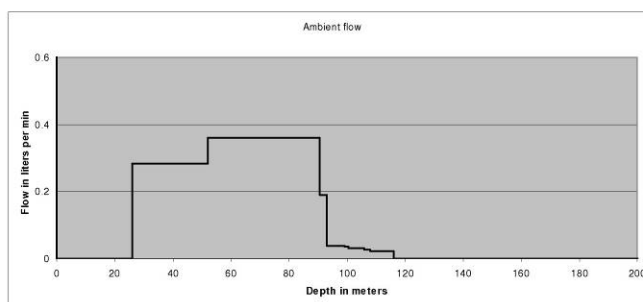


Figure 4.7-1: Example of ambient flow profile in a deep sedimentary bedrock borehole determined by the dilution modelling method.

4.8 Borehole Flow Interpretation Methods

This section describes the general interpretation methods for borehole flow tests, which are largely independent of the type of flow measurements made. The primary application of the HP, EM and other high-resolution borehole flow measurements is the identification of intervals where flow enters and exits boreholes under a known hydraulic condition. Numerous studies

have shown that the local characteristics of fractures and bedding planes as characterized at the borehole wall are not closely correlated with the amount of water those zones produce under hydraulic stressing. This is attributed to the importance of fracture connectivity (intersections between fractures) and local fracture heterogeneity (discrete flow channels embedded within fractures) in determining the rate of flow through a fracture network. Flow surveys typically identify a minor subset of fractures within the much larger population identified in the borehole as being the source of inflow (Paillet et al, 1987; Long et al, 1996, Paillet et al, 2000).

Analysis of flow logs is both qualitative (correlation of flow zones with specific features such as fractures and lithologic contacts on other logs or core photographs) and quantitative (determining the transmissivity and far field hydraulic head in each producing zone). Qualitative correlation of the flow meter survey with other geophysical logs such as caliper, resistivity, acoustic, and image (televiewer) identifies the specific features such as lithologic contacts and fractures associated with flow (Paillet, 1991). One such example is presented on Figure 4.8-1. Other evidence such as orientation and association with specific lithology can be used to infer the relationship between flow paths, lithology and state of stress (Keys, 1997; Hearst et al, 2000).

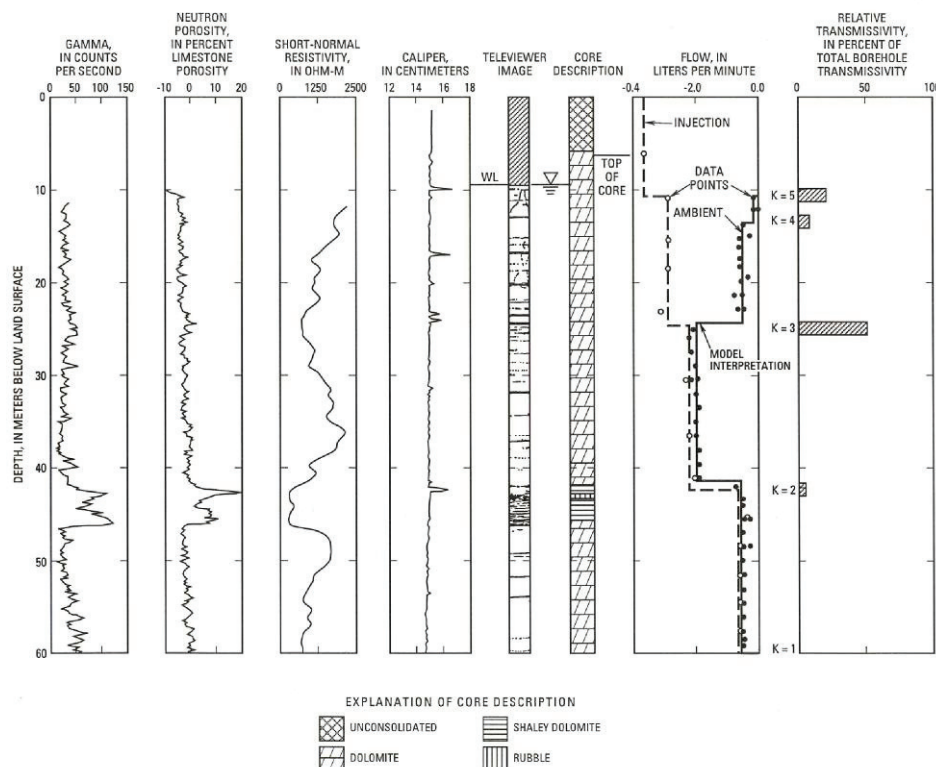


Figure 4.8-1: Flow logs correlated with other logs to relate the permeability indicated by flow logging to geology and structure.

Quantitative interpretation of flow profiles is based on recognition that the dependence on hydraulic head in the formation means that zone permeability is inferred from changes in the amount of inflow induced by changes in the flow regime (Molz et al, 1989). The simplest way to do this is to subtract one flow profile from another to eliminate the hydraulic head dependence in the data sets. This is done by identifying the discrete inflow zones in the borehole, and reading

the flow above and below each such zone (denoted by superscripts a and b) under the two different conditions (denoted by superscripts 1 and 2). If Q_0 is the total discharge rate of the borehole and T_0 is the transmissivity of the entire borehole, then the relative T of each zone (expressed as a percent of T_0) is given by (Molz et al, 1989):

$$\text{Relative T} = 100 \times T_i / T_0 = 100 \times [(Q_i^{a2} - Q_i^{b2}) - (Q_i^{a1} - Q_i^{b1})] / Q_0$$

One disadvantage of this method is that the Q_i^{kj} values are usually estimated by fitting straight line segments to the flow log data in the intervals between inflow or outflow zones. Flow profile interpretations based on such “stair step” diagrams may not necessarily satisfy the equations of flow. This becomes evident when negative relative T values are inferred from the analysis. If negative values are given, the straight-line segment interpretations need to be adjusted until the subtraction of inflows yields positive relative T values for all inflow zones. If this adjustment cannot be made within the scatter of the flow data, then the flow log data must be considered unacceptable.

A more direct method for interpreting flow profiles in boreholes is to use a flow model to match the flow log data sets with the predicted flow for a given set of transmissivity and far-field hydraulic head values. If there is no ambient flow in the borehole, T is proportional to the proportion of inflow from each zone during pumping, and it is a simple matter to match a model to the inflow values and measured drawdown. If there is ambient flow, both hydraulic head in each zone and zone transmissivity must be varied simultaneously in the model input so as to match inflows under both conditions along with the net change in open borehole water level associated with the pumping (Paillet et al, 1998; 2000). This is largely a trial and error procedure, but the formal solution is defined as the set of parameters that minimizes the least mean square difference between data and model prediction. Convergence on this minimum error is complicated by the fact that this is a nonlinear process because the error depends on the product of the two unknowns (transmissivity and hydraulic head difference in the zone). However, one recently published model approach to flow log model fitting uses an automatic convergence scheme to identify the best-fit solution (Day-Lewis et al, in press).

One common problem with flow logging is that experimental conditions do not allow flow data to be obtained under steady conditions. This happens when a steady flow rate cannot be maintained, or when the pump is removed so that logging can continue up to water level at the bottom of casing. Such data sets can be normalized to represent steady flow conditions by assuming that inflow to the borehole is proportional to drawdown (Paillet and Ellefsen, 2004). If D_0 is taken as a reference drawdown and D_i is the actual drawdown at the time when flow measurement Q_i is made, then the corrected flow is given as:

$$Q_i^c = (D_0 / D_i) * Q_i$$

The quantitative interpretation of flow logs is often thought of as estimating the permeability of each producing zone. In fact, the hydraulic head values given by flow log analysis can also be useful. The distribution of hydraulic head within the rock mass surrounding the borehole can be used to infer the presence or absence of hydraulic connections surrounding the borehole (Figure 4.8-2). If two individual zones have the same far-field hydraulic head, then this is evidence that they are connected within the vicinity of the borehole, and can probably be treated as a single aquifer unit during pump testing and water sampling programs.

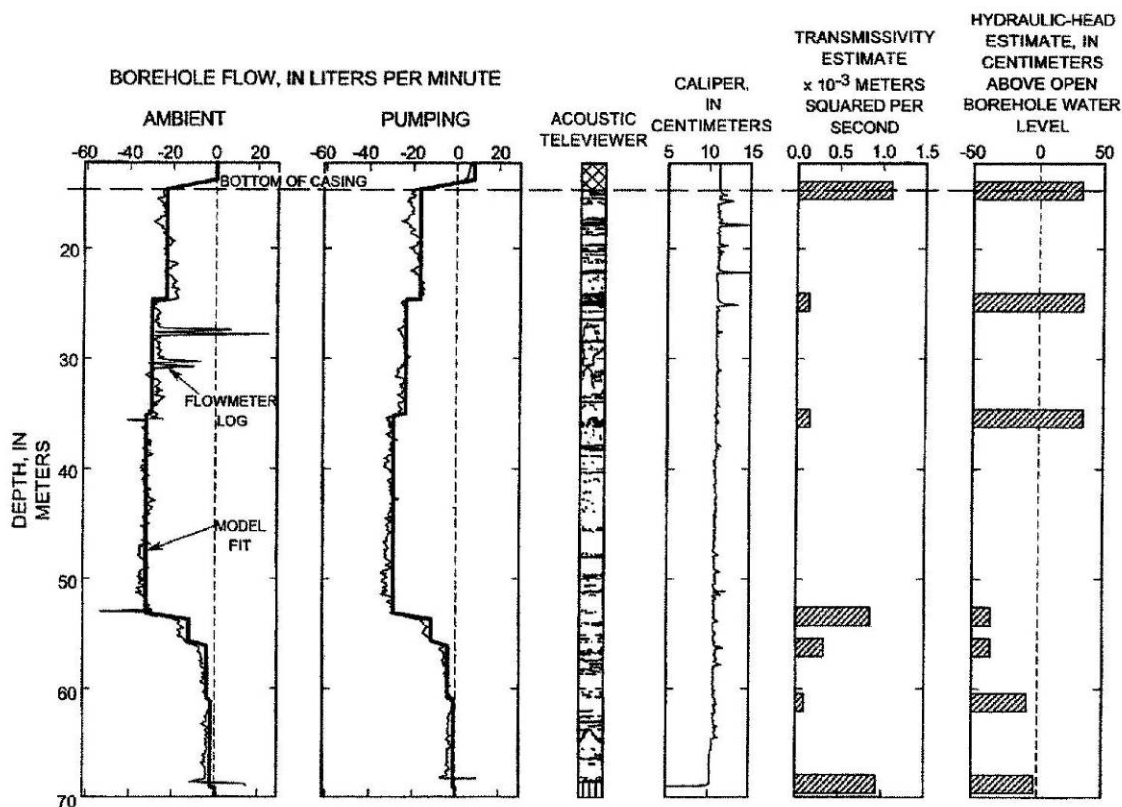


Figure 4.8-2: EM flow meter profiles and derived hydraulic parameters for a limestone aquifer in Minnesota.

4.9 Cross-Borehole Testing

Cross-borehole flow testing involves pumping from one borehole and making flow measurements in other nearby boreholes. The objective of cross-borehole testing is to assess the flow system on a larger scale than can be achieved by testing in a single borehole. Because boreholes provide access to the formation for hydraulic testing, the local properties of individual fractures always influence the ability to characterize the large-scale properties of the aquifer. For example, an observation borehole will fail to show any drawdown at all if it has no connection to the fracture network even when in the immediate vicinity of the pumped well. Borehole flow logs can address this problem through definition of a local annular boundary zone separating the observation borehole from the surrounding rock mass. The large-scale hydraulic features of the rock influence the water level and flow within the borehole whenever and wherever regional drawdown is applied to the outer edge of the discrete flow zones intersected by the observation well. The character of these discrete zones also influences the measured flows and drawdown in the observation borehole.

The annular borehole boundary layer concept is used to develop a methodology, based on cross-borehole flow logging, for delineating fracture connections within the surrounding rock. The method uses a simple flow log model to match the flow induced in an observation borehole by pulses of pumping or injection in a nearby borehole (Paillet, 1998; Williams and Paillet, 2002). Flow data are collected by repeating the cycle of pumping and recovery with the flow meter stationed progressively at locations between and then above all producing zones in the observation borehole. The results provide an independent set of data for N stations in a

borehole containing N producing zones, such that there is always as many data sets as there are unknowns in the analysis no matter how many zones intersect the observation borehole. The analysis is based on recognizing a series of type curves representing different geometries for fracture connections. The shape of the measured flow response allows selection of the type curve. The specific model with the specified connections in the region between boreholes is then run until a given set of parameters (T and S values for fracture segments in the system) causes the model to match the data sets. The model also predicts the transient drawdown in the observation borehole which can also be compared to water-level data obtained during the experiment.

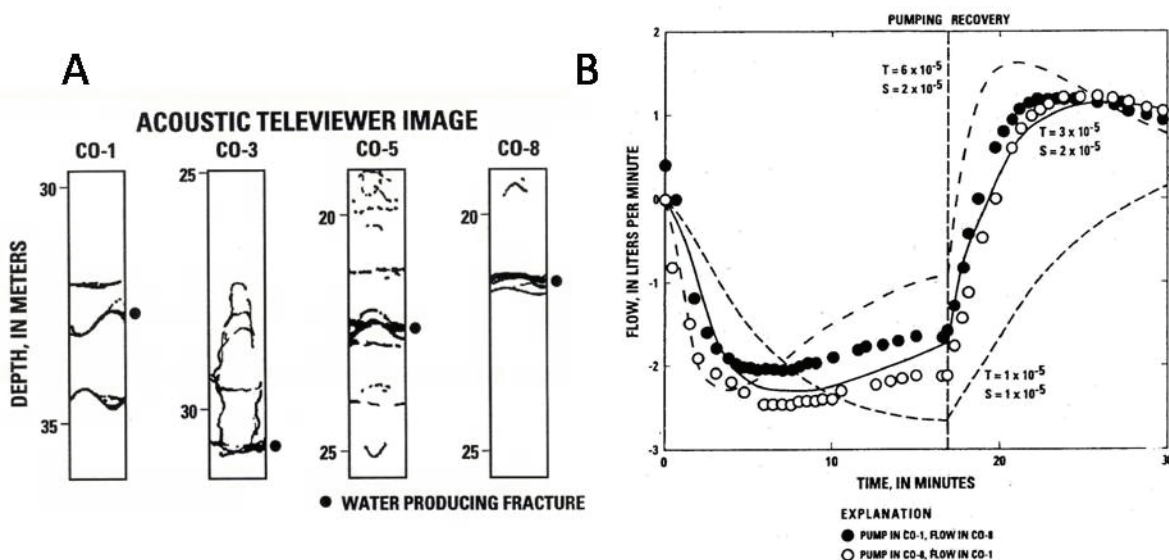


Figure 4.9-1: Cross borehole flow experiment example.

Cross-borehole logging produces results that are, in principle, similar to flow tomography, where straddle packers are used to isolate a single zone in each of the boreholes (pumped and observation). When each such pair of zones has been so tested, tomographic modelling can be used to characterize the flow paths between the boreholes. The one problem with this approach is that packer testing requires elaborate equipment and extensive test periods. If there are only 5 zones in each borehole, this indicates 25 separate tests will be required. While cross-borehole testing is no substitute for flow tomography, the results of cross-borehole tests can be very helpful in designing subsequent aquifer tests so that they address the relevant hydraulic connections at the field site.

In the example shown on Figure 4.9-1, a cross borehole flow experiment was conducted in an array of four boreholes where flow is a result of steeply dipping fractures (A) but the cross flow transients (B) indicate that the fracture zone responds as a single sub-horizontal fracture zone characterized by a single value of transmissivity and storage coefficient.

4.10 Verification of Flow Log Results with Packer Testing

The one obvious drawback with all classes of borehole flow logging is that the logs are obtained in an open borehole. This means that inflow from or outflow to relatively minor zones can go unrecognized within the scatter inflow attributed to more productive zones (Figure 4.10-1).

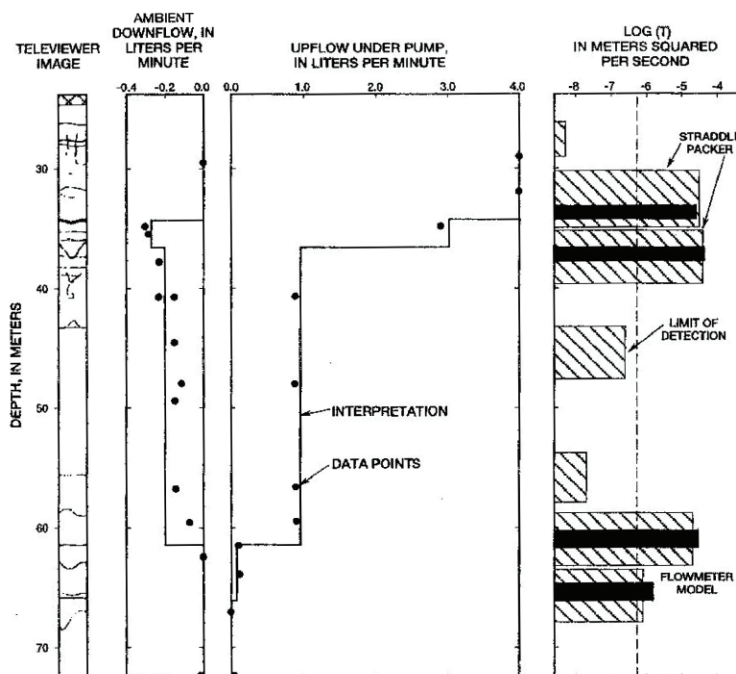


Figure 4.10-1: Comparison of packer test and HPFM logging results from Mirror Lake, NH.

Careful comparison of quantitative estimates of transmissivity from flowmeter analysis and straddle-packer hydraulic tests in the same borehole show reasonable agreement for the most productive zones (Paillet et al, 1998). But these results do show that less productive zones can be overlooked. Careful comparison of T values given by packer tests and T values of zones detected with the flow meter shows that slightly less than two orders of magnitude can be discriminated (Figure 4.10-2).

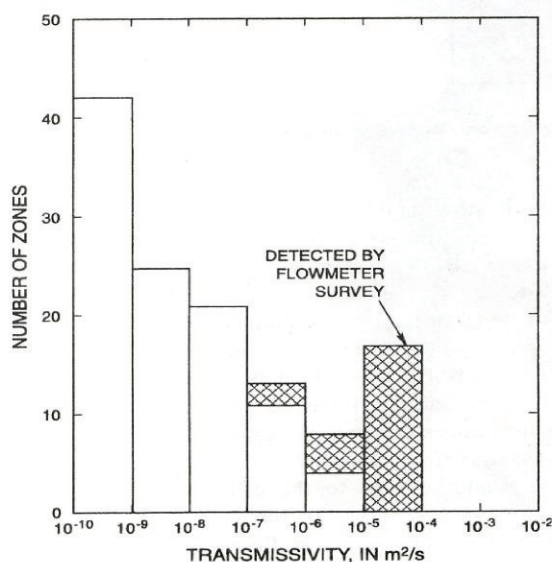


Figure 4.10-2: Comparison of fracture transmissivity by HPFM log analysis vs. straddle packer tests at Mirror Lake, NH.

Most zones with T values given by the packer tests that were two orders of magnitude less than that of the most transmissive zone were almost all undetected and uncharacterized by the flow log analysis.

Although straddle packer tests get around the requirement to test individual zones within a flow field influenced by other zones, they are both time-consuming and equipment intensive when performed in the field. Another major drawback is that packer work is rarely done at the same time as the open borehole logging. If considerable time elapses between the logging and the packer work, the hydraulic conditions are likely to have changed, making it difficult to compare the two data sets. This problem could be alleviated by using wire-line operated packer systems that can be run off of conventional logging cable at the time of logging. A few such prototype wireline packer systems have been demonstrated (Paillet et al, 1998), but the equipment is not generally available.

4.11 Summary

Applicability to Programme

Flow profiles produced by flow logging, and especially high-resolution flow logging methods are highly applicable in the characterization of the hydraulic properties such as permeability and hydraulic head distribution; this kind of direct hydraulic information is not provided by any other geophysical logs. The methods are applicable to crystalline or massive sedimentary rocks (assumed to be of negligible porosity and matrix permeability) where fracture networks dominate the flow system. Impeller flow meters are most applicable in high flow regimes (> 25 L/min), by contrast, the heat pulse flow meter, Posiva flow log or hydrophysical logging techniques are best suited to low flow regimes (< 25 L/min).

Processing and QA/QC

Processing and QA/QC for specific methods were discussed in previous sections. In general, ambient, and at least one steady pumping/injection profile, should be obtained for each borehole; and transducer records should be obtained of open borehole water levels during the logging. If a steady pumping rate cannot be maintained due to low formation permeability, the stressed part of the logging should be run under a quasi-steady drawdown condition. Data should be calibrated so that the pumping/ injection in the profile equals the known pumping/injection rate; or the measured rate of recovery if it is a constant drawdown test.

Accuracy and Resolution

Although dependent on borehole conditions, high-resolution flow logging can detect flow as low as 0.1 l/min. The ability to resolve consistent changes in flow rate depends on borehole conditions, but is in the range of 0.1 to 0.5 l/min for reasonably smooth boreholes.

Limits and Constraints

Flow logging can be performed under a wide range of conditions, and there are ways to deal with complications such as high ambient flows, low formation permeability or great depth to water level.

Strengths and Weaknesses

The primary strength of flow logging is the direct characterization of hydraulic response in situ. The primary weakness is the inability to detect inflows from zones with transmissivity two orders of magnitude less than that of the most transmissive zone.

Potential to Combine Methods

Flow logging cannot be combined with other methods, but the interpretation of flow logs is done in conjunction with any and all methods that can be used to characterize stratigraphy, rock properties and structure / fractures.

Commercial Availability

High resolution flow logging services are available in North America from a number of specialist geophysical logging / consulting engineering firms, including Golder Associates and Colog Inc., for example.

5. BOREHOLE GEOPHYSICAL METHODS III - SEISMIC RADAR AND EM

This chapter presents borehole seismic, ground penetrating radar (radar) and electromagnetic geophysical methods that can be used to characterize potential deep geological repository candidate sites. The tools and techniques described in this chapter include:

- Borehole Seismic Methods
 - Conventional Sonic Logs
 - Shear Velocity Logging
 - Full Waveform Logging
 - Tube Wave Logging
 - Cement Bond Logging
 - Seismic Tomography
- Vertical Seismic Profile (VSP) and Cross-Hole Seismic Reflection
- Borehole Radar
- Borehole TDEM
- Cross-Hole EM

Methods of analysis and interpretation of these data are presented and discussed, including the following key aspects:

- Applicability to Programme
- Processing and QA/QC
- Accuracy and Resolution
- Limits and Constraints
- Strengths and Weaknesses
- Potential to Combine Methods
- Commercial Availability

5.1 Fundamental Principles

Borehole seismic logs (Hearst et al, 2000; White, 1983) are obtained by measuring the rate of propagation of an acoustic pulse along a borehole, where the pulse originates from a source located at one end of a probe and the propagation of the pulse is measured by recording the propagating wave arrivals at a series of detectors (generally denoted as receivers) located at various distances along the exterior of the probe. A minimum of two such detectors is required because the travel time for the pulse involves propagation in both the fluid-filled annulus around the probe and the borehole wall outside of that annulus. A single receiver would record a pulse arriving along a path involving travel in both fluid and formation. If the time-of-travel of the pulses is determined at two receivers, the difference between those arrival times depends only on the portion of the travel in the borehole wall.

The source pulse generates both compression (P) wave and shear (S) wave motion in the surrounding rock, although the source energy itself is applied to the borehole fluid column which cannot support shear waves (Paillet and Cheng, 1991). The measured signal at the receiver can be obtained in the acoustic or “sonic” logging mode where the probe electronics detect only the first arrivals and the probe output represents the inverse of the compression wave travel time in the formation ($1/V_p$ where V_p is the compression wave velocity in m/s and the receiver separation is 1 m); or in the full waveform mode, where the entire pressure signal is recorded for

each receiver. With reference to Figure 5.1-1, the main modes of wave propagation in the borehole (in order of relative arrival time) are P waves, S waves and Tube waves. Tube waves are discussed in more detail later in this Chapter.

Full waveform sonic logs have sometimes been treated as a borehole version of surface seismic refraction or reflection surveys. Unfortunately, there are fundamental differences between surface and borehole seismic surveys that render almost all of the surface seismic interpretation methods invalid. This fundamental difference results from the fact that the borehole seismic methods are applied inside an acoustic resonator or waveguide (Paillet and White, 1982; Hornby et al, 1989), where constructive interference of a select subset of frequencies from within a given source spectrum determine the character of the propagating waves (Schmitt and Bouchon, 1985).

In hard rocks (defined as those in which the shear wave velocity is substantially greater than the compression wave velocity of the borehole fluid), propagating waves are separated into modes associated with specific forms of constructive interference. Compression and shear head waves propagate through the formation surrounding the borehole at velocities exactly equal to the V_p and V_s of the formation. An additional series of modes (normal modes and Stoneley waves) propagate at slower velocities but generally have greater amplitude than the head waves. These modes are characterized by dispersive velocities such that broadening of the pulse reflects more than just intrinsic attenuation of the waves (Figure 5.1-1). Although not dispersive, the P and S head waves are also separated into wave packets associated with spectral peaks defined by interference effects. Both conventional sonic and full waveform logs are therefore strongly influenced by the interaction between source frequency content and the borehole waveguide.

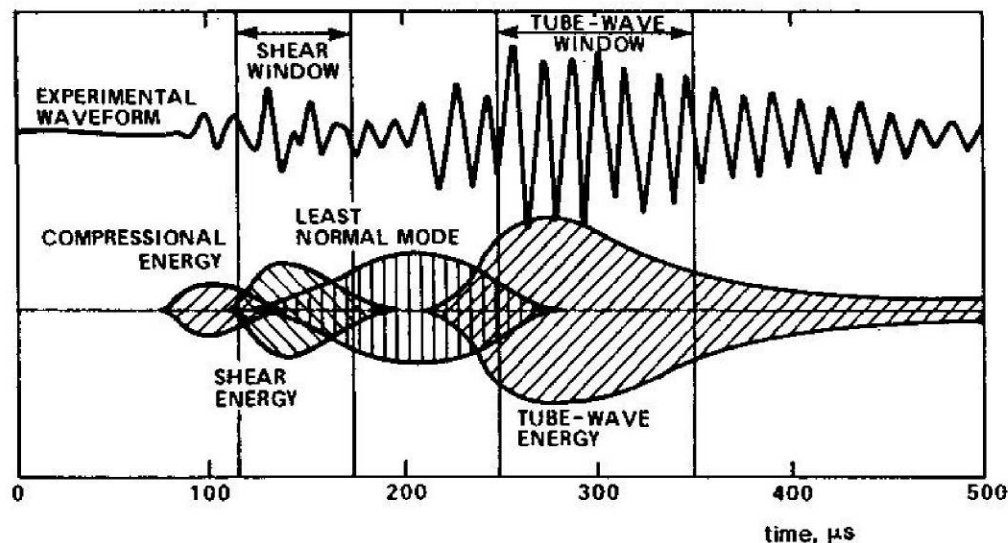


Figure 5.1-1: A typical borehole seismic waveform, wave modes and relative amplitudes in the Lac du Bonnet granite batholith, AECL URL site.

Most analysis methods depend on selecting a single wave mode from within the array of possible modes and their multiples (Paillet and Cheng, 1986). Selection of a specific mode or head wave band depends on both the seismic velocities of the formation and the geometry

(diameters of borehole and logging probes) so that one specific source spectrum cannot serve all logging applications.

5.2 Conventional Sonic Logs

In hard sedimentary and crystalline rocks, both V_p and V_s can be measured by detecting the appropriate arrivals in recorded waveforms (Hearst et al, 2000; Wyllie et al, 1956). An array of receivers allows tracking of coherent propagation of these arrivals along the borehole. The coherence and amplitude of the arrivals make this a robust measurement approach. The conventional sonic log is produced by picking the first (compression) arrivals at two or more receivers and then computing the slowness (transit time) for the P wave along the array. The sampling depth of this log is proportional to and slightly greater than the wavelength (λ) of the signal in the formation:

$$\lambda = V_p/f$$

where V_p is the compression wave velocity and f is the frequency. Since acoustic log frequencies vary from 5 to 35 kHz, the sample depth for acoustic logs varies from about 0.2 to 2.0 meters. One consequence of this scale is that the log measures compression velocity within the annular zone of modified stresses associated with the borehole opening. In massive, unfractured bedrock, the compression velocity is considered a constant property of the rock with the exception of a slow and steady increase in velocity with depth associated with increases in confining pressure, as shown for the Lac du Bonnet granite batholith at the AECL URL site near Pinawa, Manitoba (Figure 5.2-1).

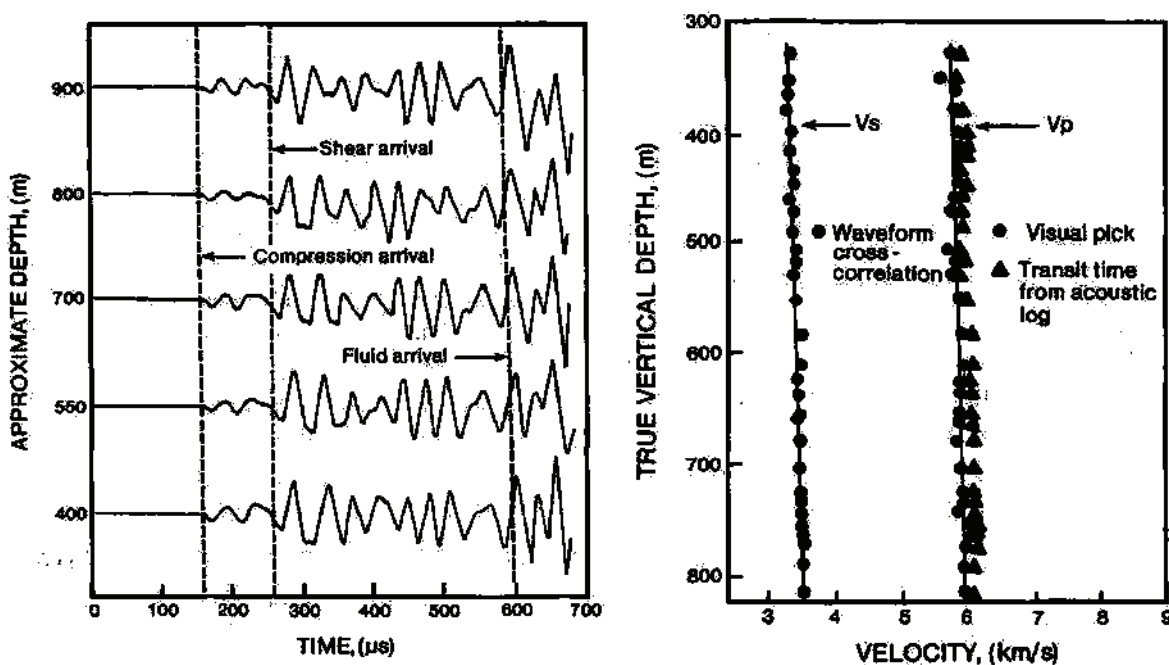


Figure 5.2-1: The effect of confining pressure on V_p and V_s , AECL URL site.

The transit-time data can be plotted as a measure of the mechanical strength of the formation (Young's modulus) (White, 1983; Wyllie et al, 1956) or of the small variations in velocity associated with variations in lithology. Many sonic log applications described in the literature are based on relating transit-time to porosity for a formation composed of mineral grains and water-filled pore spaces. Such an interpretation obviously does not work for massive rocks except in the case of consolidated sedimentary rocks where there is significant matrix porosity.

In the case of fractured sedimentary rocks, sonic logs are sometimes used to distinguish between primary and secondary porosity. This is based on the assumption that sonic logs measure primary porosity independent of secondary porosity because first arrivals travel around rather than across large-scale openings. A comparison between sonic and neutron porosity logs, for example, could be used to determine the ratio of primary to total porosity in the narrowly defined circumstances where the assumption built into the analysis are shown to apply.

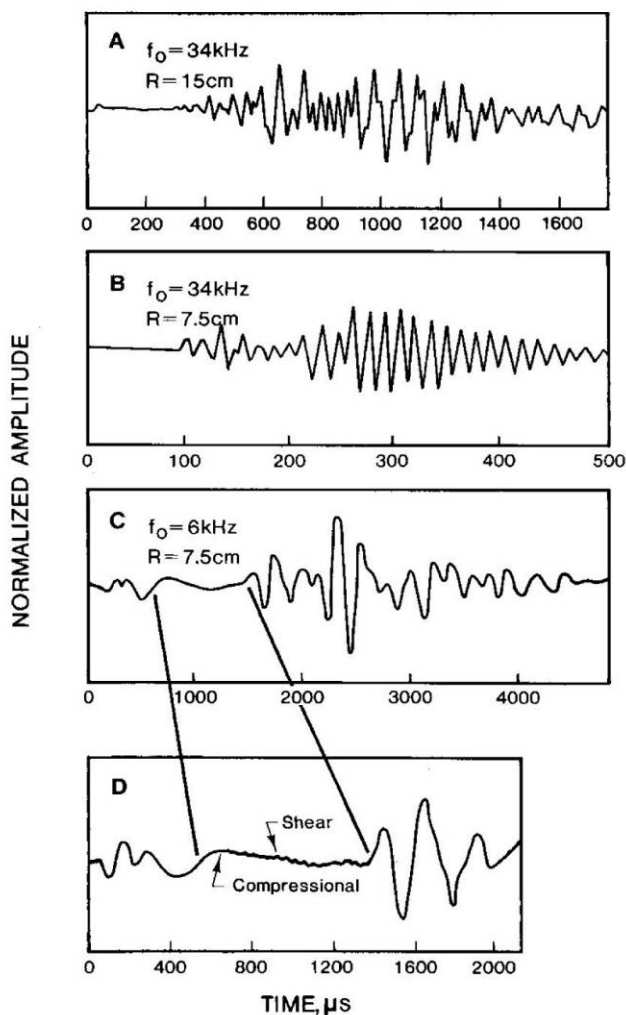


Figure 5.2-2: The effect of source frequency (f_0) and borehole diameter (R) on sonic log response.

Considerable operator experience is required in obtaining good sonic logs because the gains and frequency settings need to be determined for the specific borehole environment and lithology (Keys, 1997; Paillet and Cheng, 1991). The arrival picking algorithm in the logging system is based on recognizing the move-out of a consistent phase in an oscillatory signal. If the source frequency band and system gain are properly set, a simple sinusoid-like signal will systematically shift forward in position along the array. If the frequency band is broad enough to include more than one P-wave spectral peak, the signal will appear as an irregular interference with little obvious coherence along the array (Figure 5.2-2). Sophisticated sonic logging systems provide a broad-based source and the ability to filter the response to include a small band within that source band. Other systems provide the option to use different sources with

different frequency content. As a rule of thumb, sonic logs in hard rocks should be run so that the compression wavelength (λ_{vp}) is two to four times the borehole diameter. Obviously, selection of frequency content is an important part of the design of an acoustic full waveform logging program.

Even the most expertly run sonic logs will not characterize formation properties in fracture intervals where scattering and attenuation severely affect arrival picking. This inability to define a first arrival results in the system picking a later part of the signal as the first arrival, a process known as cycle skip. There is a temptation to interpret the increases in transit time within zones where cycle skip occurs as a representation of the reduced P-wave velocity of altered and fractured rock. In fact, there is probably no real information in this part of the log beyond the general correlation between extent of fracturing or borehole enlargement and signal attenuation (Hearst et al, 2000).

Sonic logs are typically run in open fluid-filled (mud or water) boreholes at logging speeds ranging from 3 to 10 m/min. Vertical resolution is related to source-receiver separation, and is typically on the order of 1 m. The typical accuracy of V_p measurements are approximately +/- 5% with a resolution of +/- 1%.

5.3 Shear Velocity Logging

In hard sedimentary, igneous and metamorphic rocks, acoustic sources generate both compression and shear head waves that can be detected in properly conditioned acoustic full waveform logs (White, 1983). Shear wave arrivals can be recorded by sonic logging in a fluid filled borehole because some of the shear head wave energy changes mode to compressional wave energy and is detected at the receiver(s). A typical example of waveforms from a massive crystalline rock formation is shown on Figure 5.2-2 with shear velocity picked from the prominent shear arrivals evident in the waveforms. The elasto-mechanical properties of an isotropic solid are determined by two constants (Young's and shear moduli, for example). The combination of compression and shear velocities and rock density are therefore sufficient for the characterization of the mechanical properties of isotropic rock. White and Tongtong (1981) deal with the generally much more complicated interpretation of the mechanical properties of non-isotropic rocks, which is otherwise beyond the scope of this report.

The consistent phase and amplitude shift associated with the shear arrival can be picked in waveforms using applications based on algorithms such as semblance processing (Paillet and Cheng, 1991). The shear component measured is horizontal shear where motion is in the plane orthogonal to the assumed vertical orientation of the borehole axis. Some references in the literature recommend the use of non-axisymmetric sources to provide more effective excitation of shear waves (Chen, 1987, 1988). These sources excite wave modes that depend on shear velocity and can be used in relatively soft formations where the shear velocity is less than the acoustic velocity of the borehole fluid. This is obviously not a problem when logging hard rocks. The non-axisymmetric logging source has the disadvantage that the modes traveling along the borehole are slightly dispersive so that the propagation velocity of the mode is slightly different from the formation V_s . One specific version of non-axisymmetric shear logging (suspension logging; Kitsunzaki, 1980) has been available for two decades but is designed for use in poorly consolidated sediments and has no useful application in well consolidated formations.

Shear velocity data is derived from full waveform sonic data, which are typically run in open fluid-filled (mud or water) boreholes at logging speeds ranging from 3 to 10 m/min. Vertical

resolution is related to source-receiver separation, and is typically on the order of 1 m. The typical accuracy of Vs measurements are approximately +/- 5% with a resolution of +/-1%.

5.4 Full Waveform Logging

The entire waveforms (i.e. traces of amplitude versus time at a series of discrete depths down the borehole) recorded by full waveform logging systems provide a useful qualitative indicator of rock quality (Paillet, 1980). This information is displayed by plotting the waveforms from a receiver alongside other logs such as televiwer in a composite display (Figure 5.4-1). In that example, acoustic waveforms are correlated with televiwer logs, illustrating the effects of sub-horizontal and near-vertical fractures on acoustic propagation along the borehole; the distortion in waveforms above and below the fractures on Figure 5.4-1 indicates the degree to which fractures have affected rock properties in the vicinity of the fracture faces.

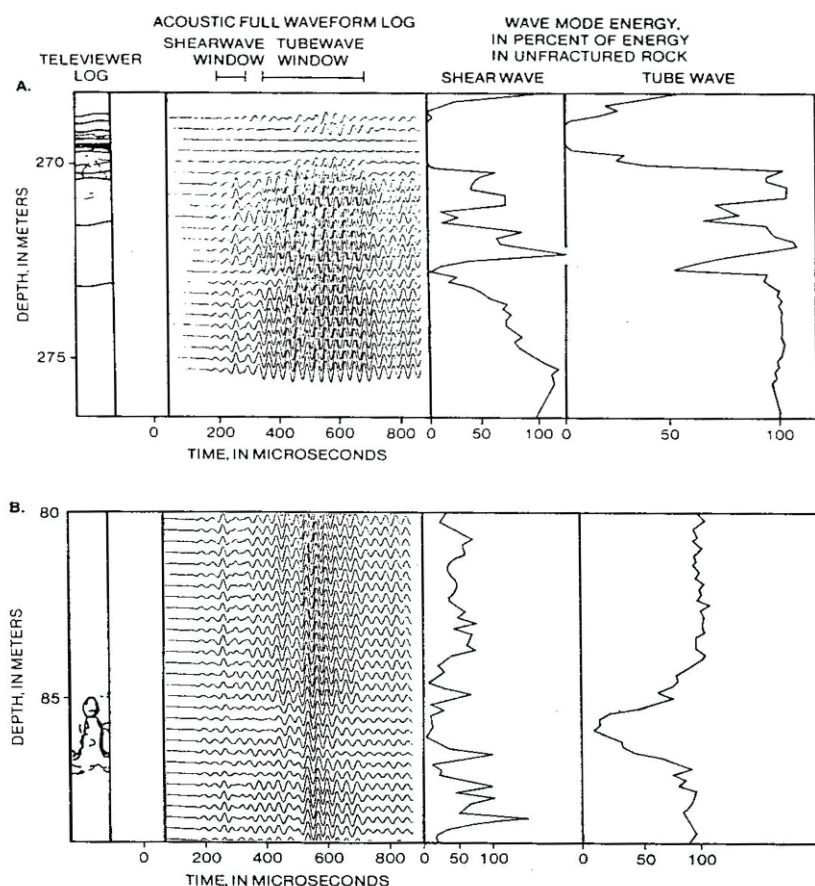


Figure 5.4-1: Correlation of acoustic logs to televiwer log response.

The closest spaced receiver data is generally used because it provides the best vertical resolution. These displays are useful in identifying fractures and fracture zones even if the data are difficult or impossible to analyze to derive specific mechanical and hydraulic properties.

Full waveform logging has similar borehole requirements, accuracy and resolution as conventional sonic logging.

5.5 Tube Wave Logging

The fundamental dispersive mode of wave propagation in boreholes is known as a tube or Stoneley wave (Figure 5.1-1). A tube wave is an axisymmetric pulse that travels along the borehole at a velocity slightly less than the acoustic velocity of the borehole fluid, and is sensitive to variations in formation permeability as well as changes in borehole diameter and washouts. Tube waves can be excited with substantial amplitude at very low frequencies where none of the other waves are excited.

The relationship between borehole wall permeability and tube wave amplitude is based on one of the following mechanisms:

- 1) Reflection of a propagating tube wave from a fluid-filled opening transverse to the borehole (Hornby et al, 1989);
- 2) Attenuation of tube wave propagation across irregular shaped but otherwise permeable openings (Paillet, 1983; Burns et al, 1988); and
- 3) Generation of tube waves by seismic waves in the formation when they squeeze permeable fractures or bedding planes where they intersect the borehole (Harden et al, 1987).

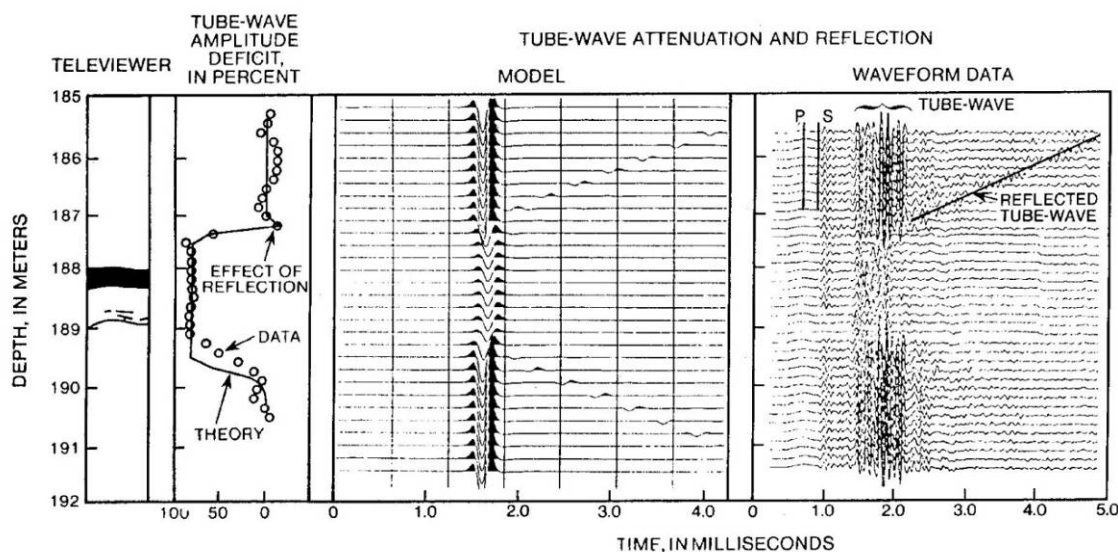


Figure 5.5-1: Example showing that tube wave reflections are more pronounced for low frequency energy sources.

Reflection is generally detected by waveform logs at relatively low frequencies ($< 5\text{kHz}$) such that tube wavelengths are much greater than fracture width (Figure 5.5-1). Attenuation is most apparent on waveform logs at relatively high frequencies (above 10 kHz) (Figure 5.5-1). Tube waves produced by passing seismic waves are generally encountered in VSP studies, where the orientation of wave propagation and the angle of the fracture to the borehole as well as fracture permeability influence the amplitude of the tube waves traveling along the borehole (Figure 5.5-2).

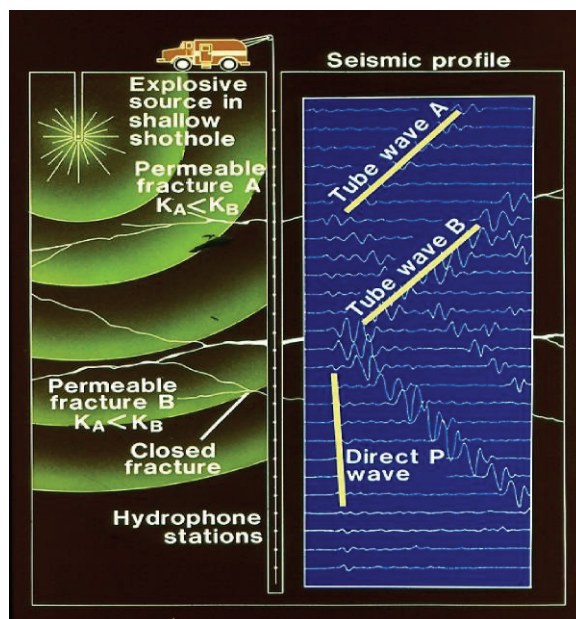


Figure 5.5-2: Schematic showing tube wave generation in a borehole by a compression wave source at surface.

Although various models have been developed to relate tube wave amplitude or tube wave reflections to fracture aperture, most studies use an empirical relation between tube waves and direct measurement of fracture transmissivity (vertically integrated product of permeability and zone thickness) to estimate fracture permeability and tube wave amplitude logs (Figure 5.5-3). In the few studies where the different applications of tube waves have been compared, the scale of investigation is shown to influence the results.

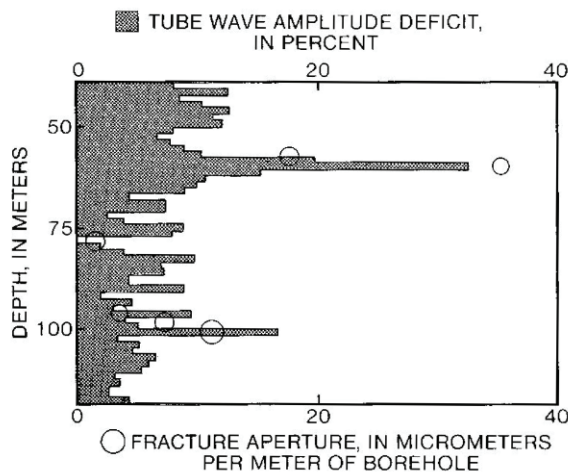


Figure 5.5-3: Tube wave attenuation (amplitude deficit) correlated to increased fracture intensity in a rock mass, AECL Chalk River site.

VSP tube wave generation (frequency less than 100 Hz) is shown to indicate the properties of the largest and most laterally extensive fractures, tube wave amplitude (frequency greater than 10 kHz) detects permeability in a number of discrete fractures indicated on the televiewer and

caliper log, and tube wave reflection (frequency about 5 kHz) detects permeability associated with a few of the largest isolated fractures on the televiewer log.

5.6 Cement Bond Logging

One specialized application of full waveform sonic logging is the testing of the integrity of the casing seal to the formation, known as cement bond logging (Figure 5.6-1).

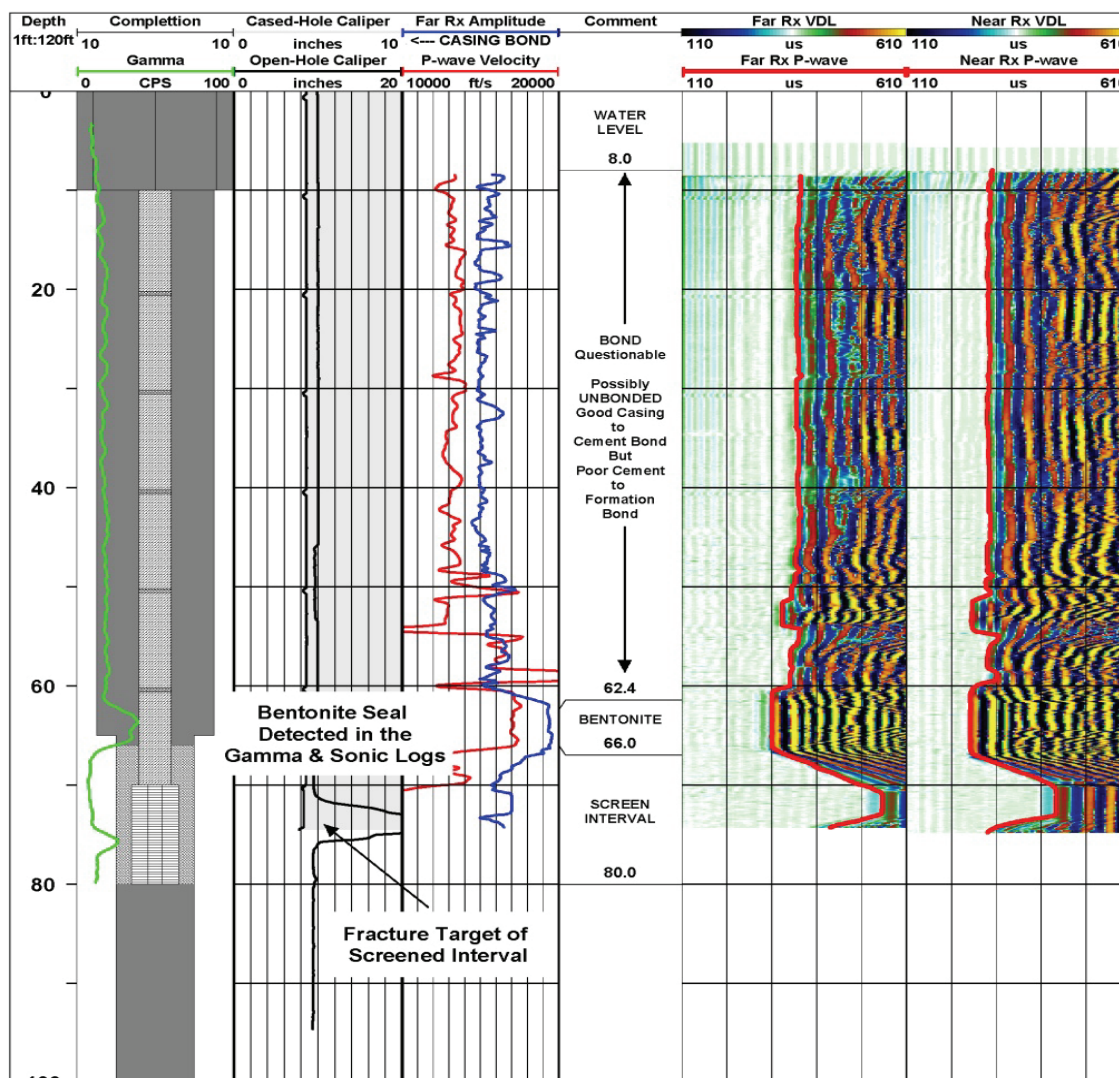


Figure 5.6-1: A cement bond log example. (Golder Associates)

In cement bond logging, the sonic waveform traces versus depth are displayed as a colour or shaded amplitude plot, rather than a wiggle plot. The display is then used to identify sections where the casing is not well bonded to the formation, based on looking for intervals where the seismic signal is “ringing”. A well bonded casing will produce a seismic signal that approximates the signal obtained in the open borehole. Refer to Section 6.6.1 for further discussion.

It should be noted that the response is averaged around the circumference of the casing, so that the signal is not sensitive to the presence of channels aligned along only a small fraction of the entire borehole circumference.

Cement bond logging has similar accuracy and resolution as conventional sonic logging.

5.7 Seismic Tomography

Seismic tomography uses an energy source in one borehole and a series of receivers in an adjacent borehole to image velocity structure in the region between the two boreholes. A typical survey consists of moving the source along the borehole at 1m intervals from top to bottom in the source borehole and collecting seismograms at each source location. Receiver data would be collected along the entire length of the receiver borehole using a multi-channel array. This typically requires many seismograms to be collected, depending on the receiver array size and spacing, and the length of the receiver borehole.

The P (or S) wave arrival times are picked for each seismic trace collected for each source-receiver combination, and the 3D position data for all stations in the two boreholes is determined by a survey. The arrival times and survey data are then fed into an inversion algorithm (typically a least-squares method), which computes the rock velocity distribution in the region between the boreholes. Two example inversion programs for engineering applications are GeoTomCG (from GeoTom LLC) and GeoCT-II (from GeoTomo LLC). Seismic tomography performed on a local scale can serve to expand outward the information already provided by waveform and sonic logging.

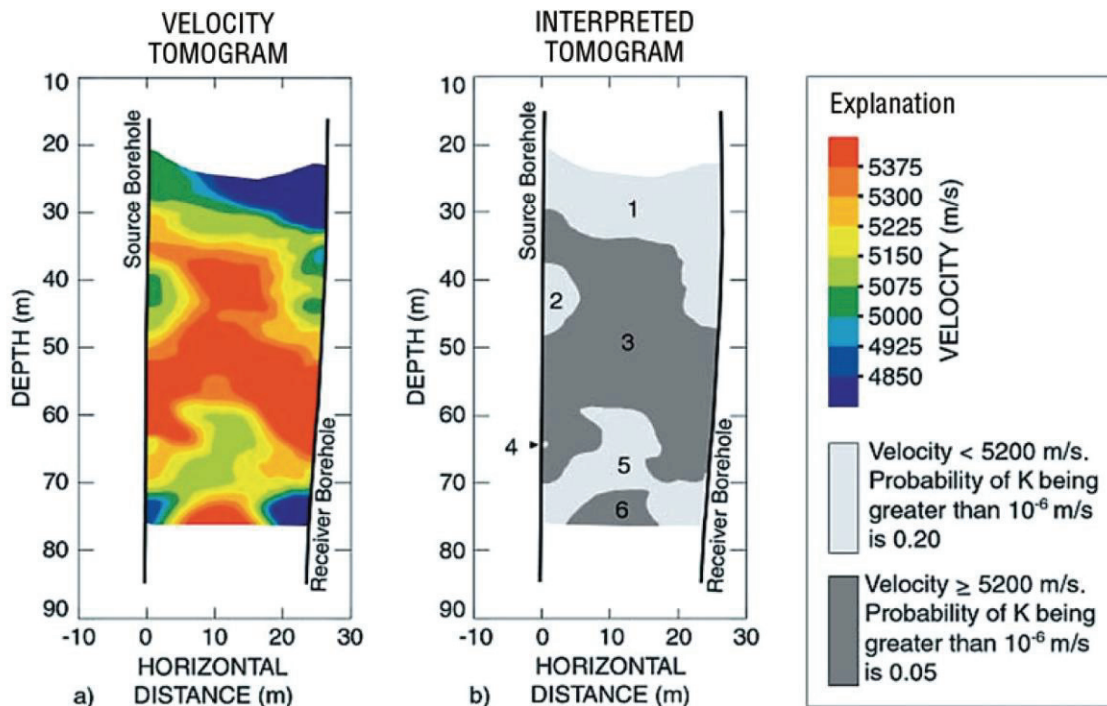


Figure 5.7-1: Seismic tomography example from the USGS Mirror Lake, NH site.

As an example, the tomogram between two boreholes at the USGS Mirror Lake, NH site (Figure 5.7-1) shows an irregular region of lower velocity (ex: zone 5 in 5.7-1b) that is interpreted to be the outward extension of a permeable fracture zone identified on other geophysical logs in the receiver and source boreholes.

A seismic tomography survey has a spatial resolution on the order of the spacing used between borehole sources and receivers, but it also influenced by the frequency characteristics of the source signal. The geometry of the set of source-receiver raypaths used to create the tomogram also influences the resolution and accuracy of the result. In cases where there is a high velocity contrast, some first arrivals may be critically refracted events and not direct arrivals, which can also introduce errors into the tomogram. Given that hundreds or even thousands of traces need to be collected in most surveys, seismic tomography is time consuming and somewhat expensive in comparison to conventional wireline logging surveys.

5.8 Borehole Seismic Summary

Applicability to Programme

Seismic velocity measurements and seismic imaging techniques are very applicable to site characterization programmes in both sedimentary and crystalline rock environments. Seismic velocities of crystalline and sedimentary rocks are closely related to the mechanical properties of such rocks, and can be highly relevant to geomechanical studies. Seismic velocities obtained in boreholes can be important in evaluating results from surface seismic surveys, and seismic tomography can be used to extrapolate fracture zones out into the surrounding rock mass. Some specialized applications of acoustic logs in boreholes can be used to estimate formation permeability. The method also is used to derive compression and shear wave velocities for estimation of engineering properties such as Poisson's Ratio and Young's, bulk and shear moduli.

Processing and QA/QC

Processing and QA/QC for specific methods was discussed in previous sections. An experienced operator is needed to insure that frequency bands and gain setting are properly selected to run either conventional sonic or full-waveform acoustic logs. Subsequent processing to obtain compression velocity is straightforward and shear velocity can be obtained with readily available software.

Accuracy and Resolution

Sonic logs provide highly accurate estimates of formation V_p at the logging frequency, but this value needs to be adjusted for velocity dispersion before comparing with values derived at lower frequencies from surface reflection or refraction. Seismic velocities obtained from acoustic logs can be converted to such elastic properties as Young's modulus or shear strength, but empirical relations are needed to relate these dynamic values to the static values that would be recovered from engineering tests.

Borehole acoustic logging equipment needs to be selected to provide the proper frequency response in a given borehole, which depends on both rock properties and the diameters of the borehole and probe.

Strengths and Weaknesses

The strength of acoustic logging lies in the direct relationship between seismic velocities in situ and the geomechanical properties of the formation. The primary weakness lies in the need for an experienced operator to recognize an acceptable signal and to insure that the logging

equipment used is appropriate for the given borehole environment. The separation distance between boreholes for seismic tomography is in the range of 10's of metres, which limits its application to small-scale, localized investigations.

Potential to Combine Methods

There is little opportunity to combine this tool with others during acquisition, although sonic data is used in conjunction with other log data for interpretation, as illustrated in Chapter 6.

Commercial Availability

Most logging companies will include sonic logs as part of their service offering and many equipment manufacturers produce sonic tools in a variety of formats. The suppliers of slim-hole sonic tools in North America include: Century Geophysical Corp., Mount Sopris Instruments Co. Ltd. and Robertson Geologging Limited.

Seismic tomography surveys are more specialized and are only available from a small number of specialty contractors and consultants.

5.9 Vertical Seismic Profiling

5.9.1 Fundamental Principles

Vertical seismic profiling (VSP) is a seismic imaging method that employs a surface source and receiver array in a borehole (Figure 5.9-1). The receivers can be geophones or accelerometers to record particle motion or hydrophones to record pressure, or in some cases, both reside in the same down-hole array. The seismic source(s) are typically repeatable vibrators on surface or piezoelectric in shallow, offset, source-boreholes.

By far the greatest use of VSP is in sedimentary environments for the analysis of coherent reflections from stratified rock sequences. VSP usage is far less common in crystalline rock environments because stratified sequences are generally not present in the rock, although the VSP method can be used to identify fracture zones. The main focus of this discussion on VSP is its application to sedimentary rocks.

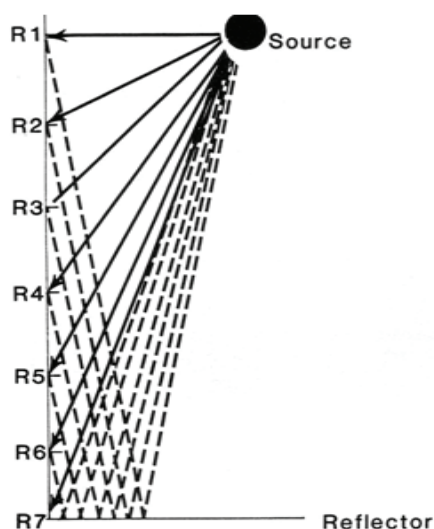


Figure 5.9-1: Source-receiver geometry in the VSP method (direct arrivals shown as solid lines and reflected arrivals as dashed lines).

Advances in VSP surveying can be traced to continuous development of down-hole receivers and those advances have occurred in all engineering aspects of the down-hole system including number of receivers, clamping force of each receiver, depth at which receivers can be deployed, data transmission rate to the surface and orientation limitations on three-axis sensors.

The VSP technique records both the down-going and up-going wavefields, therefore the interaction of the down-going wavefield with formation features (interfaces, fractures, faults, etc.) is observed directly when the borehole containing the receivers intersects those features. VSP surveys are therefore used to “tie” reflections (Figure 5.9-2) seen in surface seismic data to originating interfaces in true depth. Without VSPs, it is necessary to attempt to tie a low frequency surface seismic reflection data set to a high frequency sonic log or full waveform log from the borehole through the convolution of those logs with a selected wavelet.

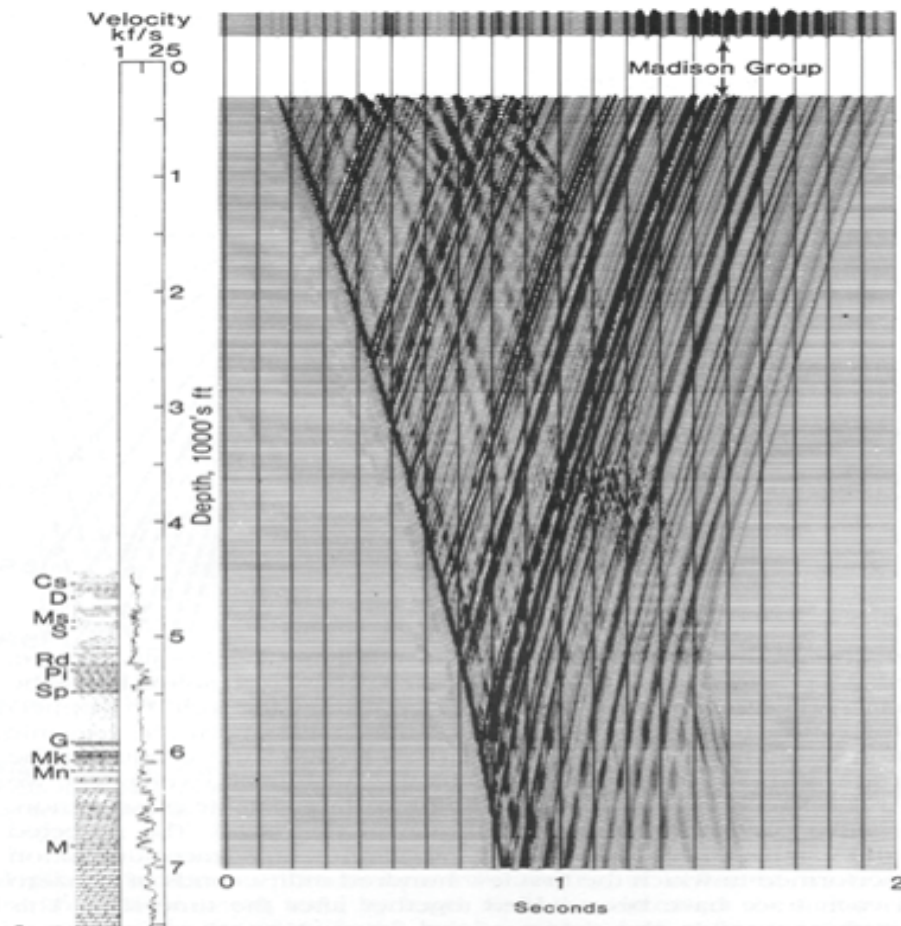


Figure 5.9-2: Example of VSP data (center), borehole log data (left) and surface seismic reflections (top) for the Madison Group.

Although the logs are measured in depth, the uncertainty of that “selected” wavelet and the absence of attenuation in this processing method makes this technique of tying surface information to borehole information difficult. The sources used in the VSP method are the same as that used in conventional surface seismic reflection imaging. These are low frequency (10-150 Hz) sources and the fact that the down-going ray paths must pass through the near surface layer means that VSP data is not much higher in frequency content (factor of 2 or 3) than conventional reflection data. The difference between this frequency band and the frequency

band used in cross-well imaging (1-3 KHz) is dramatic and must be kept in mind when selecting a technique for a given exploration/imaging task. To increase frequency content for VSP work, sources equivalent to those used for cross-hole work can be deployed in shallow, offset boreholes.

5.9.2 Reflection VSP Applications

Zero Offset VSP

Vertical seismic profiles are used as the tie between borehole information and surface seismic reflection images. For this purpose it is sufficient to place the source near the well head which yields near-normal incidence reflections from horizontal layers. Once the wavelet parameters of the VSP source are matched to the surface seismic source, a corridor stack from the VSP data can be displayed within the reflection data to tie the reflection data to the borehole data.

Offset VSP

Offset VSPs are used to image the earth a short distance away from the borehole. Here the intent is primarily to image the earth with a little better resolution (2 or 3 times shorter wavelengths) than seen in the surface seismic data and to tie the reflection data to the borehole information. Because the wavelet undergoes large phase changes when the angle of incidence is larger than 40° - 50° (Figure 5.9-3) it is important to keep the source relatively close to the borehole. This, in turn, means that the imaged region extends out from the borehole only to a distance of half the borehole depth.

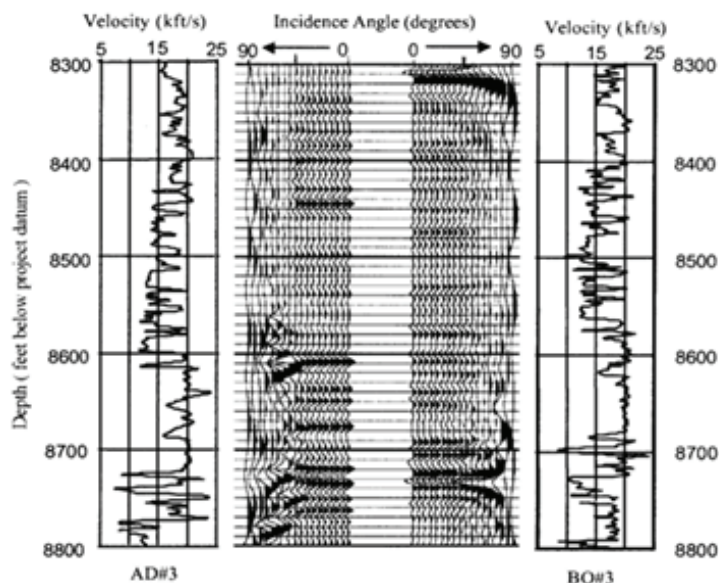


Figure 5.9-3: Synthetic seismograms for varying angles of incidence computed from well logs, showing that reflections produce poor wavelets at high angles of incidence.

3D VSP

If an image all the way around a borehole is desired then sources must be placed in several positions around a borehole. This could take the form of a simple circle of sources around the borehole if an image of one or two interfaces is desired. If it is required to image all of the interfaces from (near) the surface to the total depth (TD) of the borehole, then because of the

phase change problem mentioned above, sources must occupy the entire two dimensional field around the hole out to a distance equal to the total depth (TD) of the borehole.

Walkaway VSP

This is a subset of 3D VSPs. Here the geophone string remains in one position and multiple source positions are used in a straight line away from the borehole. The method was devised especially for offshore VSPs where it was easy to move the shooting boat while raising the receiver string was time-consuming. Moreover, receiver strings contained very few sondes therefore the task of raising the string occurred frequently. Today, with 80 level receiver strings available, the string need not be moved at all, therefore time can be devoted to the deployment of sources in any spatial array desired around the borehole.

Reverse VSP

The arrangement of source(s) and receivers in 3D VSP can be reversed. Many geophones can be placed around a borehole, far more than the number of source locations used in 3D VSP. Today, seismic recording systems of up to 50,000 channels are available and 10,000 channels are common place in hydrocarbon exploration. Furthermore, geophones can be placed in locations where sources are not permitted and in unconsolidated weathered layers it has been observed that the frequency content seen in the reverse VSP exceeds that seen along the same ray path for conventional VSP. However, the borehole source used in reverse VSP must be strong and repeatable.

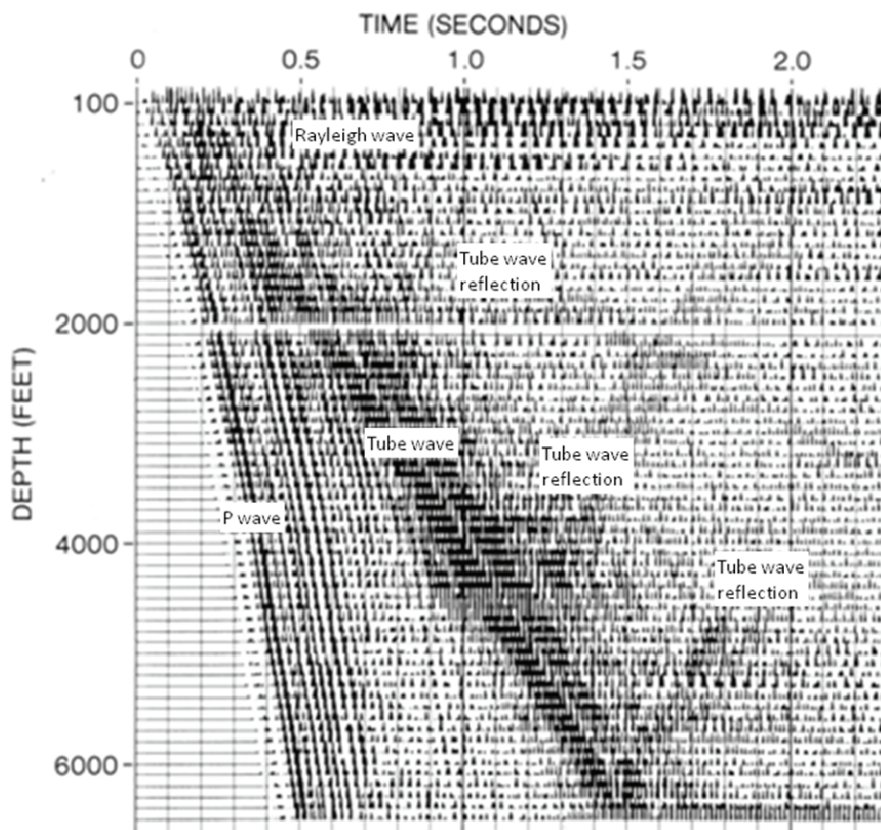


Figure 5.9-4: Raw VSP data showing tube wave interference with compression wave reflections. (DiSiena, Byun and Fix, 1980)

Tube Wave Interference

Rayleigh waves (ground roll) generated by surface seismic sources can induce tube waves in the borehole, with an amplitude that is large enough to interfere with the desired compression wave reflections (Figure 5.9-4). As such, great effort is often exerted to prevent tube waves from being generated or to suppress them after they have been generated, when P wave reflections are of interest in the survey.

Several different techniques are available, including lowering the fluid level in the borehole a distance at least equal to one half a wavelength of the lowest frequency Rayleigh wave. Tube wave reflections themselves can also be useful to identify fractures that intersect the open borehole; this is particularly relevant to crystalline rock environments.

Data Processing

VSP data processing is generally done using software packages designed for surface seismic reflection applications. The main steps generally involve correcting for energy loss in the signal, wavelet shaping (deconvolution), and removing unwanted events, such as down-going events, tube waves and multiples (f-k or median filtering, for example).

Imaging

Once the desired events, usually reflections, are isolated and shaped, the imaging step is one of placing them correctly in space. The simplest version of this operation is CDP (Common Depth Point) mapping which stretches each trace along a curve in (z,t) space and locates reflections from horizontal layers for a constant velocity earth and the particular source location. Migration methods using a variety of ray tracing methods as their forward modelling components (Sena and Toksoz, 1990; Dong and Bleistein, 1990) allow mapping in more heterogeneous media. For 3D VSP the development of imaging techniques is taking place today.

Resolution

In seismic methods, the frequency content of the signal determines the wavelength and therefore the resolving power of that method. Surface seismic reflection surveys provide the poorest resolution and cross-well seismic reflection surveys provide the best. The VSP method lies between the two and closer to the low resolution surface seismic reflection technique.

5.9.3 Tube Wave VSP Applications

If a fracture intersects the borehole (Figure 5.9-5; Figure 5.9-6) it can be the source of tube waves when a body wave strikes it. The search for such fractures can be termed a hydrophone VSP because the receiver string can be composed simply of hydrophones. However, the tube waves are usually strong enough to be seen on clamped geophones or accelerometers.

When the body wave strikes the fracture one can model the ensuing phenomena as a wave within the fracture or as a simple, massive closing of the fracture. Cicerone (1991) chooses the former. He then derived the relationship between the amplitude of the observed tube wave given the amplitude of the observed body wave (usually the first arrival P wave) and the parameters of the fracture. Using this method and given three or more VSP shot points, one can obtain the 3D orientation of the fracture and an estimate of the fracture's hydraulic conductivity.

Obviously, real fractures are always more complex than those that can be numerically modeled. Therefore the value of the hydraulic conductivity obtained here does not usually match that seen

in flow testing. However, flow testing cannot provide the 3D orientation of the fracture(s) nor its 3D extent.

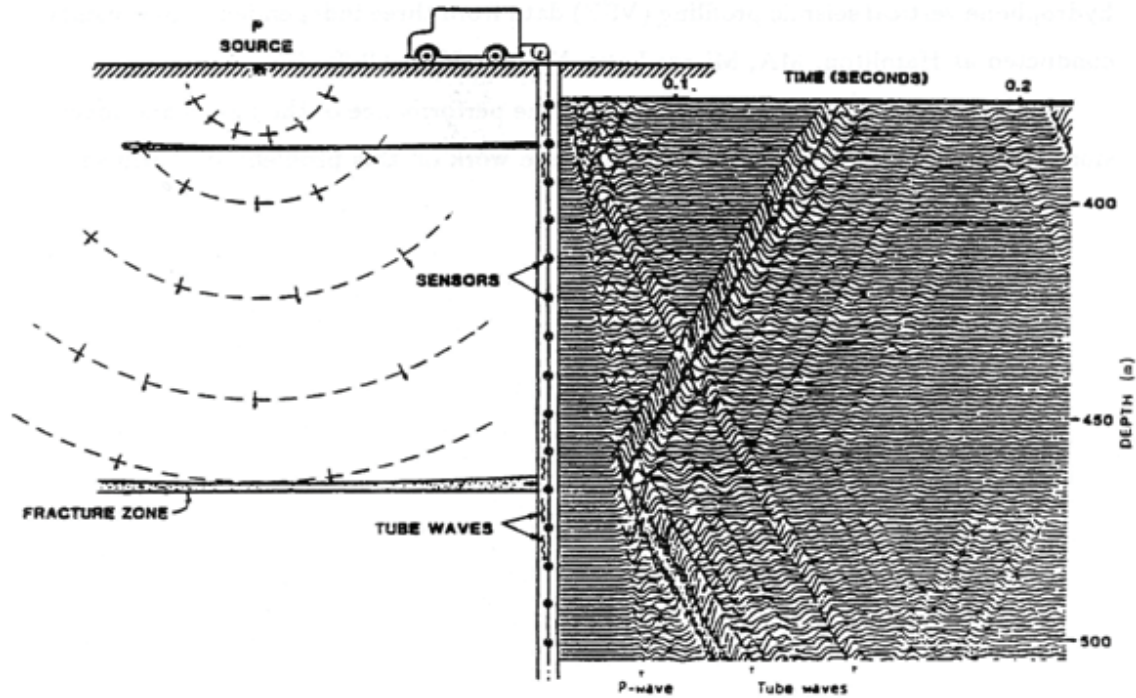


Figure 5.9-5: Generation of a tube wave in an open borehole from the compression of an intersecting fracture.

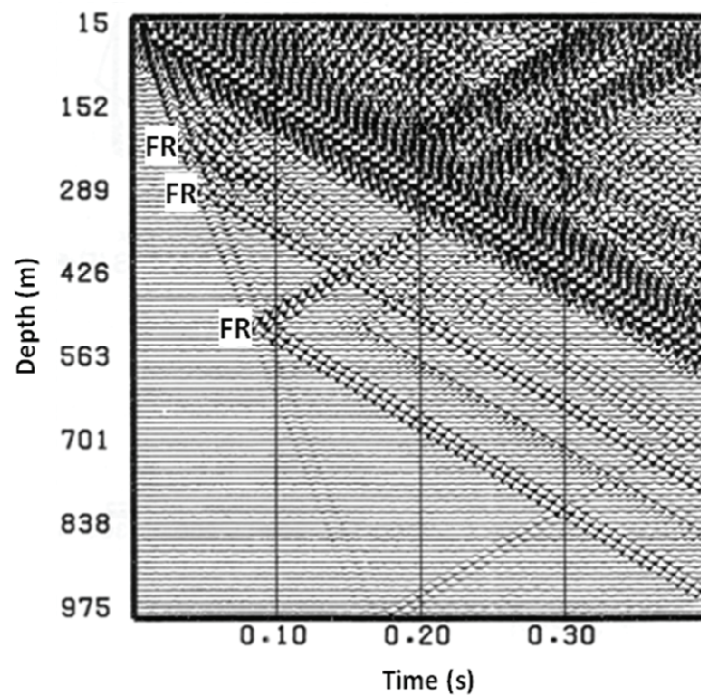


Figure 5.9-6: Tube wave VSP showing the location of three fractures.

5.10 Cross-Hole Seismic Reflection

Cross-hole seismic reflection is a seismic imaging method that involves accessing two or more boreholes simultaneously.

Data Acquisition

A seismic source is lowered into the bottom of one well, and a receiver array string is lowered into the bottom of one or more adjacent wells. Very high bandwidth sound waves (typically 100 to 2,000 Hz) are transmitted from the source to the receivers as the source is moved up the well bore (Figure 5.10-1a and b). The receiver array is then moved one array length up the well bore, and the source again transmits sound waves as it travels up the well bore (Figure 5.10-1c). This process is replicated (Figure 5.10-1d) until the area of interest between the boreholes is covered vertically - ensuring that seismic data are fully collected between the boreholes.

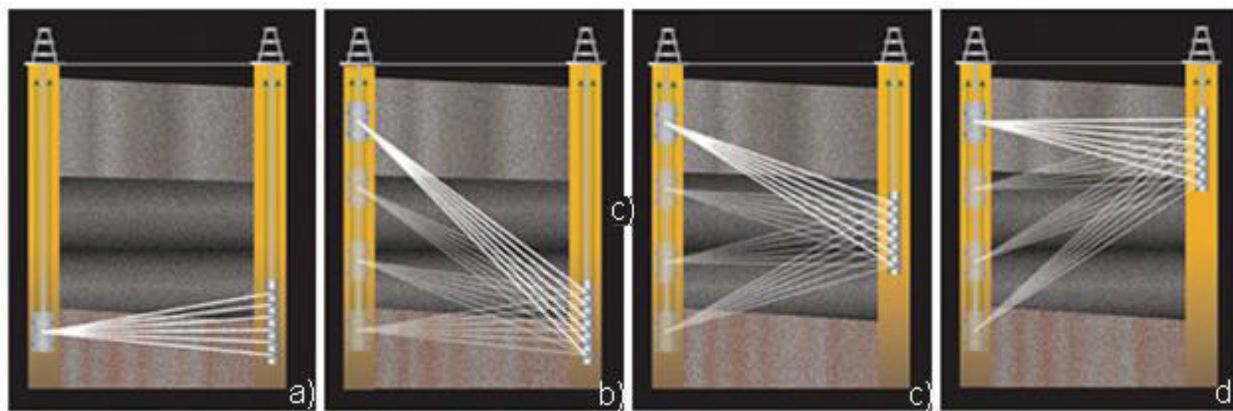


Figure 5.10-1: The cross-hole seismic method. (Z-Seis Reservoir Imaging)

Cross-hole seismic reflection is very similar to VSP work with a few important distinctions:

- The work is conducted between a pair of boreholes so instead of one surface source firing into a receiver array, there is an array of sources firing into an array of receivers – effectively multiplying the shot pattern for a VSP by the number of source points.
- Many of the processing steps are similar between VSP and cross-hole work with the exception of generating a velocity tomogram of the area between the boreholes.

The source frequency is much higher than with VSP or surface seismic techniques.

Data Processing

Most sources (piezoelectric or airgun) used in cross-hole seismic testing generate both P and S waves which, via mode conversion upon reflection and refraction, generate a number of different types of reflected and refracted P and S waves. The P wave to P wave reflections are the wave type of primary interest, so separating these P-P events from the other types of events is the first important processing step. This can be achieved by several different processing techniques, such as frequency filtering, median filtering, f-k filtering, simple stacking, etc., depending on the situation. Figure 5.10-2 shows the results of removing the direct arrivals by median filtering.

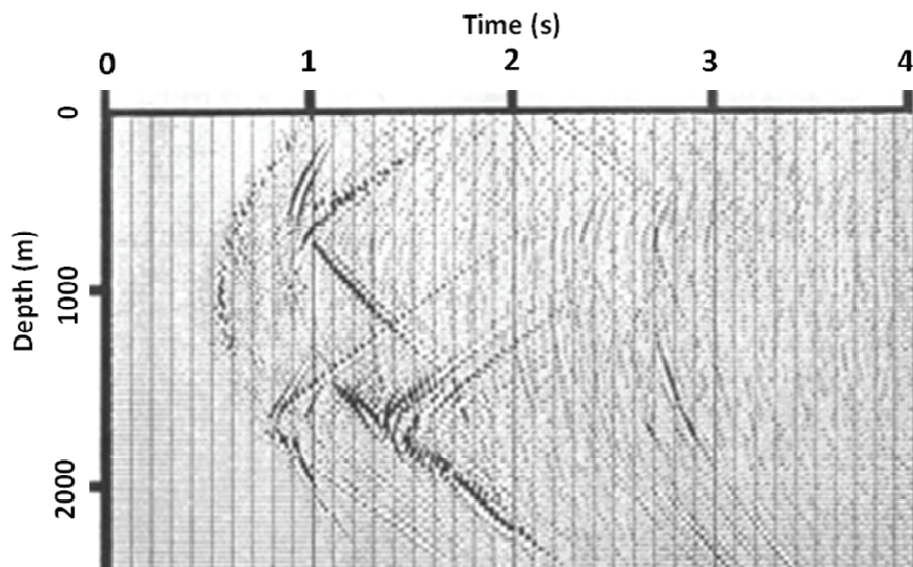


Figure 5.10-2: Cross-hole reflection data after median filtering. (Stewart et al, 1991)

Cross-hole reflection traces in a “common source” gather, are essentially the same as a VSP geometry. As with VSP data, the cross-hole reflection data is transformed to move the reflections along a path determined by the velocity structure, to a position in horizontal distance from the borehole and depth.

Figure 5.10-3 shows this “stretching operation” where the seismic traces are stretched along the proper downward curved trajectory thereby placing each reflection wavelet at its correct position in space. These transformed shot gathers are then stacked to produce a single image for that set of reflectors.

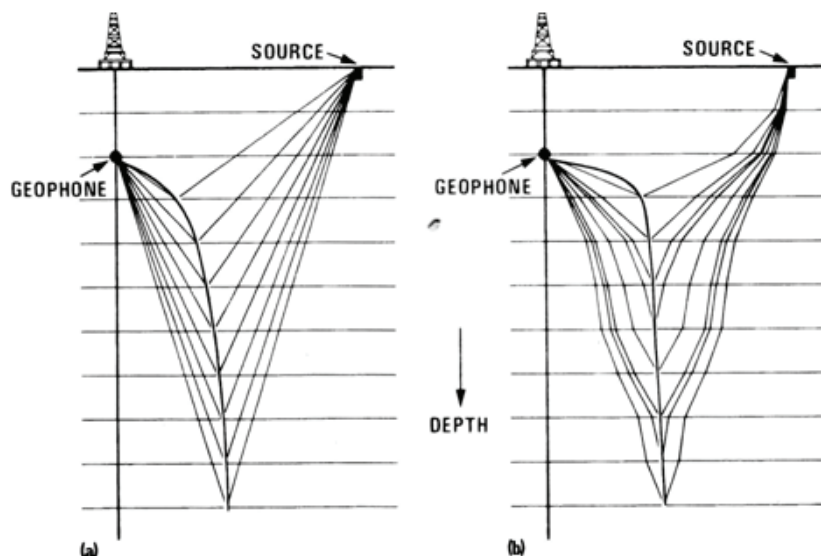


Figure 5.10-3: The VSP to CDP transform for (a) constant velocity structure and (b) layered velocity structure. (Dillon and Thompson, 1984)

As in any seismic imaging task, the quality of the VSP-CDP operation depends on the quality of the velocity information. In the cross-well geometry it is possible to obtain very good velocity

data from cross-well tomography. However, given the high frequency content of cross-well data, the reflection wavelets, even after stretching in the VSP-CDP operation, remain sharp, high frequency wavelets. This, in turn, means that they must be precisely aligned just prior to stacking. If they are not well aligned the resulting wavelet will be smeared and degraded during that summing operation. Good velocities are needed to assure proper alignment.

Figure 5.10-4 presents an example of data collected as part of an engineering investigation of the Salina Formation in Windsor, Ontario. In this example, the reflection data are plotted as an overlay to the velocity tomogram – both derived from the cross-hole seismic imaging. The traces on the left and right depict the natural gamma (red) and sonic velocity (black) logs to show the correlation of clear reflectors associated with changes in geology. The figure demonstrates the level of detail that can be acquired for a cross-hole seismic survey in sedimentary rock.

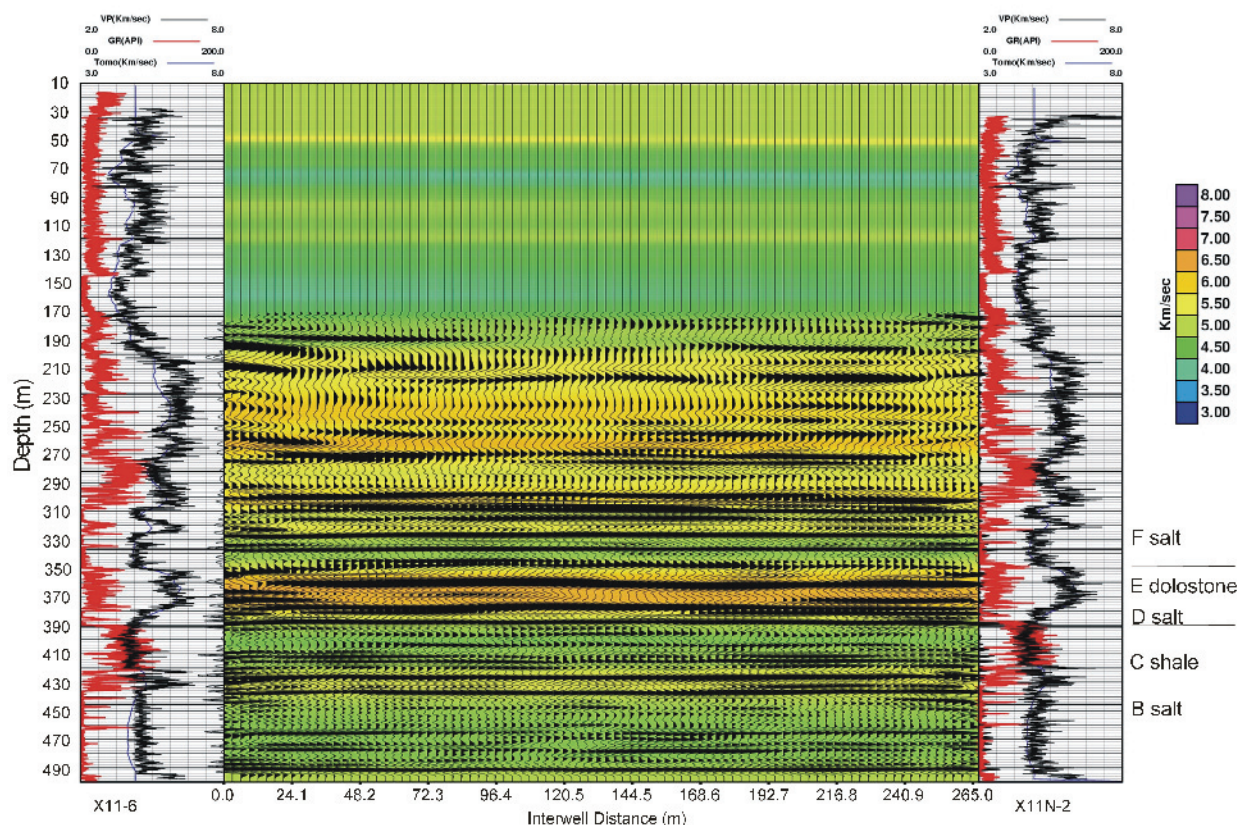


Figure 5.10-4: Cross-hole seismic reflection results in the Salina Formation - Windsor Ontario. (Z-Seis Reservoir Imaging)

The VSP-CDP operator is only one of several operators that can be used to transform data from the depth-time domain to the horizontal distance-depth domain. Other operators such as paraxial ray Kirchhoff migration (Keho and Beydoun, 1988), 2.5 D Kirchhoff migration (Dong and Bleistein, 1990) and a vertical moveout operation on common mid-depth gathers (Stewart 1991) can replace the VSP-CDP operation demonstrated here.

5.11 VSP and Cross-Hole Summary

Applicability to Programme

The VSP and cross-hole seismic reflection methods are generally applicable to sedimentary bedrock environments and the development of the methods has stemmed from work in hydrocarbon exploration. Clear contrasts in seismic properties exist between layers and sedimentary rock sequences, and provide for numerous reflectors that aid in the processing of such data sets.

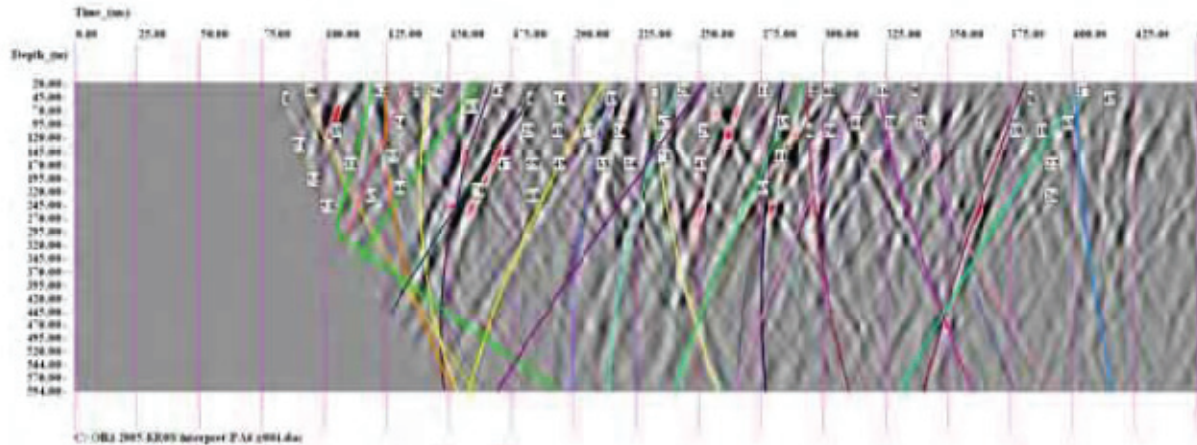


Figure 5.11-1: Processed VSP reflectors in borehole KR08 - reflector PA04 - Olkiluoto, Finland. (Enescu, Cosma and Balu, 2007)

Most cross-hole seismic work in crystalline bedrock has been limited to generating tomograms of the velocity field between boreholes. Significant work has also been done by Posiva in Finland (e.g. Enescu, Cosma and Balu, 2007) in applying reflection VSP to crystalline bedrock (Figure 5.11-1).

Processing and QA/QC

It is generally noted that VSP and cross-hole seismic reflection surveys both benefit from modelling prior to implementation of the field program. This is an important step and provides a basis for providing QA/QC during the field data collection. A critical part of these surveys is to include expert observers during the data collection to ensure that good quality data is collected. Processing for these data sets is very complex with a large number of checks and balances. The process is often iterative and requires ancillary data from other logs such as natural gamma for stratigraphic correlation across the seismic reflection sections and sonic logs.

Strengths and Weaknesses

The main strength of a VSP is to tie stratigraphy encountered in a borehole to reflections recorded in a surface seismic reflection survey. Offset and walk-away VSPs can also provide information regarding the attitude of bedding encountered in the borehole. The main strength of cross-hole seismic reflection is to fill the gap between boreholes – to establish the continuity of the stratigraphy, identify pinch-outs and, possibly the presence of voids or partial collapse structures. However, the work is field and processing intensive and requires highly skilled operators for the field work, highly skilled processors to generate the sections and, finally, highly skilled interpreters to provide context for assessing final product.

Potential to Combine Methods

VSP and cross-hole seismic reflection acquisition cannot be combined with other methods. They are undertaken to complement surface seismic surveys and, in combination with other borehole logs, extend coverage to the region between the boreholes.

Commercial Availability

Most of the large service providers for borehole geophysics (e.g., Schlumberger, Baker Atlas and Halliburton) provide VSP and cross-hole seismic reflection data collection and interpretation. As noted, VSP work is usually completed to accompany surface seismic reflection surveys and is done to tie the stratigraphy encountered in the borehole to reflectors observed in the seismic sections.

Cross-hole seismic reflection work in hydrocarbon exploration and development is undertaken to identify disruptions in stratigraphy (e.g., faults, pinch-outs and reef structures). There are a limited number of contractors that can supply these services for geotechnical applications or that can work in boreholes less than 15 cm in diameter. Two companies with offices in Canada that provide these services are Z-Seis Reservoir Imaging and Vibrometric Canada Limited.

5.12 Borehole Radar

Borehole ground penetrating radar is a geophysical technique which uses electromagnetic waves at radio frequencies in the range of 10 MHz to 1 GHz. These waves are generated and detected in boreholes to produce a high resolution image beyond the borehole wall. These systems consist of a transmitter and receiver antenna pair and can be set up for different survey modes consisting of reflection, cross-hole and surface-to-borehole. The surface to borehole application has a limited depth of application (<20 m) and is not discussed further here.

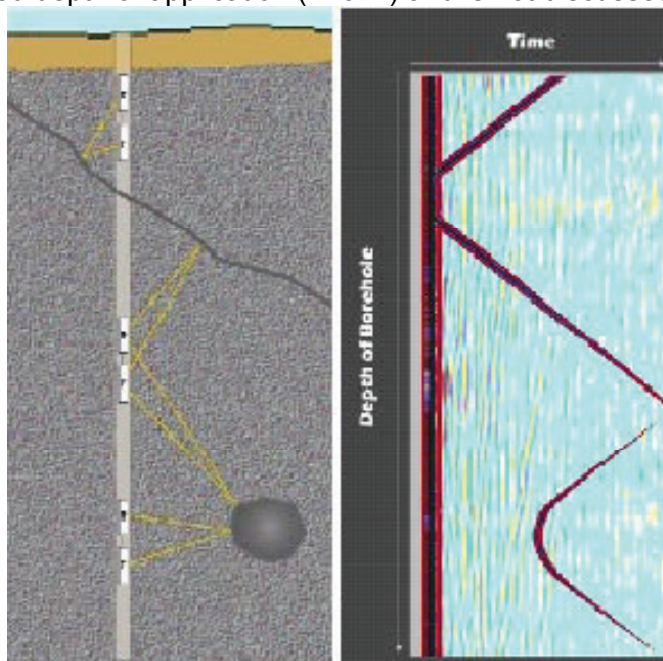


Figure 5.12-1: Model showing the principle of borehole reflection radar (left) and an example of synthetic radargram for the same model.

In the case of the dipole reflection radar surveys, the transmitter and the receiver are combined in a single probe or a single borehole as an antenna pair (Figure 5.12-1). The dipole antenna

(transmitter and receiver) is lowered continuously into the borehole and data are recorded at a given interval. The antennae (transmitter and receiver) are kept at a fixed separation. Radar-reflection surveys can be conducted with omni-directional or bidirectional antennas. In the case of cross-hole surveys the transmitter and the receiver are packaged separately and the transmitter and receiver are lowered into different boreholes.

The principles of borehole radar reflection logging are similar to surface ground penetrating radar (GPR). A radar pulse is transmitted into the bedrock surrounding the borehole. Some of this transmitted energy is reflected back to the receiver when it encounters material with different electromagnetic properties such as a lithologic boundary, fracture zone or void while some of the energy is transmitted further into the ground (Figure 5.12-1).

In a borehole, reflections are recorded from a 360 degree radius. If borehole data are collected within a single borehole using omni-directional antennae it is not possible to determine the dip direction of the fracture, but the distance and the dip can be determined. (Figure 5.12-1, left plot). In the directional mode, the strike of planar reflectors and the azimuth of reflectors can be determined.

Figure 5.12-1 shows that a fracture localized to the left side of the borehole will be imaged when the probe is above the fracture and a fracture to the right of the borehole will be imaged when the probe is below the fracture. This is represented in the synthetic radargram (right plot) where the two sides of the fracture are imaged. This figure also indicates that a point reflector is imaged as a hyperbola. In reflection mode, borehole radar will provide a high resolution image of the borehole surroundings displaying the presence of local features and provide some information regarding their geometry.

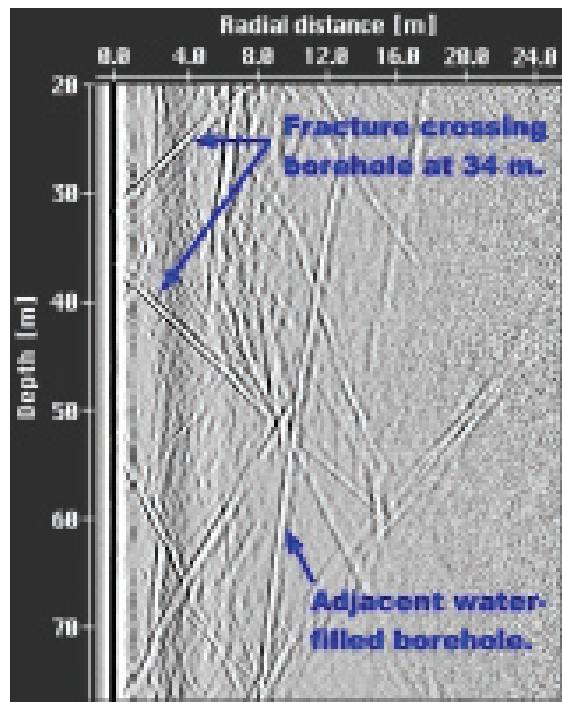


Figure 5.12-2: Borehole radar survey example using a 100 MHz system in granite.

The depth of penetration of the radar system is very site specific and is controlled by two primary factors which are the subsurface bedrock conditions and the antenna frequency. The

radar signal is attenuated as it propagates through the earth with a greater attenuation through conductive material.

Depending on the bedrock condition, at 20 MHz, structures as small as 2.5 m in size may be detected, while using a 50 MHz antenna, structures may be detected down to a size of about 1 m. Again, depending on the bedrock condition, borehole radar can image reflectors up to 25 m away using a 50 MHz antenna and up to 70 metres for a 20 MHz antenna. Radar recordings are often presented as a radargram (Figure 5.12-2).

Borehole-radar reflection is an excellent tool not only to provide information on the location, orientation and lateral extents of fracture zones that intersect the borehole, but also to image features such as fractures in the rock surrounding the borehole (Figure 5.12-2).

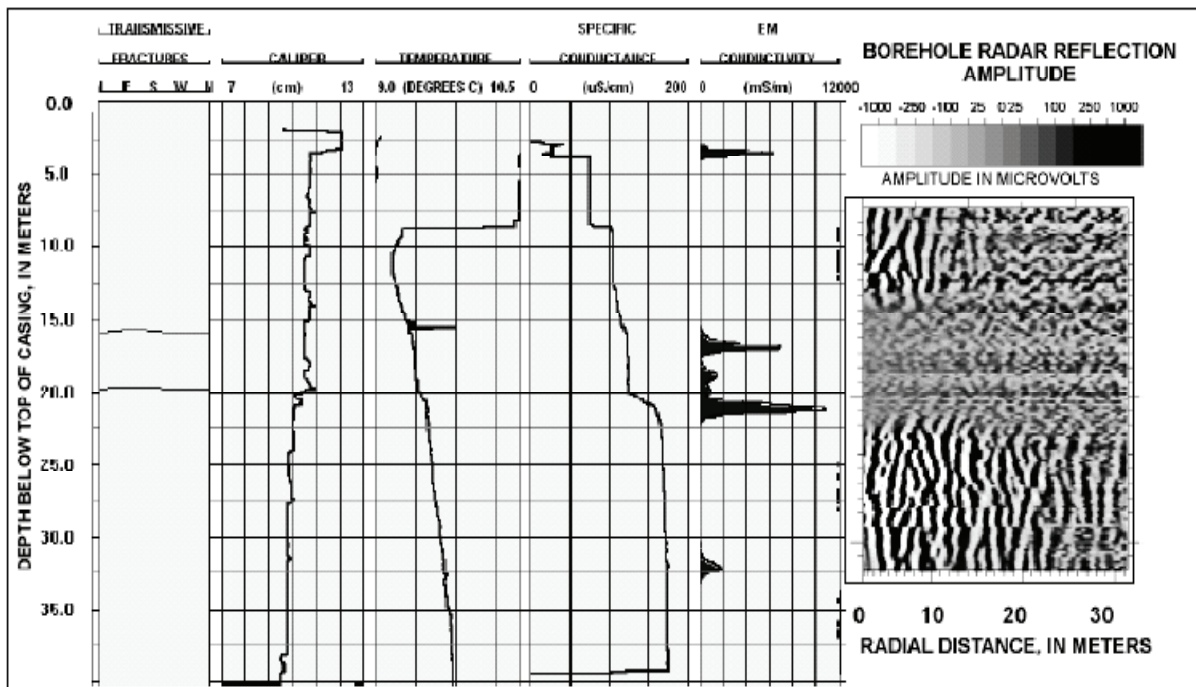


Figure 5.12-3: Borehole Radar and Ancillary Logs. Example of well logs measurements collected at the University of Connecticut Landfill area. (Johnson et al, 2002)

The data presented in Figure 5.12-3, using a directional borehole radar antenna, indicates a large zone of radar attenuation that correlates with anomalies in the EM conductivity log. In this case, it appears to be a result of the sulphide mineralization that was observed in the optical televiewer and core logs.

Cross-hole radar surveys (tomography) are another survey mode that provides a 2D image between two boreholes (Figure 5.12-4). Although it is more time consuming to acquire than the reflection mode, it provides cross section maps of the electromagnetic properties of the bedrock. The travel time and amplitude for each radar pulse propagating from the transmitter to the receiver is measured and all the various raypaths are used to construct tomograms that map the velocity and attenuation properties of the bedrock between the two boreholes. The measured variations in velocity and attenuation are used to identify fracture zones, lithologic interfaces and voids. They have also been used to support tracer tests.

A typical velocity image, shown in Figure 5.12-4, indicates the presence of attenuated zones (low velocities) due to the presence of conductive zones within the rock mass. Another application of cross-hole radar tomography is to inject a saline tracer in a fracture zone and observe the difference in the amplitude data between the initial tomography scan prior to injection and the scan after injection in order to image the attenuation zone that shows the movement of the tracer via the fracture network (Figure 5.12-5).

Single-hole radar reflection and cross-hole radar tomography surveys have been used to assist in characterizing the granite at the AECL URL site near Pinawa, Manitoba (Serzu et al, 2003).

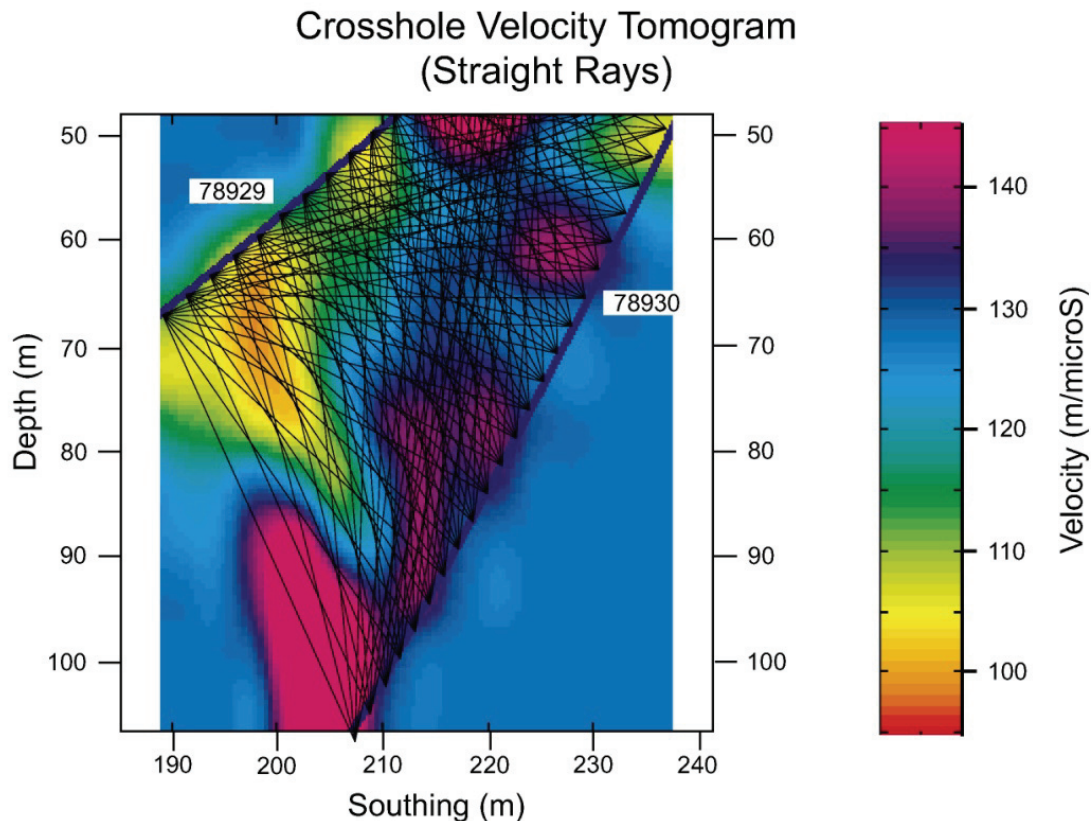


Figure 5.12-4: Example of velocity tomogram derived from the cross-hole radar survey using straight ray paths shown. (Calvert and Livelybrooks, 1997)

Applicability to Programme

Borehole radar techniques are generally of greater use in crystalline rock or in massive sandstone or carbonate sedimentary rocks. Depth of investigation is limited in conductive materials, so the presence of clay (shale) or saline pore water limits the application of the method. In general, borehole radar is used to locate and characterize bedrock fractures and lithologic changes.

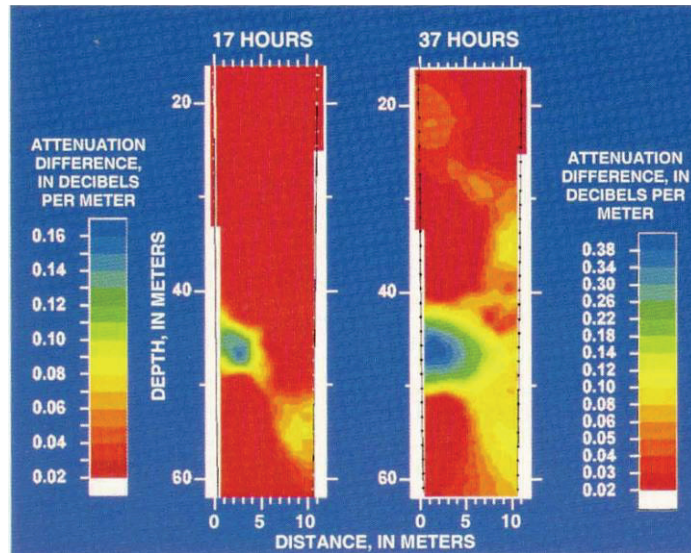


Figure 5.12-5: Example of borehole radar attenuation difference tomograms during a saline tracer experiment.

Strengths and Weaknesses

Borehole radar can provide a high resolution image of the borehole surroundings and is a non-invasive technique. However, the signal is strongly attenuated by conductive materials such as shale or porous rock with saline pore water. Most borehole antenna systems are omnidirectional so that is not possible to determine the direction of reflective anomalies. Even the directional antenna systems are bi-directional to a degree with some reception out of the bi-directional plane and there may be a level of ambiguity for determining the direction to reflectors beyond the borehole wall. Depths of investigation are typically greater than most borehole logging methods but are typically limited to 20 to 50 m depending on the transmitter voltage, frequency and conductivity of the surrounding rock.

Processing and QA/QC

The basic processing includes DC and low frequency removal, assessing time gains and applying appropriate filters (dewow, background removal). The data are often presented as variable display logs (VDL – similar to full wave form sonic logs) for presentation and interpretation together with other borehole logs. Many other advanced techniques used in seismic reflection surveys can be used to process GPR data such as velocity analysis and migration. Usually, the boreholes will be deviated to some degree so it may be required to plot the data along a trajectory. Tomographic surveys use inversion techniques, analogous to seismic tomography, to solve for the velocity distribution in the rock mass.

QA/QC steps are limited to ensuring accurate depth encoding, appropriate data acquisition parameters (time windows and hardware settings), selecting the appropriate frequency for the antenna systems according to the borehole and rock conditions and appropriate data processing steps. Low antenna frequency provides less resolution but a greater depth of investigation compared to a higher frequency.

Limits and Constraints

Borehole-radar methods are limited by subsurface conditions because they are primarily controlled by the conductivity of the medium. The radial distances of penetration and the scale

of features that can be imaged depend on the electromagnetic properties of the rock and ground water and on the frequency of the antenna.

Potential to Combine Methods

Borehole radar acquisition cannot be combined with other methods, although the results can be integrated with other borehole geophysical methods such as OTV, gamma, fluid temperature, fluid resistivity and electromagnetic induction to help characterize the hydrogeology of the fracture-rock aquifer and image lithologic changes and fractures.

Commercial Availability

Borehole radar systems are generally not available through the usual manufacturers of logging systems. Suppliers of borehole radar systems include Sensors and Software Inc. (Canada), Geophysical Survey Systems, Inc. (USA), Mala Geoscience (Sweden), GeoMole Pty. Ltd. (Australia) and T&A Radar BV (Netherlands).

5.13 Borehole TDEM

Time domain electromagnetic (TDEM) surveys can be used to map geologic structures in the subsurface and in particular, locate conductive bodies (McNeil 1980b and 1994; Telford et al, 1990). The method involves the application of an electric current to a transmitter coil, often a large loop laid out on the ground. The waveform applied to the transmitter is typically a pulse that is switched on, then off, at a predetermined frequency. In the absence of conductors, a sharp transient pulse proportional to the time derivative of the induced magnetic field is detected at the receiver coil. When a conductor is present, the sudden change in magnetic field intensity will induce the flow of eddy currents in the conductor which will tend to slow the decay of the field.



Figure 5.13-1: The BH UTEM4 borehole TDEM receiver system. (Lamontagne Geophysics Ltd.)

An extension of surface time-domain electromagnetic (TDEM) surveying is to keep the transmitter at surface, but deploy a 3-component receiver array down a borehole. This results in a much higher sensitivity to detecting subsurface targets. An example of the receiver equipment used in TDEM surveying is shown on Figure 5.13-1.

The TDEM technique is commonly used in mineral exploration; borehole TDEM can locate conductive rock bodies in the subsurface as great as 500 m away from the axis of the borehole. The method can be used in site characterisation for determining/providing geologic and structural information. A typical vertical component response from a borehole TDEM survey is shown on Figure 5.13-2.

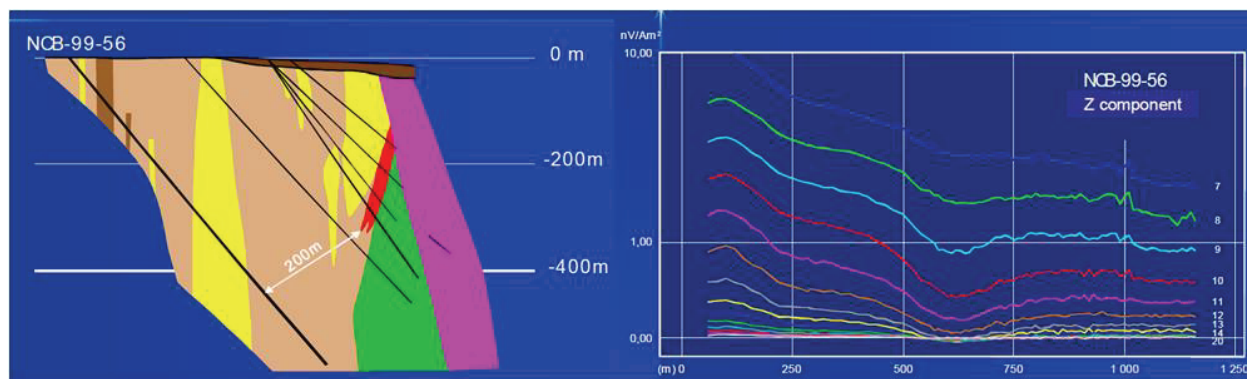


Figure 5.13-2: Vertical component response at right from a borehole TDEM survey near a conductive body. (Abitibi Geophysics)

Applicability to Programme

Borehole TDEM surveys are most likely to be applicable to site characterization in a crystalline rock environment, where there is an interest in imaging regions of the rock mass away from the borehole and there are expected to be detectable variations in the conductivity of the rock units. It may also be used to help determine whether or not there are economic mineral deposits at the site. The borehole TDEM technique is not likely to be as applicable in a sedimentary rock environment, as there are other geophysical methods that would provide better subsurface imaging in this type of rock environment.

Strengths and Weaknesses

The greatest strength of borehole TDEM is the ability to image conductive bodies in the subsurface at a significant distance from the borehole. This ability is somewhat unique amongst geophysical methods.

Potential sources of noise for borehole TDEM surveys are spurious noise generated by other man-made sources, interference from metallic structures and induced polarization effects.

Potential to Combine Methods

While it is not possible to combine borehole TDEM acquisition with other methods, the model results can be better constrained by other geological and geophysical inputs.

Commercial Availability

Borehole TDEM is a very effective mineral exploration tool, therefore a range of geophysical consultants and contractors in Canada offer this service to clients in the mining sector.

5.14 Cross-Hole EM

Cross-hole EM is an electrical resistivity imaging method for use between borehole pairs – generally at distances of up to 1,000 m apart. Development of the technology since 1990

(equipment and interpretation algorithms) has been mainly for petroleum reservoir characterization and for monitoring steam and water flood testing programs (Wilt et al, 2001). The system is similar to borehole radar with the main difference being the frequency of operation (typically in the 10 to 50 kHz range). The technology was developed at the Lawrence Livermore National Laboratory – primarily from 1991 through to 2000.

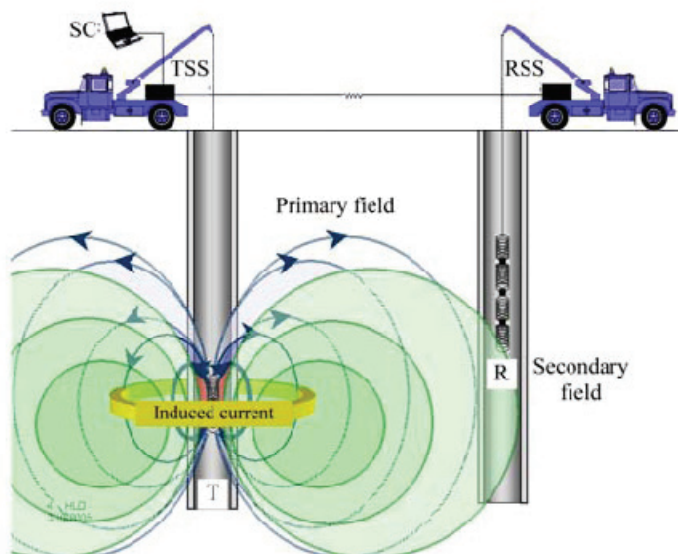


Figure 5.14-1: Deployment of Cross-Hole EM (Xie et al, 2005)

Schlumberger has developed a system (DeepLook-EM) with interpretation software for use as a well field service that was launched at the Middle East Oil and Gas Show (MEOS) in 2009. However, there is a limited amount of information regarding the use of this technology for engineering and geotechnical applications (Groom and Candy, 2001).

The cross-hole EM system, which is based on earlier radar imaging technology, consists of a transmitter antenna deployed in one borehole and a receiver (or set of receivers) deployed in another (Figure 5.14-1). It is necessary to have accurate borehole deviation data for describing the position of the boreholes in space as separation is a critical parameter for the data inversion process. The transmitter coil is tuned to broadcast at frequencies ranging from 10 Hz to 50 kHz. The frequency is set to suit the borehole separation and the average formation resistivity. Similar to an induction tool, an electromagnetic field produced by the transmitter induces eddy currents, which flow in conductive materials surrounding the borehole. Of note is that the strength of the field for cross-hole EM is on the order of 10^5 times stronger than for conventional borehole logging tools. The eddy currents in turn generate secondary magnetic fields and the receiver coil records the total time varying magnetic field including both the primary and secondary magnetic fields. Instrumentation for the receiver system consists of a magnetic field sensor (3-component receiver) and a “lock-in” amplifier at surface – the amplifier measures signals coherent with the transmitted signal and rejects incoherent background noise.

Readings are acquired in a standard scheme for cross-hole tomography, typically at 1 to 2 m intervals down the length of the boreholes or to encompass the zone of interest. The recorded data are interpreted by computer modeling including a variety of tomographic inversion techniques (Wilt et al, 2001).

Typically, the area between boreholes is divided into 2D square blocks with dimension on the order of 1 to 5 m. For the starting models, the apparent resistivities of the blocks are assigned based on apparent resistivity data from conventional induction or normal resistivity logs run in the source and receiver boreholes. Tomographic inversion is then completed based on matching calculated and measured data. This is generally a 12 to 24 hour process on a computer work station depending on the amount of data. Modeling packages include in-house, proprietary software by Schlumberger, commercially available packages such as EMIGMA (Petros Eikon Inc.) and a 2-D inversion code (SINV2D) developed by Sandia Lab (Wilt et al, 2001).

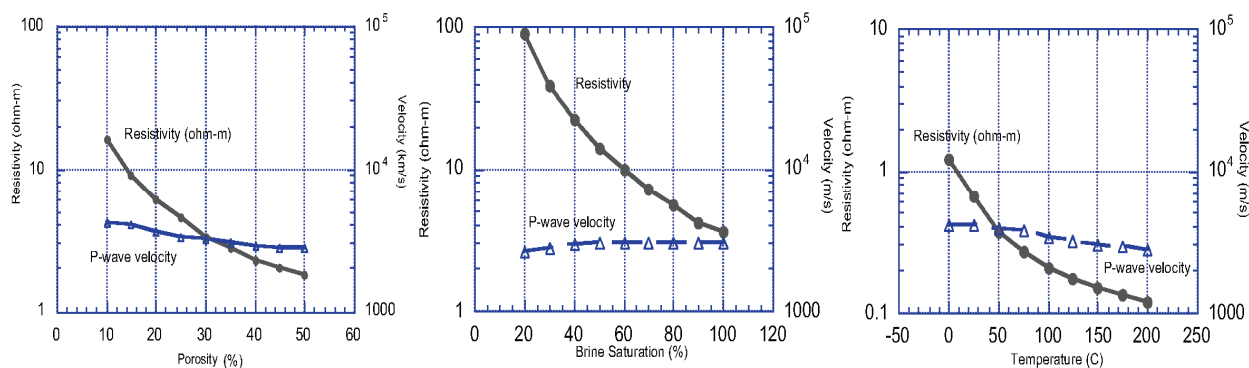


Figure 5.14-2: Resistivity and compression wave velocity as a function of porosity, saturation and temperature of a sandstone core. (Wilt, 1998)

The concept of cross-hole EM is appealing for characterizing the materials between boreholes based on electrical resistivity. Low frequency, cross-hole EM results yield different but complimentary data compared to cross-hole seismic (Wilt, 1998). Seismic velocity and attenuation are sensitive to variations in the rock matrix whereas electrical resistivity is generally more sensitive to variations in the pore fluid: fresh or saline water and oil (Figure 5.14-2). These plots show there is a greater potential sensitivity for cross-hole EM versus seismic techniques.

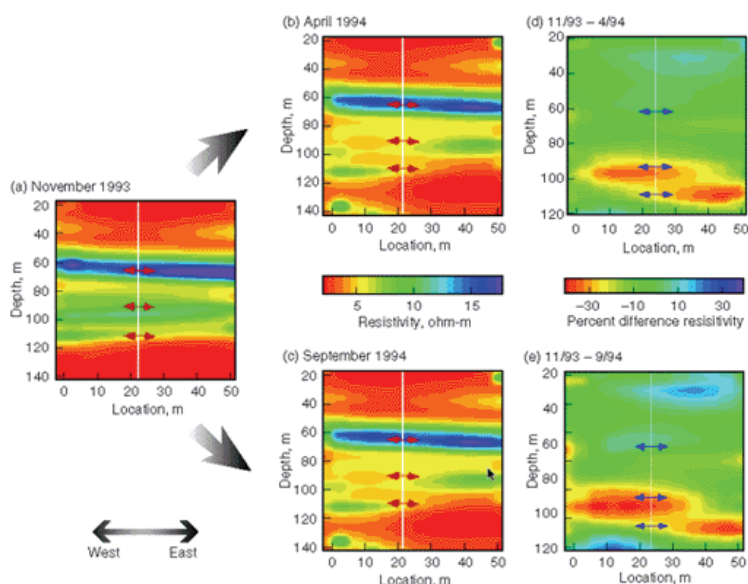


Figure 5.14-3: Interpreted resistivity images and percent difference image before and after steam flooding – Lost Hills Oil Field. (Wilt, 1998)

Figure 5.14-3 shows the results of a cross-hole EM survey carried out to monitor steam injection in a shallow oil sand deposit (Wilt, 1998). Two fibreglass-cased boreholes were installed and steam was injected at depths of 65, 90 and 120 m into upper, middle and lower members of the target oil sand. The images in the figure show the distribution of the high resistivity oil sands and the intervening shale layers. The difference plot for resistivity (before and after) shows that the significant decline in resistivity is associated with the middle and lower sands. This is interpreted as being due to an increase in temperature due to the steam flooding and the replacement of oil by water and steam.

Recent Developments

The Radio Imaging Method (RIM) has been developed for work in coal seams (Figure 5.14-4). The frequency of operation is in the low to high kHz range (90 kHz to 890 kHz) and is applicable where the host material (e.g. coal seam) for the survey acts as a wave guide for horizontal antenna systems. The method is less applicable for cross-hole applications where the boreholes are vertical and intersect a series of layers (McGaughey and Vallee, 1997).



Figure 5.14-4: The Crosswell 3D RIM system antenna assemblies. (Stolar Research Corp.)

Groom and Candy (2001) provide a description of the preliminary development of cross hole EM systems based on an alternative design (Figure 5.14-5) but the data acquisition and processing is still evolving. For engineering and environmental applications, it appears that there is still room for developing antenna design, operating frequencies and modeling software.



Figure 5.14-5: Normal mode helical electrical antenna system and instrumentation for cross-hole EM. (Groom and Candy, 2001)

Applicability to Programme

Cross-hole EM may be applicable to crystalline rock environments, where it could be used to map fracture networks. The technology is quite new and there are limited case histories to fully understand the potential applications to repository site characterization.

Strengths and Weaknesses

Cross-hole EM has an advantage over borehole radar in that it is a lower frequency measurement and can therefore achieve greater distances of penetration in the same geological environment. It is a very new technology, therefore it is not well developed and there are limited service providers.

Potential to Combine Methods

While it is not possible to combine cross-hole EM acquisition with other methods, there is a potential to combine data interpretation with other methods, such as cross-hole seismic.

Commercial Availability

Currently, the DeepLook-EM system is available through Schlumberger as a logging service and is applied for oil field resource characterization. The RIM™ system is available as a service through Stolar Research Corporation. Other equipment appears to be in development but field data acquisition and processing may be available through Petros Eikon Inc.

6. APPLICATIONS

Chapters 3 to 5 describe a wide range of borehole geophysical tools and techniques that can be used in site characterization studies for deep geological repositories in sedimentary or crystalline rock environments. These methods and their typical application in engineering, environmental and mining investigations (adapted from Crowder, 1995) are presented in Table 6.0-1 in a matrix format.

The general categories of applications presented include:

- Lithology and Stratigraphy
- Physical Properties
- Rock Structure
- Fluid Parameters
- Casing Evaluation
- Borehole Parameters

This chapter provides further discussion on these logging techniques and interpretation methods for a range of applications. Illustrative examples are provided, drawing upon direct experience by the authors in sedimentary and crystalline rock environments similar to those in Canada, wherever possible. Case histories, which provide further specific example applications, are presented in Chapter 7.

Table 6.0-1: Log Application Selection Chart (adapted from Crowder, 1995)

		Borehole Orientation				Electric Logs					Passive Nuclear		Active Source Nuclear			Caliper		Borehole Imaging				
		Tropari	Reflex	Gyroscopic	3-X Magnetometer / Accelerometer	SP	SPR	16", 64" Normal	Guard Focused Resistivity	Induction Log	Natural Gamma	Spectral Gamma	Neutron Porosity	Gamma Density	Photoelectric	Three Arm Caliper	Four Arm Caliper	Optical Televiwer	Acoustic Televiwer	Dipmeter	Electrical Resistivity formation Scanner	Video Inspection
Lithology and Stratigraphy	Contacts					●	●	●	●	☆	✓	✓	Δ	Δ	Δ			◇	●	●	●	◇
	Bed Thickness					●	●	●	●	☆	✓	✓	Δ	Δ	Δ			◇	●	●	●	◇
	Lithology					●	●	●	●	☆	✓	✓	Δ	Δ	Δ			◇	●	●	●	◇
	Stratigraphy					●	●	●	●	☆	✓	✓	Δ	Δ	Δ			◇	●	●	●	◇
	Discontinuities (cavities, faults, Shear)															✓	✓	◇	●	●	●	◇
	Clay Typing/Iron Content										✓	✓										
	Shale/Clay Content					●	●	●	?	☆	✓	✓	Δ	Δ	Δ							
	Mineral Identification										✓	✓		Δ	Δ							
	K-U-Th Content											✓										
	Sulfide detection									?		✓		?	Δ							
Physical Properties	Density													Δ					?			
	Elastic Moduli													Δ								
	Fracture Frequency, Apparent RQD					●	●	●								✓	✓	◇	●	●		◇
	Formation Resistivity						●	●		☆												
	Injection/Production Profiles						?			?			?	?								
	Permeability Analysis													Δ								
	Porosity (amount & type)						●	?		☆			Δ	Δ				◇	●			◇
Rock Structure	Bed Dip and Dip Direction																	◇	●		●	◇
	Fracture Detection					●	●	●								✓	✓	◇	●	●	●	◇
	Fracture Orientation																	◇	●	●	●	◇
	Fracture Character																	◇	●			◇
	Thin Bed Resolution					●	?	●								✓	✓	◇	●			◇
Fluid Parameters	Borehole Fluid Resistivity																					
	Fluid Flow																					
	Formation Water Resistivity					●	●	●		☆												
	Moisture Content - Water Saturation						?			?			Δ	Δ								
	Temperature																	◇	●		●	◇
	Water Level/Water Table					●	●			?			Δ	Δ				◇	●		●	◇
Casing Evaluation	Integrity					?	?		?					Δ	Δ			◇	●			◇
	Bond Logs													Δ								
	Leaks					?	?									?	?	◇				◇
	Damage																	◇				◇
	Screen Location					?	?			?				Δ		✓	✓	◇	■			◇
Borehole Parameters	Deviation	☆	✓	✓	☆													◇	●			
	Diameter															✓	✓		●			
	Stress Investigations																		●		●	
	Examination Behind Casing									☆	✓	✓	Δ	Δ	Δ				●			
	Location of Debris									☆						✓	✓	◇	●			
	Borehole Stability																	◇	●			
	Seal Location									☆	✓	✓	Δ	Δ	Δ							
	Grout Verification																	■				

Legend

- | | |
|---|---|
| ✓ No restrictions | ◆ Cased, dry or clear fluid-filled borehole |
| ? Possible application | ■ Cased, fluid-filled borehole |
| t Steel casing only | ☆ Open or non-conductive/non-magnetic cased borehole, dry or fluid-filled |
| ● Open, fluid-filled borehole | ◇ Open, clear fluid-filled or dry borehole |
| ○ Cased or Open, fluid-filled borehole | □ Screened or open, fluid-filled borehole |
| Δ Active source nuclear log to be run in stable holes | Large diameter boreholes only (>15 cm) |

Note: Many Logs are used in combination to correct measurements for borehole effects and aid interpretation (i.e. caliper, deviation, etc.)

Table 6.0-1: Log Application Selection Chart (continued)

		Fluid Logs/Flow Testing						Acoustic Methods				Seismic Methods		Other Methods						
		Fluid Temperature / Conductivity	Impeller Flow meter	Heat Pulse Flow Meter	Posiva	Fluid Sampler	Hydrophysical Logging	Conventional Sonic	Shear Velocity	Full Wave Form Sonic	Tube Wave Logging	Tomography	VSP	Cross-Hole Seismic Reflection	Borehole Gravity	Borehole TDEM	Borehole Radar	Cross-Hole EM Tomography	Mag. Susceptibility	Nuclear Magnetic Resonance
Lithology and Stratigraphy	Contacts							●	●	●		○	○	○			☆	☆	☆	
	Bed Thickness							●	●	●			○	○			☆		☆	
	Lithology																			
	Stratigraphy							●	●	●		○	○	○			☆	☆	☆	
	Discontinuities (cavities, faults, Shear)							?	?	●		○	○	○	✓	☆	☆	☆	☆	
	Clay Typing/Iron Content																		☆	
	Shale/Clay Content																			☆
	Mineral Identification																			
	K-U-Th Content																			
Sulfide detection															☆			☆		
Physical Properties	Density														✓					
	Elastic Moduli									●		○	○		✓					
	Fracture Frequency, Apparent RQD									●										
	Fm. Resistivity																			
	Injection/Production Profiles	□	□	□	□		□													
	Permeability Analysis	□	□	□	□		□		●	●		○	○							☆
Porosity (amount & type)									●		○	○							☆	
Rock Structure	Bed Dip and Dip Direction												○							
	Fracture Detection	□	□	□	□		□			●	●	?	?							
	Fracture Orientation																			
	Fracture Character						□													
	Thin Bed Resolution																			
Fluid Parameters	Borehole Fluid Quality	□	?	?	□	□	□													
	Fluid Flow	□	□	□	□		□													
	Formation Water Quality	□				□	□													
	Moisture Content - Water Saturation																			☆
	Temperature	□					□													
	Water Level/Water Table	□			□		□													
Casing Evaluation	Integrity	■	■	■	■		■			■										
	Bond Logs									■										
	Leaks	■	■	■	■		■													
	Damage									■										
	Screen Location	■	■	■	■		■												t	
Borehole Parameters	Deviation																			
	Diameter																			
	Stress Investigations																			
	Examination Behind Casing							■	■	■										
	Location of Debris																			
	Borehole Stability																			
	Seal Location																			
	Grout Verification									■		○								

Legend

- | | |
|---|---|
| ✓ No restrictions | ◆ Cased, dry or clear fluid-filled borehole |
| ? Possible application | ■ Cased, fluid-filled borehole |
| t Steel casing only | ☆ Open or non-conductive/non-magnetic cased borehole, dry or fluid-filled |
| ● Open, fluid-filled borehole | ◇ Open, clear fluid-filled or dry borehole |
| ○ Cased or Open, fluid-filled borehole | □ Screened or open, fluid-filled borehole |
| Δ Active source nuclear log to be run in stable holes | ■ Large diameter boreholes only (>15 cm) |

Note: Many Logs are used in combination to correct measurements for borehole effects and aid interpretation (i.e. caliper, deviation, etc.)

6.1 Lithology and Stratigraphy

Geophysical logs can be used to identify lithology (i.e. rock type) and map stratigraphy (i.e. correlate geologic units from borehole to borehole). Geophysical logs can, for example, be used to:

- Identify stratigraphic contacts and determine bed / rock unit thickness;
- Identify discontinuities such as cavities, faults, or shear zones;
- Estimate clay/shale content;
- Identify major mineral types (in some cases);
- Estimate K-U-Th Content; and
- Identify massive sulphides or other conducting minerals, such as graphite.

6.1.1 Qualitative Approaches

One of the primary purposes of borehole geophysical logging for any geotechnical, hydro-geological, mining or hydrocarbon investigation is to identify lithology and correlate stratigraphy across the site. This is also a primary objective of geophysical logging at potential deep geological repository candidate sites.

The simplest and perhaps most effective way to relate geophysical log response to lithology is to compare the geophysical log data directly to rock core (or cuttings). Qualitative log analysis to assign lithology can also be based on knowledge of the local geology and examination of outcrops and cuttings, combined with an understanding of geophysical log responses.

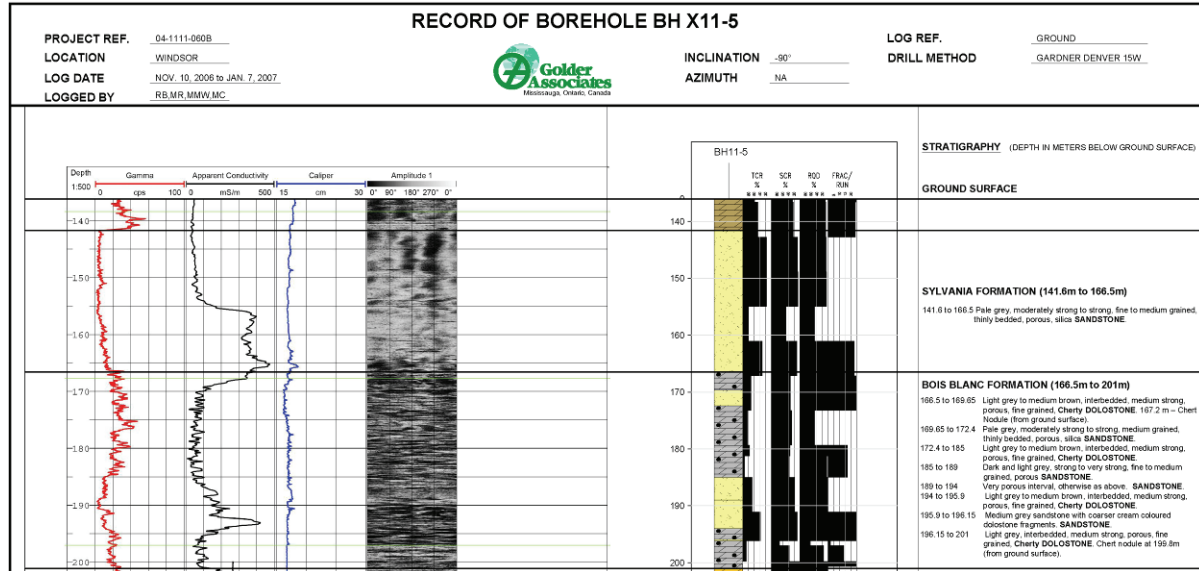


Figure 6.1-1: A combined geophysical / geologic borehole log. (Golder Associates)

During a typical site investigation, core samples (or cuttings) are obtained during drilling and then the borehole is geophysically logged. Subsequently, it is very beneficial to conduct more detailed geological logging of the cores (or cuttings) together with reviewing the geophysical log data, culminating in an integrated log (Figure 6.1-1).

This process helps the geologist accurately assign depths for contacts identified in the core based on correlation to the log response and also produces a “type” geophysical log for the site. Quite often, core may be visually undifferentiated but the formations will have a very characteristic log response. In addition, portions of core may be missing due to “bad ground” or recorded depths for the core may be inaccurate. Examining the geophysical log data in conjunction with core data is a critical QA/QC step – geophysical data and core data should be consistent and not contradictory.

In the sedimentary rock example shown on Figure 6.1-1, core from the borehole was carefully logged with reference to geological descriptions of the local stratigraphy and in comparison to the geophysical log data. Marker beds were identified and the “type” geophysical log from this borehole was used to correlate stratigraphy at 11 other boreholes on the site.

Geophysical logging is very useful in identifying lithology and correlating stratigraphy where cores have not been recovered from all of the boreholes at the site. In many situations this is the case, primarily due to the high cost of coring boreholes in comparison to drilling with other techniques. Obtaining oriented cores is particularly expensive.

Figure 6.1-2 shows an example where lithology and stratigraphy could be inferred from gamma and conductivity log response, combined with knowledge of local geology, for Palaeozoic sedimentary rocks in southern Ontario. The log responses match virtually peak-for-peak, borehole-to-borehole.

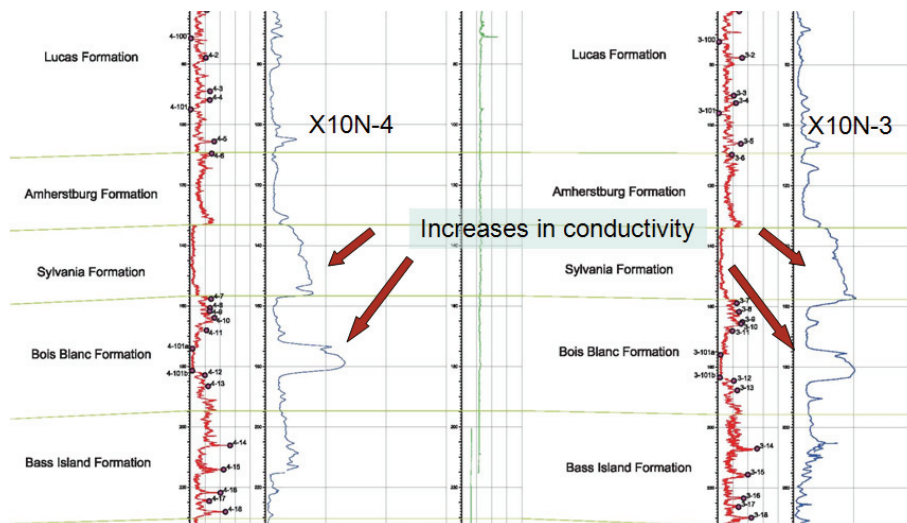


Figure 6.1-2: Stratigraphic correlation using gamma (red) and conductivity (blue) log responses in sedimentary rock. (Golder Associates)

The process of qualitative assignment of lithology and the correlation of stratigraphy between boreholes should, however, be approached with some caution. It is often more complex and even less applicable in crystalline rocks, where there can be abrupt lateral changes in rock type or rocks are folded, faulted and altered. Even within sedimentary rock basins, the character of a particular log response may change, for example, due to lateral facies changes (e.g. change in gamma response) or variability in pore fluid (e.g. change in conductivity or neutron response).

On Figure 6.1-3, the logs for induction resistivity, sonic Δt , neutron and natural gamma are presented as a cross-section for three boreholes located south of Chicago, Illinois. The boreholes are approximately equally spaced over a distance of 600 metres (<2,000 feet) and the geology is comprised of dolomite and shale. It is noted that although the character of individual logs change (e.g. induction resistivity in the Elwood Formation), the overall character of the suite of logs allows for a precise correlation of the stratigraphy.

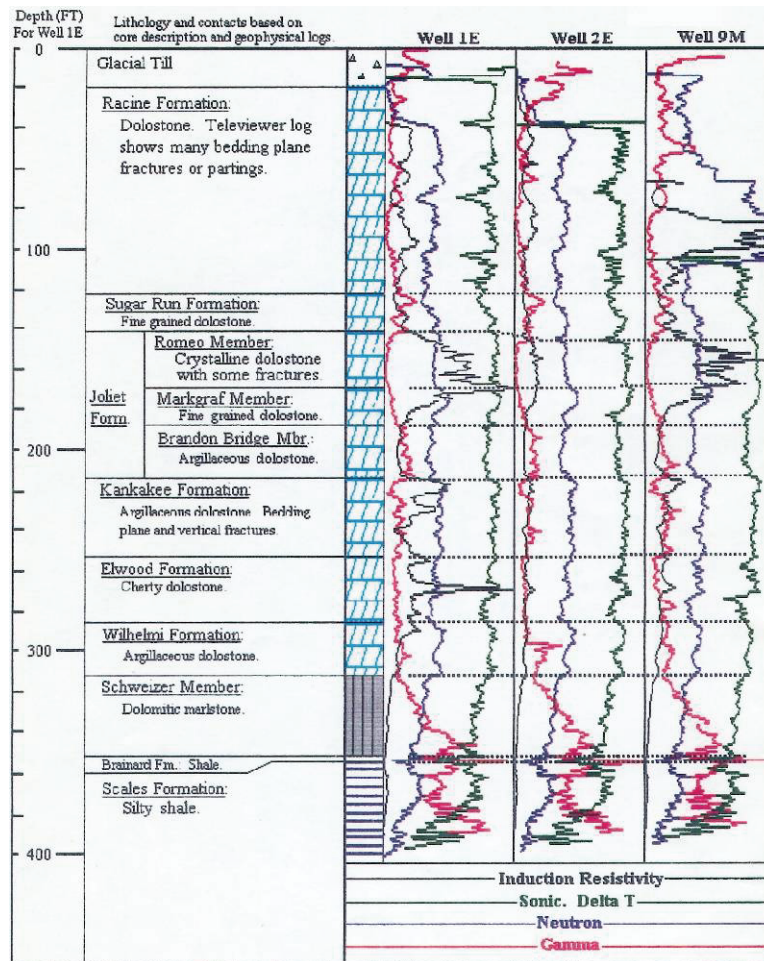


Figure 6.1-3: Example of stratigraphic correlation in sedimentary rock - Chicago, Illinois. (Golder Associates)

6.1.2 Quantitative Approaches

Quantitative analysis of log data for definition of lithology requires an increased level of interpretive care and skill. A number of the logging tools provide a partial estimate of the mineralogy but in combination can provide robust evidence of specific lithology within a given geologic setting. For any given site, these could include: natural / spectral gamma, gamma density, neutron porosity, photoelectric, sonic, electric or induction logs. All of these measure physical properties that can be partly diagnostic of lithology; when analysed in combination, for example using cross-plots or principal component analysis (PCA), they can be fully diagnostic.

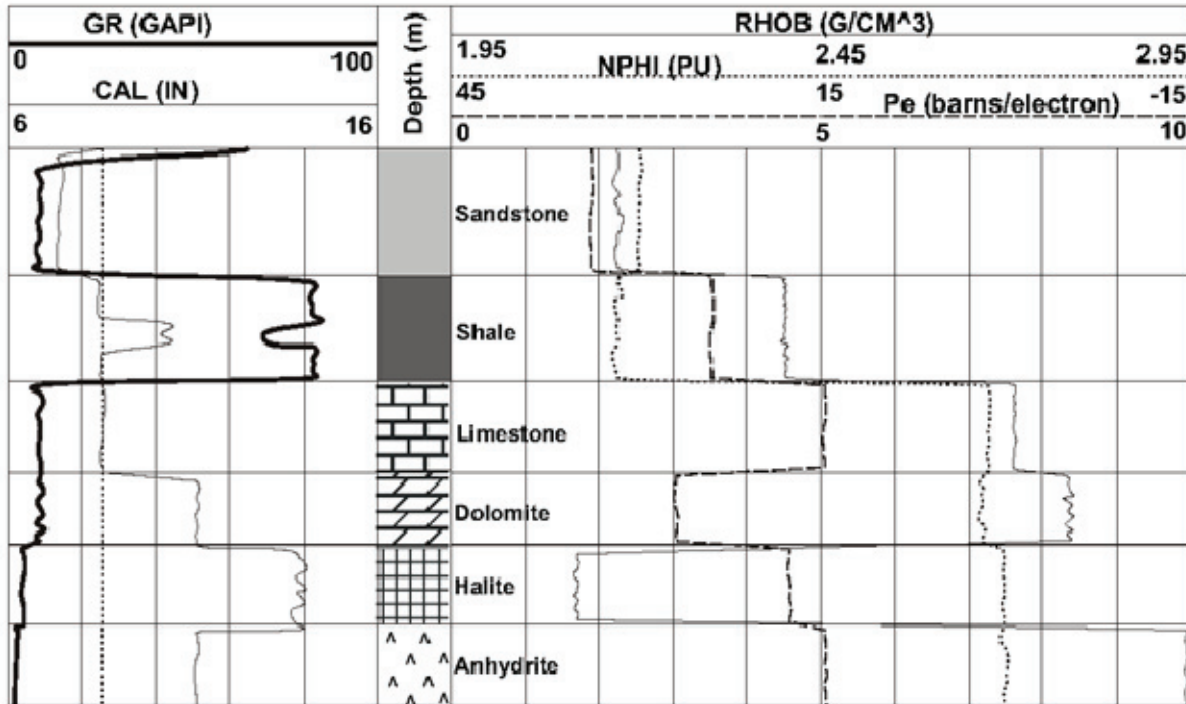


Figure 6.1-4: Typical log responses for sedimentary rocks. (GR – natural gamma, CAL – caliper, RHOB – gamma density, NPHI – neutron porosity and Pe – photoelectric adsorption index (Glover, 2009)

Figure 6.1-4 shows a typical set of log responses for sedimentary rocks where the differences in the combination of logs are indicative of specific lithology.

Cross-Plots and Principal Component Analysis (PCA)

A graph of two log responses versus one another is called a cross-plot. Cross-plots have been used extensively in the oil and gas industry for at least 50 years to determine sedimentary rock lithology and pore fluid properties. Any two geophysical logs can be cross-plotted with one another, for example gamma-neutron, neutron-sonic, gamma-density and gamma-resistivity are common types of cross-plots. A particular rock type generally occupies a certain area on the cross-plot graph. For example, a shale has a high natural gamma response and a low resistivity response, so it plots in the upper left quadrant of a gamma vs. resistivity cross-plot. Conversely, a limestone would plot in the lower right quadrant of the same cross-plot.

An example cross-plot of gamma-density vs. sonic logs acquired in a crystalline rock environment is shown on Figure 6.1-5, from MacMahon et al (2002). In this case, cross-plots are used to characterize the diamond bearing zones within kimberlitic rock formations. Note how each rock type (differentiated by the colour on the plot) plots in a unique area of the cross-plot space. Geophysical log responses are first correlated to diamond bearing zones in the rock core; subsequently, these zones can be identified solely on their geophysical log response when cross-plotted.

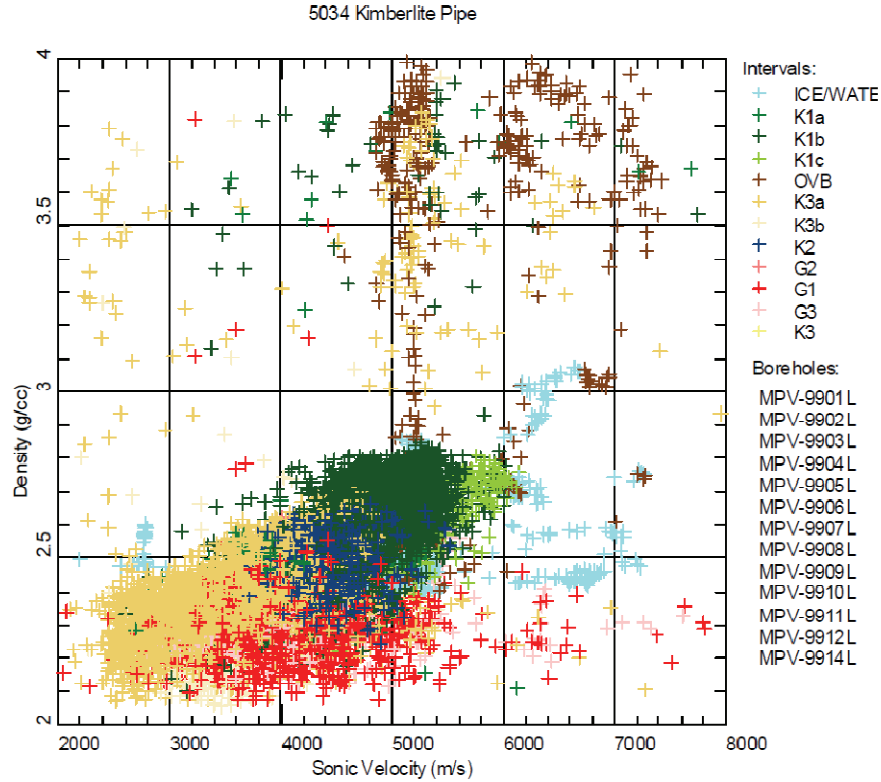


Figure 6.1-5: Density – sonic velocity cross-plot example for 5034 Kimberlite Pipe – Guacho Kue, NWT. (MacMahon et al, 2002)

Principal component analysis (PCA) is the extension of the cross-plot concept beyond two dimensions and can be used to automate the interpretation of geophysical log data (Kassenaar, 1989), as shown in the 3D cross-plot on Figure 6.1-6. Multi-parameter geophysical log interpretation for lithology at Guacho Kue, NWT, was integral in the development of a detailed geological model of the kimberlite pipes in the area.

5034 Kimberlite Pipe

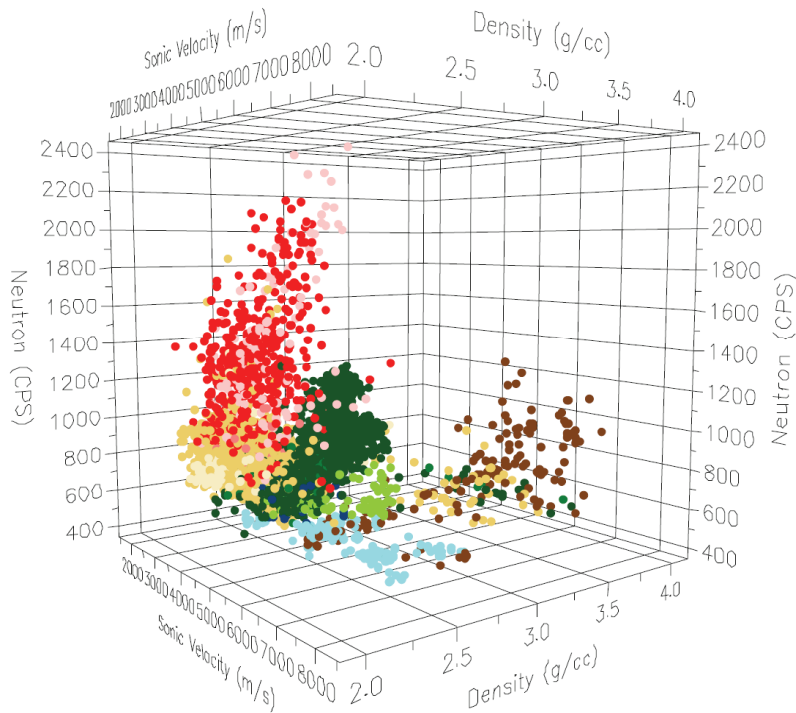


Figure 6.1-6: A 3D multi-well cross-plot example for 5034 Kimberlite Pipe (density – neutron - sonic) – Guacho Kue, NWT. (MacMahon et al, 2002)

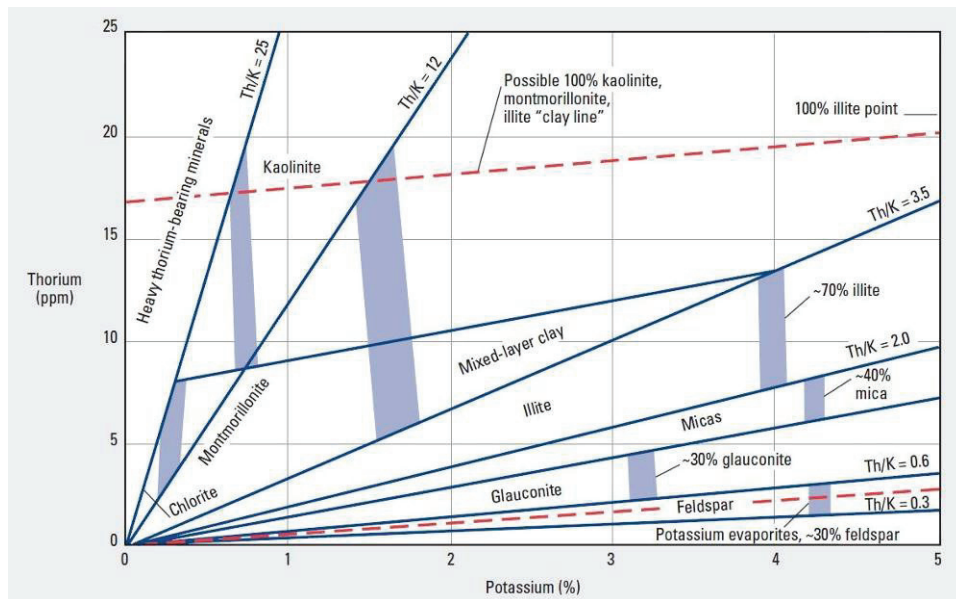


Figure 6.1-7: Example mineral identification chart for spectral gamma log responses. (Schlumberger, 2009)

Cross-plotting techniques and more complex interpretive charts continue to be used extensively in oil and gas exploration to identify lithology. The example chart shown on Figure 6.1-7 is used

to determine the type of minerals in a shale formation from the spectral gamma log response (Schlumberger Log Interpretation Chart Book - 2009).

When utilizing geophysical log data for the determination of lithology, the following key factors for success should be considered:

1. Tool Calibration - Even if all the correct calibration procedures are observed for the various logging probes, the calibrations need to be tied to the particular rocks and the wells logged. This can be done by acquiring samples for lab analysis and then comparing these data to logged results.
2. Borehole Rugosity - Variations in the diameter of the borehole (wash outs, voids, scour, etc.) are important in the log analysis process. If anomalies occur in the data that contradict the expected log response, it is important to examine the caliper data. Accurate caliper data are required to effect corrections to logs.
3. Bed Thickness - If the thickness of a bed is less than the vertical resolution of a logging tool, the response will be affected by adjacent beds – a true value for the bed will not be measured. In some cases, if the thickness of the bed is less than the sensor source-receiver separation on the probe, the resulting reading could be erroneous as in the case of a normal resistivity log.

Acquiring data with adequate vertical resolution is critical for lithological determination. For example, the vertical resolution required in oil and gas exploration may be significantly coarser than that required for an engineering or environmental application.

6.2 Physical Properties and Fluid Parameters

Another important objective of borehole-based geophysical measurements is to derive quantitative values for various physical properties of the rock mass intersected by the borehole. There are many properties that can be computed from individual logs or combinations of logs, including:

- Bulk Density;
- Elastic Moduli;
- Apparent Rock Hardness;
- Porosity / Transmissivity;
- Formation and Fluid Resistivity; and
- Temperature.

6.2.1 Bulk Density

Bulk density is calculated directly from the compensated density log response. Bulk density is inversely related to gamma-density response, noting that the gamma-density response is actually the electron density, but electron density and bulk density are directly related. The calculation is based on a best-fit to calibration data, with density generally being reported in units g/cm^3 . The density response can be adversely affected by irregularities in the borehole diameter (i.e. washouts and voids), therefore it is important to interpret density log data in conjunction with a caliper log.

6.2.2 Elastic Moduli

Elastic moduli of rocks can be estimated in situ from geophysical measurements of bulk density, compressional velocity (V_p) and shear velocity (V_s). Typically, the in situ measurements of V_p and V_s are considered to be more representative than measurements made on core samples.

Measurements of compression and shear velocities and bulk density can be derived from essentially two volumes from within a borehole: the near borehole environment (full wave form sonic and compensated density logs) and a deeper formation or bulk measurement (compression and shear wave VSP and borehole gravity). The former provides detailed information in the near vicinity of the borehole (within 0.5 metres) and the later represents more of a bulk measurement possibly over as much as tens of metres. The near borehole measurements may include non-representative estimates due to a number of borehole effects such as fluid invasion, borehole rugosity and stress relief. The bulk volume measurements may lack resolution and these data may not be readily available due to the added cost of acquiring the data, as VSP and borehole gravity surveys are typically supplied by the larger logging companies that service oil and gas exploration activities.

Values for Poisson's ratio (ν), shear modulus (G), Young's modulus (E) and bulk Modulus (K) are calculated from compression and shear wave velocities and bulk density as:

Poisson's Ratio:	$\frac{(\text{lateral strain})}{(\text{longitudinal strain})}$	$\nu = \frac{\frac{1}{2}(V_p / V_s)^2 - 1}{(V_p / V_s)^2 - 1}$
Young's Modulus:	$\frac{(\text{applied uniaxial stress})}{(\text{normal strain})}$	$E = V_p^2 \rho (1 + \nu)(1 + 2\nu) / (1 - \nu)$
Shear Modulus:	$\frac{(\text{applied stress})}{(\text{shear strain})}$	$G = E / (2(1 + \nu))$
Bulk Modulus:	$\frac{(\text{hydrostatic pressure})}{(\text{volumetric strain})}$	$K = 2G(1 + \nu) / 3(1 - 2\nu)$

where ρ is the bulk density in kg/m^3 , V_p is the compression wave velocity (m/s) and V_s is the shear wave velocity (m/s). Poisson's ratio is a unitless parameter.

Continuous values for V_p , V_p & V_s , and ρ are available from sonic, full wave form sonic and gamma density logs respectively. Estimates for V_p & V_s can be either picked from the variable display logs (VDL) or automated picking routines can be applied – usually a combination of both. Modulus logs can then be calculated with the log calculation option available with most processing software and the equations provided above. However, these logs may contain random measurement and picking errors. To reduce the effect of these errors and to derive representative engineering modulus values, the following general procedure can be applied:

1. Zones of approximately homogeneous sonic and density characteristics are picked using the full wave form sonic, density and other logs. These usually correspond to lithologic zones within named formations.

2. Average values of V_p , V_s , and ρ are assigned over the zones of interest. Results from other tests (borehole gravity and VSP) can be used to refine the estimation of average values.
3. These “averaged” logs can then be used to derive new logs for the modulus values. At this point, the results should be compared to measurements made on core – either in the spreadsheet or as imported “mud-logs” in the log processing software.

6.2.3 Apparent Rock Hardness Log

One of the logs that can be computed from acoustic televiewer (ATV) data is an Apparent Rock Hardness (Arh) log (Figure 6.2-1), which is intrinsically related to elastic moduli of the rock. This log is an approximation of a qualitative formation property, percent rock hardness.

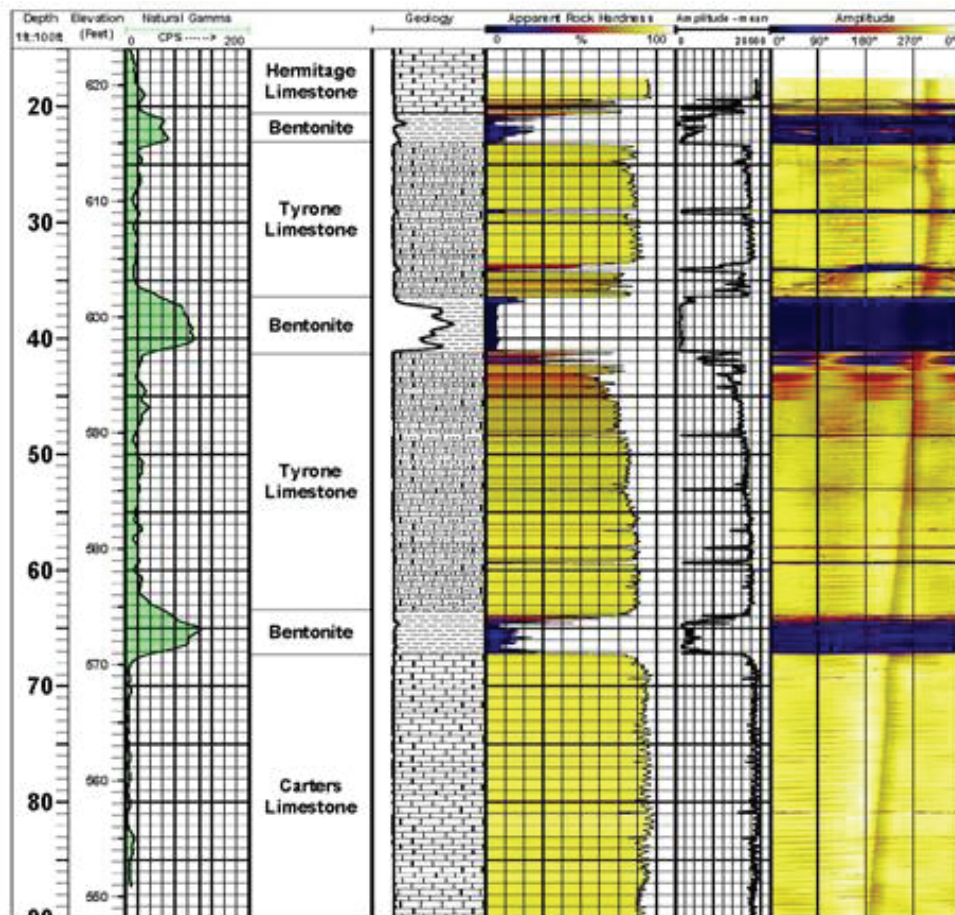


Figure 6.2-1: Example of a computed apparent rock hardness log. (Golder Associates)

An acoustic televiewer (ATV) tool produces an image of the borehole wall from the amplitude and travel time of a reflected acoustic signal. The tool emits an ultrasonic beam that travels through the tool's acoustic head and borehole fluid to the borehole wall. At the borehole fluid and formation interface when the beam strikes the formation, a part of the beam's energy is reflected back to the tool, the remainder continuing on into the formation at a changed velocity. The energy of the reflected signal is measured in dB, a unitless ratio of the detected signal's amplitude divided by the amplitude of the transmitted signal.

The principle behind a computed Arh log is that the amplitude of the reflected signal is primarily dependent on the impedance contrast between the borehole fluid and formation. This contrast can be described by the reflection coefficient r , which is given by the equation:

$$r = \frac{\rho_b c_b - \rho_m c_m}{\rho_b c_b + \rho_m c_m}$$

where ρ_b is the density of the formation, ρ_m is the density of borehole fluid, c_b is the speed of sound in formation and c_m is the speed of sound in borehole fluid. As the reflection coefficient increases, so does the reflected signal amplitude. The equation used to compute an Apparent Rock Hardness log A_{rh} is:

$$A_{rh} = \frac{(\text{Amplitude Mean} * \text{Borehole Factor})}{\text{Amplitude Normalizing Factor}} * 100$$

where, *Amplitude Mean* is the statistical mean of the amplitude image, a log created from the amplitude image, *Borehole Factor* is a factor used to normalize the log for different borehole conditions across a given site, such as different borehole diameters, etc., and *Amplitude Normalizing Factor* is a factor used to normalize to the amplitude maximum across a given site.

Tool centralization is critical to obtaining an Arh log that is representative of the formation. Even the slightest decentralization will negatively impact the computed log; usually resulting in an erroneously low formation rock hardness assessment. This can be seen in Figure 6.2-1 from 41ft to 55ft where the ATV has become slightly decentralized as it passes the washed-out bentonite zone from 36ft to 41ft.

Another factor is the type and model of the acoustic viewer used; whether it is an older model, such as the ALT FAC40, or a newer model, such as an ALT ABI40 (a full-waveform tool). The method by which the tool applies signal gain is an important consideration for determining the *Amplitude Normalizing Factor*.

6.3 Rock Structure

Geophysical measurements in the borehole provide information regarding rock structure at two spatial scales:

- Detailed structure at the borehole scale, where structures intersect the borehole (borehole imaging logs); and
- Structure between boreholes (cross-hole seismic reflection, seismic tomography) or beyond the borehole wall (VSP, borehole gravity).

6.3.1 Borehole Imaging Logs

Borehole image logging techniques are described in Section 3.7 and while these methods provide the most detail, the information is highly localized.

Data acquired with televiewer tools is comparable to the more traditional oriented core methods (e.g. clay impression, easy mark and ball mark systems). There is a clear advantage in that televiewer tools can acquire oriented images of the wall in a vertical borehole where most of the oriented core techniques do not work (Figure 6.3-1 top). Also, if a zone is highly fractured or broken, the oriented core systems will not work as the core will be broken in the core barrel upon retrieval (Figure 6.3-1 bottom).

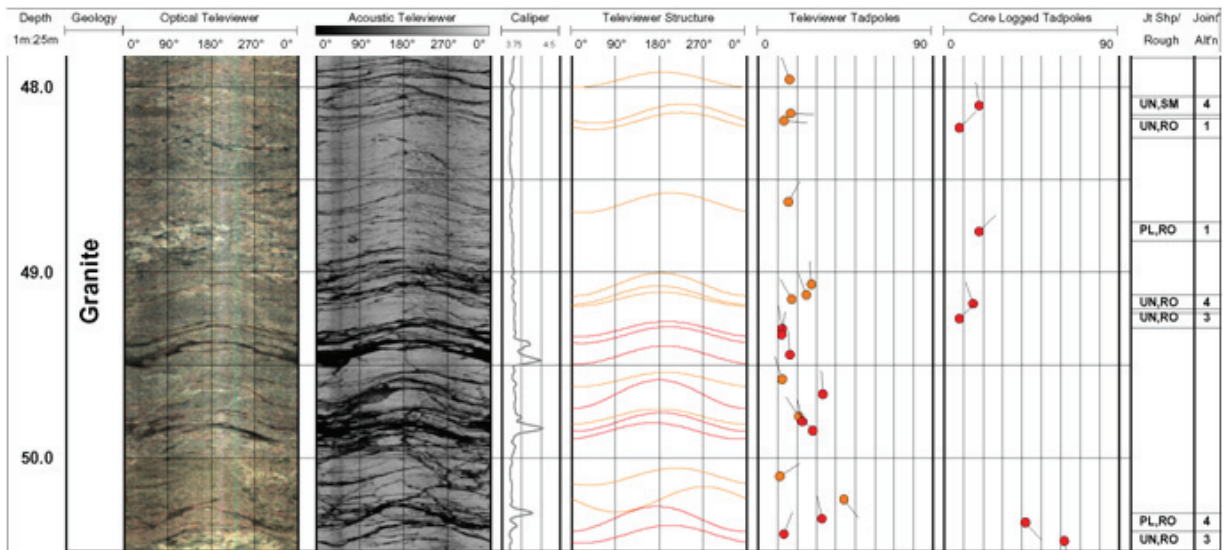


Figure 6.3-1: Televiwer data can provide structural information in a vertical borehole (top) and through intervals where core recovery is poor, e.g. 48.5 to 52.0 m (bottom). (Golder Associates)

As described in Section 3.7, processing of the televiwer data for structure involves marking the planar features that intersect the borehole with sinusoids; either with the images oriented to high side in the borehole (in the case of an inclined borehole) or oriented to magnetic north. These data can later be rotated to true north, and then imported into structural analysis software.

From the televiwer data, it is possible to measure dip and dip direction, fracture aperture and make an estimate of the roughness. However, it is generally not possible to make detailed observations about alteration associated with the fracture or gouge or to see the fracture surface to check for evidence of slickensides.

6.3.2 Cross-Hole Surveys

The surveys that extend the mapping of structure beyond the borehole can provide information at the site or even regional level (Figure 6.3-2). These include cross-hole seismic reflection, tomography and VSP surveys.

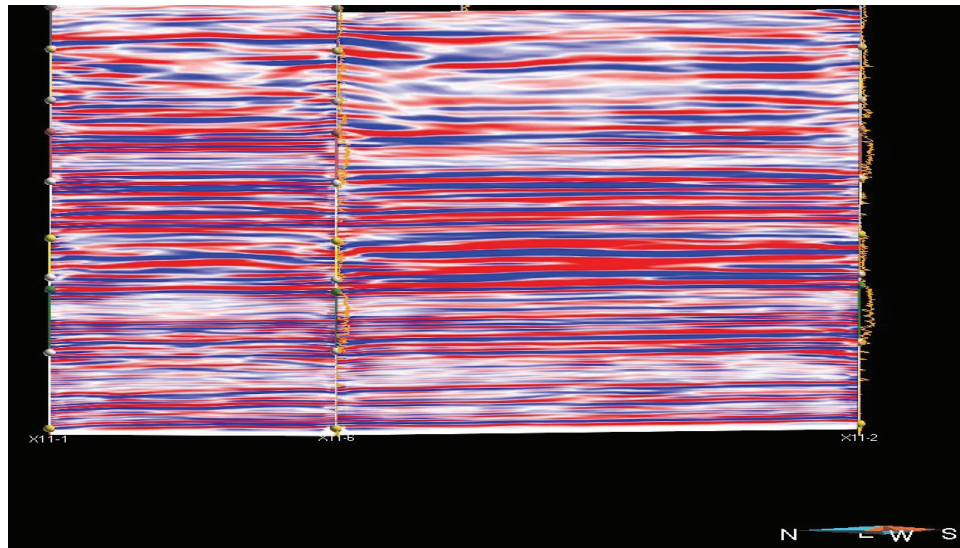


Figure 6.3-2: Cross-hole seismic reflection survey results in Palaeozoic sedimentary rock - Windsor, Ontario. (Z-Seis Reservoir Imaging)

Cross-hole and VSP methods are most useful in site investigations when they can be combined with the borehole scale data obtained through televiewer surveys.

Borehole gravity is another technique for inferring the presence of structure beyond the borehole albeit, the method lacks directionality. However, if borehole gravity is run in more than one borehole, it may be possible to remove the ambiguity from a single borehole survey and triangulate to estimate the location of the anomaly.

6.4 Hydrogeologic (Hydraulic) Properties

6.4.1 Porosity Methods

The hydrogeologic properties of porous sedimentary rocks (e.g. sandstones and shales) are mainly determined by properties of the porous matrix, mainly its porosity.

Porosity can be obtained from a variety of logs but the main ones are the neutron, gamma-density and sonic logs. The log response for each of these methods is affected by formation porosity, borehole fluid and formation matrix. The tool response for each can be related to porosity if the matrix and fluid effects can be determined. It is noted that these porosity techniques respond to the formation characteristics immediately adjacent to the borehole and the depth of investigation varies from 0.1 to 1 m depending on the measurement type.

Sonic Porosity

Sonic porosity estimates are based on the Wyllie Time Average Equation (Wyllie et al., 1958) which has the form:

$$1/v = \phi/v_f + (1-\phi)/v_m$$

where ϕ is the sonic porosity estimate, v is the formation velocity, v_f is the fluid velocity and v_m is the formation matrix velocity. Sonic logs are usually presented as the interval transit time (Δt)

in units of $\mu\text{s/m}$ (or $\mu\text{s/ft}$) of a compression wave travelling through 30.48 cm (1 ft) of formation – the receiver separation for most sonic tools - and the equation reorganizes to the following:

$$\phi_{\text{sonic}} = (\Delta t_{\text{log}} - \Delta t_{\text{ma}}) / (\Delta t_{\text{f}} - \Delta t_{\text{ma}})$$

where Δt_{log} is the transit time of the formation, Δt_{ma} is the transit time of the matrix and Δt_{f} is the transit time of the fluid. This relationship is used to calculate the porosity for consolidated sandstones and carbonates with intergranular porosity. Sonic porosities of carbonates with fractures are calculated based on the matrix velocity rather than secondary porosity and the values obtained do not represent total porosity.

Neutron Porosity

Neutron porosity is a measure of the hydrogen ion concentration in the formation, as hydrogen ions have the greatest effect in slowing down and capturing neutrons. Because hydrogen in the porous formation is concentrated in water filled pores, the lost energy is a function of the porosity. The matrix and type of fluid also have an effect but the log is calibrated to read the correct porosity assuming that the pores are filled with fresh water for limestone, sandstone or dolomite. The calibration must be completed at facilities where the porosities of the materials around specially constructed boreholes or tubes are known and also for borehole diameter. The calibration process is based on a regression technique and involves relating count rates to percent porosity.

Neutron logs are affected by bound water (e.g. gypsum) and saline formation water (Cl^- also has a large capture cross-section). The depth of investigation is about 15 cm so the log responds to porosity in the invaded zone around the borehole. Another key point is that the neutron porosity log is strongly affected by clay and gas – gas has a low hydrogen density, so that gas zones have very low apparent porosity.

Density Porosity

The compensated density log measures the electron density (bulk density) of the formation. Formation bulk density is a function of the matrix density, porosity and fluid density. For a clean formation of known matrix density, ρ_{ma} , having a fluid density of ρ_{f} , and a measured bulk density of ρ_{b} , density porosity, Φ_{den} can be calculated as:

$$\phi_{\text{den}} = (\rho_{\text{ma}} - \rho_{\text{b}}) / (\rho_{\text{ma}} - \rho_{\text{f}})$$

The main tool for adjusting density porosity estimates is to adjust the input for the matrix porosity to match with other estimates of porosity such as neutron and sonic porosity and direct measurements on core.

Density-Neutron Porosity

The combination of density and neutron logs is used commonly as a means to determine porosity in sedimentary rocks that is largely free of lithology effects. Each individual log records an apparent porosity that is only true when the zone lithology matches that used by the logging engineer to scale the log. A limestone-equivalent porosity is a good choice for both neutron and density logs, because calcite has properties that are intermediate between dolomite and quartz. By averaging the apparent neutron and density porosities of a zone, effects of dolomite and quartz tend to cancel out. The true porosity may be estimated either by taking an average of the two log readings or by applying the equation:

$$\phi = \frac{\sqrt{\phi_n^2 + \phi_d^2}}{2}$$

where Φ_n and Φ_d are neutron and density porosities. It has been suggested that the square-root equation is preferable as a means of suppressing the effects of any residual gas in the flushed zone.

Porosity Analysis

For larger investigations, where there may be a statistically significant number of core samples with measurements for porosity and grain density, analysis is conducted to determine if these data can be used to calibrate the geophysical logs. Even when density, neutron and sonic logs are plotted with a porosity scale based on system calibrations, it is essential to correct the calibration based on the core sample data from each unique geologic layer being logged.

One approach is to compare sonic porosity against density porosity and usually the comparison will show that differences are related to clay content, where the greatest departure corresponds to shale layers. In a dolomite-shale sequence, since the error in the density porosity is related to clay content in dolomite (which reduces the grain density) the natural gamma log can be used to effect a correction. To estimate the percent shale, it is necessary to estimate the clay content in the cleanest and shaliest layers and record the associated natural gamma minimum and maximum log responses.

$$\%Shale = (\gamma_{\log} - \gamma_{\min}) / (\gamma_{\max} - \gamma_{\min})$$

where $\gamma_{\log}$ is the log response, $\gamma_{\min}$ is the log response corresponding to the cleanest material and $\gamma_{\max}$ is the log response corresponding to the shaliest layer. The shale volume as a percentage can then be used to correct the density porosity according to the following equation:

$$\Phi_{\%shale} = \frac{[(\%shale) * 2.65 + (1 - \%shale) * 2.87] - \rho_b}{[(\%shale) * 2.65 + (1 - \%shale) * 2.87] - \rho_f}$$

where %shale is the shale volume, $\Phi_{\%shale}$ is the shale corrected density porosity, ρ_b is the bulk density from the density log and ρ_f is the density of fluid. The densities of shale and dolomite are 2.65 and 2.87 g/cm³ respectively. This discussion provides one of a number of techniques for effecting a correction to the density porosity log. It is necessary to compare the results to measurements made on core samples and determine if the correction is appropriate. The log response is a bulk volume measurement over a volume of 40 cm in height with a depth of investigation of 15 cm whereas the samples may be as small as a piece of chalk.

The SP log can also be used in some circumstances to estimate shale content and therefore correct porosity estimates from log responses.

6.4.2 Fracture Transmissivity Methods

The hydrogeologic properties of crystalline and massive sedimentary rocks (e.g. limestone and dolomite) are mainly determined by the hydraulic conductivity of fractures and bedding planes within the rock. Matrix porosity in these rocks is negligible, falling in the range of < 0.1 to no more than 0.5%, and consisting of microfractures present on mineral grain boundaries (Nelson

et al, 1983; Long et al, 1996). This minimal porosity may influence the propagation of tracers and the retardation of solutes, but does not affect the large-scale rate of flow through the rock mass.

A large part of borehole characterization of hydrogeologic properties involves the characterization of fracture populations and the identification of that subset of fractures associated with measurable flow. The relative size of fractures intersecting boreholes can be estimated from various borehole measurements, including caliper, electric and televiewer (optical and acoustic) logs. The size of fractures or sets of fractures varies between these measurements because fractures consist of a complex combination of features, including water-filled openings or flow channels between asperities in contact along the fracture face, infilling mineral deposits and an alteration halo where exposure to groundwater has enhanced mineral grain weathering. Local estimates of fracture size are also influenced by mechanical damage and stress relief associated with drilling. The permeability within a single fracture is heterogeneous because part of the fracture face is in contact at asperities, and flow occurs along irregular channels between these contact points.

Variation of permeability within the local fracture is almost always impossible to characterize. Instead, local fracture permeability is given as transmissivity (T). The transmissivity of sets of fractures identified as hydraulically active during flow meter or other hydraulic tests is estimated by modelling borehole flow logs or isolating individual fracture zones with straddle packers and conducting hydraulic slug tests or using tracer test methods on that isolated zone (Paillet et al, 2000).

Numerous studies demonstrate that fracture transmissivity can be inferred from flow meter logs in fractured formations (Long et al, 1996). Comparison of such tests with T given by straddle-packer hydraulic tests generally confirms that the flow meter analysis gives similar results (Paillet, 1998). However, this applies to only the two highest orders of magnitude of transmissivity in a borehole. The scatter in depth point flow measurements or the noise in logged flow logs make it impossible to identify minor inflow or outflow zones in the presence of flow between much more productive zones. Fluid column logs may sometimes help identify minor zones when they lie below all of the more productive zones. Nonetheless, the necessity of collecting data in open boreholes imposes the lower limit on fracture transmissivity characterization.

Although fracture zone transmissivity is relatively simple to estimate from flow meter logs, fracture storativity is not. The water produced from fractures by changes in hydraulic gradient are produced by the small changes in fracture aperture associated with changes in confining stress on the openings between asperities in fracture faces. Straddle-packer aquifer tests generally show that the fracture storage coefficient, defined as the volume of water released per unit area of fracture per unit water level decline (unitless), is of the order of 10^{-5} or 10^{-6} or less. Fracture storage is therefore exceedingly small, and drawdown propagates outward very quickly in aquifer tests.

It is impossible to measure these rapid changes in a single borehole by the usual methods even though some models suggest that these measurements are at least theoretically possible (Kabala, 1994). The one single-borehole method that does provide the ability to make a direct measurement of fracture storage coefficient is the in situ extensometer. This is an extremely sensitive device that is capable of measuring the changes in fracture aperture as a function of drawdown in the borehole (Schweisinger et al, 2009). This device is only available from a few research programs and is not generally provided as a service by commercial contractors.

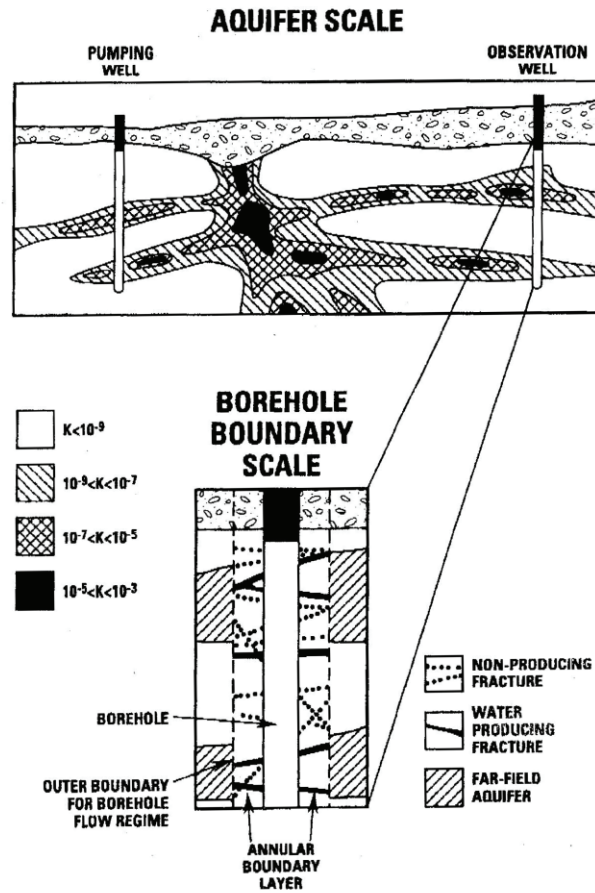


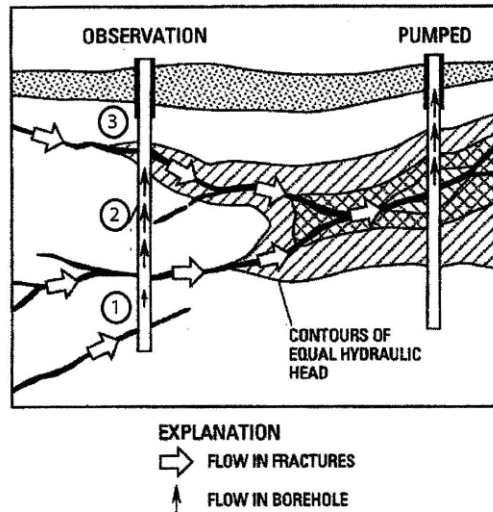
Figure 6.4-1: Schematic illustration of the fractures controlling the flow in the immediate vicinity of a borehole with the large-scale structure of fracture flow zones in the surrounding rock mass.

Almost all studies of rock mass permeability in fractured rocks conclude that the pattern of fracture connectivity and not the permeability of individual fractures control the large-scale rate of flow (Long et al; 1996). Borehole methods can also be used to infer the large-scale structure of flow paths in the rock mass. This can be done by using borehole image logs to infer the properties of the entire fracture population, and of that much more restricted set of fractures associated with measurable transmissivity. Various statistical models can be used to generate possible fracture flow network models, which can be checked against aquifer tests. More direct information about large-scale flow paths in the rock surrounding a borehole can be obtained by estimates of hydraulic head variations among the various transmissive fractures or fracture zones inferred from flow meter logs. When fractures have very similar water levels they are probably in hydraulic communication in the surrounding rock. If they are hydraulically isolated, flow meter logging will probably detect the presence of ambient flow in the open borehole, and flow log analysis will indicate that fractures are connected to reservoirs with distinctly different water levels.

One major disadvantage of borehole logging in estimating the large-scale hydraulic properties of rocks is the requirement that aquifer tests communicate with the surrounding aquifer or aquifers by means of a discrete set of individual fractures that control flow into or out of the borehole (Figure 6.4-1). This schematic illustration shows how the discrete fractures connect the local

borehole to the surrounding fracture flow system by means of a few specific fractures drawn from the much larger population of such fractures in the rock mass. The fractures in the annular region surrounding the borehole conduct flow from the far-field hydraulic boundaries, so that flow losses associated with flow along the fractures in the annular boundary need to be taken into account when conducting hydraulic tests to infer the properties of the large-scale aquifer.

A. Illustration of transient flow and heads in a fractured aquifer



B. Transient vertical flow measurements at three depths in the observation borehole

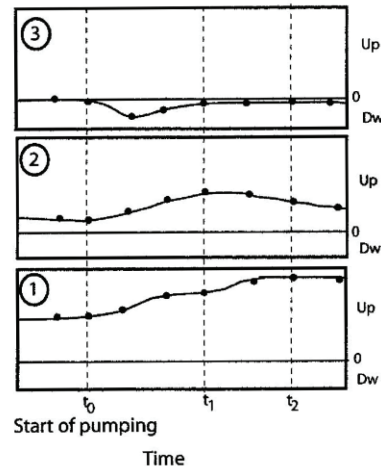


Figure 6.4-2: Cross-borehole flow experiment at Mirror Lake, New Hampshire indicating that steeply dipping fractures intersecting individual boreholes matches the type curve for a large horizontal fracture connecting the boreholes.

The most effective borehole logging method in characterizing the relationship between local fractures and the far-field aquifer is the cross-borehole flow meter test. For example, a series of boreholes at the USGS Mirror Lake study site showed steeply-dipping fractures intersecting each borehole (Paillet, 1998). One or more of these fractures was found to be transmissive in single-well tests in each borehole. Cross-borehole tests showed unambiguously that flow induced in one borehole by pumping in another fit the type curve for a single fracture of uniform transmissivity and storage coefficient (Figure 6.4-2), even though local flow into or out of boreholes occurred by means of steeply dipping fractures. Subsequent study showed that the fractured bedrock at the Mirror Lake site was characterized by many of these subhorizontal zones. These probably represent stress-relief features produced by uplift and unloading as the Wisconsin continental ice mass melted. The zones were apparently created by connecting short segments of existing, dipping fractures rather than by the development of entirely new subhorizontal fractures (Shapiro et al, 2007).

Although fracture characterization using borehole geophysics features in numerous studies of large-scale fracture flow in bedrock formations, additional information is almost always required to relate the local fracture populations to rock-mass hydrogeology. This additional information can be provided by surface geophysical sounding, multi-well aquifer tests and regional geologic mapping. Development of useful models is thus an iterative process of integrating data from numerous scales and testing various alternative aquifer configurations. A single example illustrates how apparently similar fracture populations can be assembled into very different flow systems. Shapiro et al (2007) and Leborgne et al (2006) describe nominally similar granitic bedrock aquifers where individual fractures are associated with a wide range of transmissivity

values from 10^{-4} to 10^{-8} m²/s. Shapiro shows that the large-scale transmissivity of the aquifer is approximated by the lower limit of this cloud of data points because large-scale flow is controlled by the relatively low transmissivity of the rock in intervals separating permeable fracture sets. In contrast, LeBorgne shows that large-scale transmissivity is controlled by a major local fault zone so that large-scale transmissivity is approximated by the upper limit on the cloud of transmissivity values. The importance of using local geologic and surface geophysical information in establishing these two aquifer models is self-evident.

6.5 In Situ Stress Investigations

Estimation of the in-situ stress state is particularly important when evaluating the suitability of a site to host a deep geological repository or similar large scale underground structure. Several factors that are essential for developing a comprehensive geomechanical model of the site such as placement location, rock permeability and tunnel stability are directly influenced by the magnitude and orientation of the principal stresses. Therefore, it is critical to constrain, as much as possible, the underground stress tensor despite its complexities. This section describes how borehole geophysical techniques are used as part of various stress investigation methods.

6.5.1 Hydraulic Fracturing

Hydraulic fracturing (hydrofracturing) is a common technique that can be used to great depths and in almost any rock formation to determine the state of stress in boreholes. The technique is carried out in an open borehole below the water table. The hydro-fracturing technique measures the least principal stress in the plane normal to the borehole axis. This is done by pumping a small volume of water into unfractured sections of the borehole that are isolated by inflatable straddle packers (Figure 6.5-1).

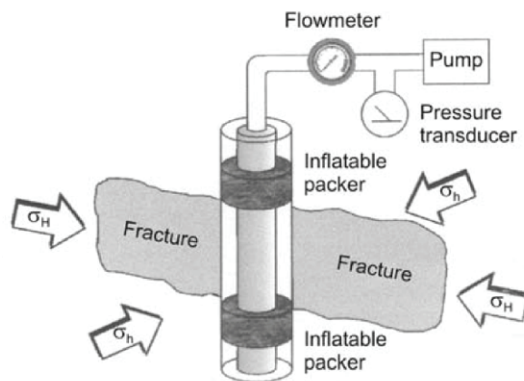


Figure 6.5-1: Schematic illustration of the hydraulic fracturing technique for in situ stress measurements.

After sealing off these portions of the borehole, water is pressurized to the point of generating a small rock fracture. Usually this pressure varies from about 35 bar (3.5 MPa) in soft rocks to over 140 bar (14 MPa) in hard rocks (Ramstad, 2004). The fluid pressures necessary to create, sustain and reopen tensile fractures are recorded as a function of time. Following the fracturing of the formation, the drop in pressure is measured as the water leaks off. The pressure should drop until the pressure drop-off is no longer linear, which is interpreted to be the in-situ closure stress point (shut-in pressure or P_s) representing the minimum horizontal stress for that depth (Figure 6.5-2). The fracture will re-open with re-pressurization (reopening pressure P_r). Elementary elastic relationships are established between the two recorded pressures and *in situ* stresses and between fracture direction and stress orientation. Both the two horizontal

components of stress (S_h and S_H) are determined mainly from these two borehole pressures (P_s and P_r) as indicated by the following equations (Haimson and Cornet, 2003):

$$P_r = 3S_h - S_H - P_p \quad (\text{Equation 6.5-1})$$

$$P_s = S_h \quad (\text{Equation 6.5-2})$$

with P_p being the pore pressure of the fracture before opening. In a vertical hole, the hydrofrac is expected to be vertical and perpendicular to the minimum horizontal stress. In hydrofracture stress measurements, Equation 6.5-1 indicates that the magnitude of the maximum horizontal stress (S_H) is estimated from the borehole pressures required to close and to reopen an induced axial crack.

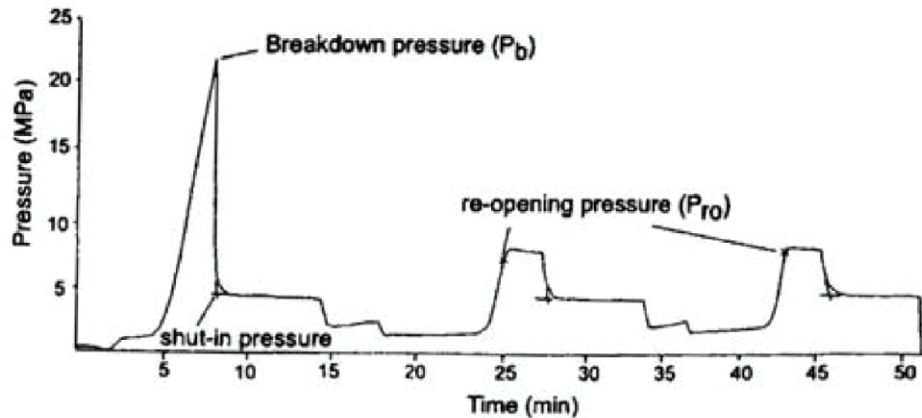


Figure 6.5-2: A typical pressure versus time plot obtained during a hydraulic test.

Acoustic and optical borehole televiewer, formation micro-scanner, caliper or down-hole camera logs are often acquired prior to hydro-fracturing to image fractured zones and to locate suitable unfractured intervals of the borehole wall. After completion of the hydro-frac testing, logging is repeated to record the effects of the test and to measure the orientation, direction and distribution of the induced hydraulic fractures (Figure 6.5-3). Figure 6.5-3 clearly identified the presence of near-vertical induced fractures around an azimuth of about 150° . An impression packer-oriented tool can also be used to measure the orientation of the induced fractures but these are difficult to deploy and often the impressions are indistinct or the orientation is inaccurate.

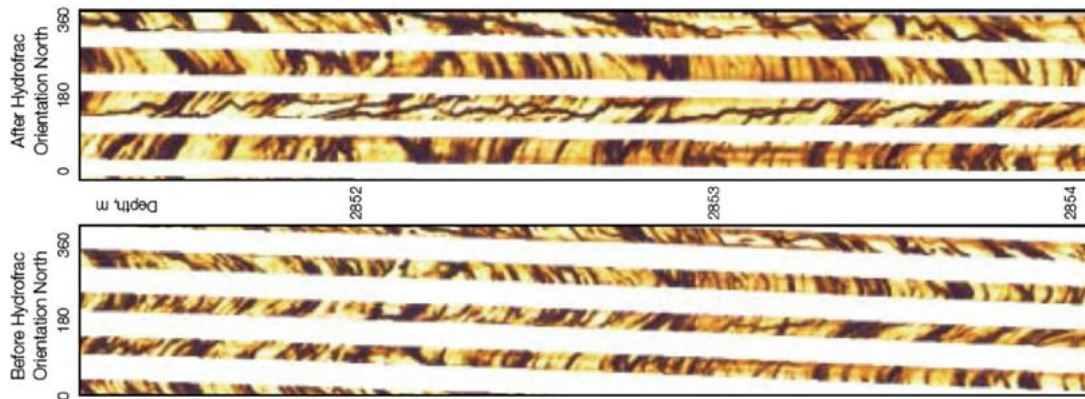


Figure 6.5-3: MicroScanner images before and after hydraulic fracturing in the KTB borehole, Germany. (Bram et al, 1995)

When hydraulic methods are employed for stress measurements at great depths, the three-dimensional stress field can only be assessed by combining several methods and/or measurements.

6.5.2 Over-Coring

Over-coring, commonly used in shallow boreholes, has the advantage of providing an estimate of the full 3D stress tensor using a single measurement. The over-coring technique requires several stages. First, a borehole is drilled to a desired depth and, after removing the core, the bottom of the hole is flattened with a special drill bit and a concentrically smaller diameter hole is drilled approximately 30 cm deeper. A cell that contains a strain gauge rosette and an oriented device is inserted into the hole with a special tool and glued to the bottom of the hole. After the measuring cell is fixed to the borehole and initial reading is done, the small hole is then overcored by a larger diameter bit allowing stresses to be relieved from the core and recorded by the strain gauge. The core is then caught with a special core catcher and a second measurement is done. The recorded strains and the elastic parameters determined from biaxial tests on the core will permit the determination of the stress field.

Although this technique is known for its limitations in terms of rock volume covered and over-coring depth, recent over-coring studies have been successfully conducted at great depth (650 m). This is the case for example at the SKB Forsmark site where they used the Borre probe, which is presently the only three-dimensional over-coring cell that allows measurements in deep (> 500 m) water-filled, vertical boreholes (Sjöberg et al., 2008). A recent compact conical-ended borehole over-coring technique has been developed for rock stress measurement at great depth in a water-filled vertical/sub-vertical borehole (Sakagushi et al., 2003).

6.5.3 Borehole Breakouts

Borehole breakouts, which are a natural phenomenon occurring in deep boreholes subjected to high in-situ stresses, are also an important indicator of horizontal stress orientation. They can be measured using mechanical (caliper), acoustic televiewer (BHTV) or electrical resistivity tools such as the Formation MicroScanner (FMS) and Formation MicroImager (FMI). Borehole cameras can also be used to image borehole breakouts. These breakouts are stress-induced enlargements of the wellbore and are due to a concentration of stresses in the wellbore wall due to the removal of material during drilling.

The development of intersecting conjugate shear planes produces the break-off of part of the borehole wall. If the borehole is vertical, these breakouts occur in the direction of the minimum horizontal stress S_h where tangential stress concentration is a maximum (Figure 6.5-4). Therefore, the elongated direction of borehole breakouts is oriented approximately normal to the maximum horizontal stress (S_H) orientation (Plumb and Hickman, 1985). Previous breakouts analysis results have shown consistency with other indicators of stress direction such as hydraulic fracturing, overcoring measurements or earthquake focal mechanisms. If breakouts are commonly used to infer stress direction, it has also been shown that in non-vertical holes it is possible to estimate the direction of all three principal stresses and provide constraints on their relative magnitude (Zajac and Stock, 1997).

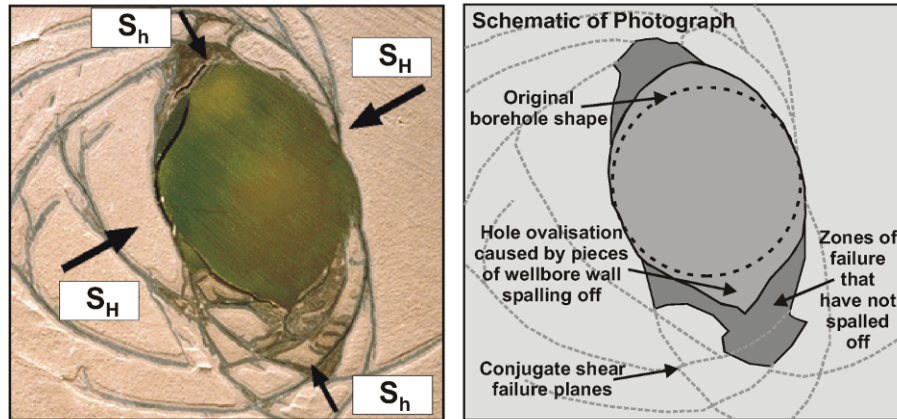


Figure 6.5-4: Results of a hollow cylinder lab test simulating borehole breakout. (Reinecker et al, 2003)

Breakouts have been observed and oriented by studying 4-arm dipmeter logs in the Western Canadian Sedimentary Basin, with the majority of breakouts observed between depths of 1000 to 3500 m.

6.5.4 Microseismic Monitoring

A new approach for estimating the in-situ stress state by analyzing microseismicity induced by hydraulic injections has been developed for fractured reservoir characterization (Tezuka and Niitsuma, 2000; Tezuka et al., 2008). Microseismic monitoring was conducted after a large hydraulic injection in order to delineate the spatial distribution of fractures. Source locations were estimated by a hypocenter determination technique and the stress tensor estimated from focal mechanisms analysis. Results indicate that the preferential direction of microseismic events showed a good consistency with the fracture network model developed using fracture information obtained from core samples, acoustic borehole televiewer images and pressure, temperature and spinner logs.

6.6 Well Inspections

Hydrogeologic characterization is an important component of the investigation of a deep geological repository candidate site. Groundwater monitoring wells are used to measure hydraulic pressures, obtain water quality samples and conduct aquifer response tests. The assurance of proper well construction (casing, bond, seal placement, and screen location and integrity) is critical to ensuring the quality of the hydrogeologic data obtained from these wells and also to isolate groundwater producing zones from cross-contamination.

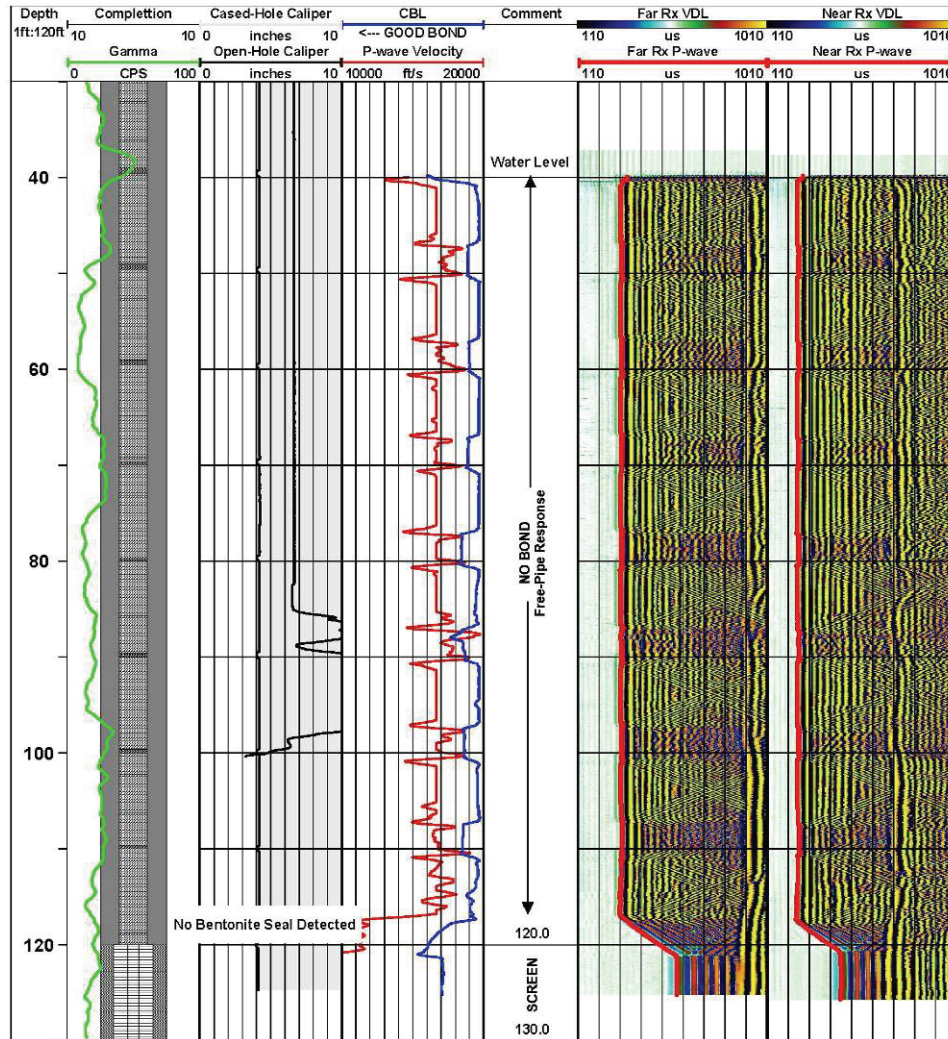


Figure 6.6-1: Example of “free pipe” response seen in geophysical logs. (Golder Associates)

6.6.1 Sonic Methods

The cement bond log (CBL) produced by a borehole sonic tool is a traditional log used for borehole/casing evaluation. The full-waveform sonic tool also generates variable display log (VDL) plots for each receiver, and a calculated compression wave velocity from the transient time computed from the compression wave first break arrivals from each receiver. Figure 6.6-1 presents an example of the logs from a two-receiver full-waveform sonic tool run in a cased well for casing evaluation. In this instance, there is no bond between the casing and the cement, a condition known as “free-pipe” (Paillet et al, 1991).

The key log features evident on Figure 6.6-1 indicative of a free pipe condition are:

- CBL amplitude log shows consistently high values;
- VDL exhibits a “ringing” character;
- Casing joints are clearly visible in the VDL;
- Caliper log confirms the casing joints;
- Velocity log is in the range expected for steel casing;

- The bentonite seal is not visible in the gamma log or in the VDL; and
- The well screen “signature” is apparent in the VDL.

Figure 6.6-2 presents an example of the logs from a two-receiver full-waveform sonic tool run in a cased well for casing evaluation. In this log there is evidence of good bond between the casing and the cement, but possibly a poor bond between the cement and the formation, this is known as “unbonded casing” (Paillet et al, 1991).

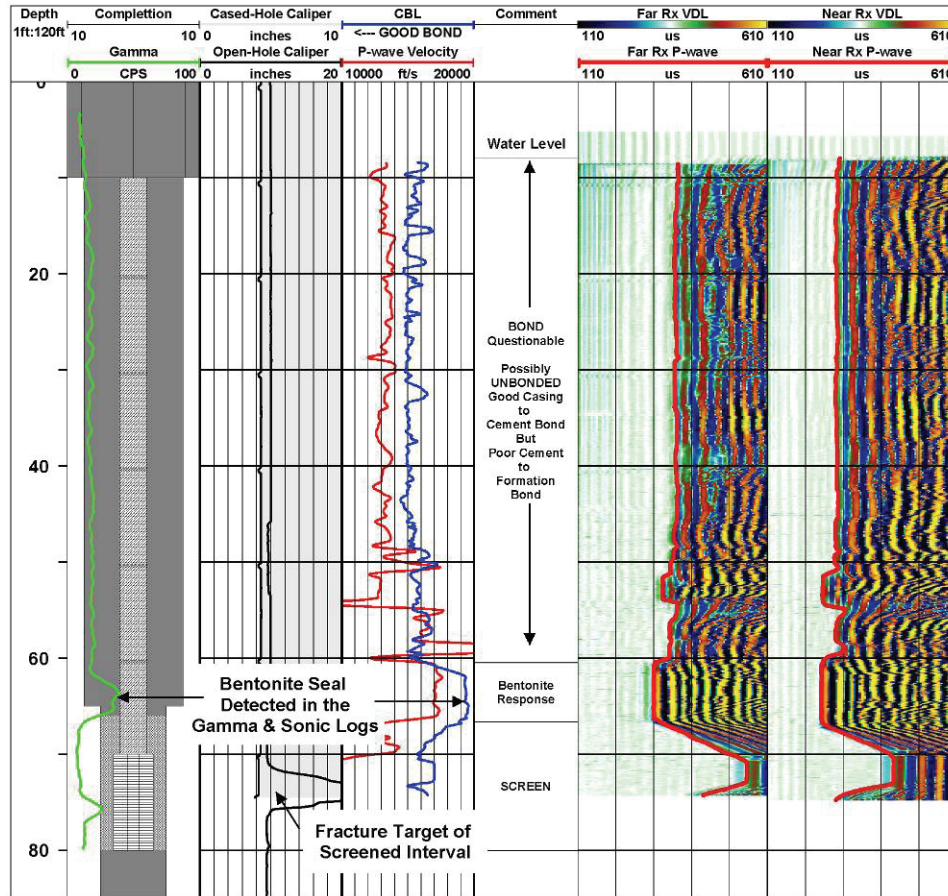


Figure 6.6-2: Example of unbonded casing response seen in geophysical logs. (Golder Associates)

The key log features evident on Figure 6.6-2 indicative of an unbonded casing condition are:

- CBL amplitude log shows consistently lower values, not like the free-pipe case;
- VDL does not exhibit the strong “ringing” character indicative of free-pipe;
- Casing joints are barely visible in the VDL;
- Caliper log confirms the casing joints;
- Velocity log is in the range expected for cement;
- VDL exhibits the “ringing” character indicative of free-pipe over the bentonite seal;
- The bentonite seal is confirmed by the gamma log;
- CBL amplitude and velocity log indicate the bentonite seal; and
- The well screen “signature” is apparent in the VDL

Figure 6.6-3 presents an example of the logs from a two-receiver full-waveform sonic tool run in a cased well for casing evaluation. In this case there is evidence of good bond between the casing and the cement, and between the cement and the formation.

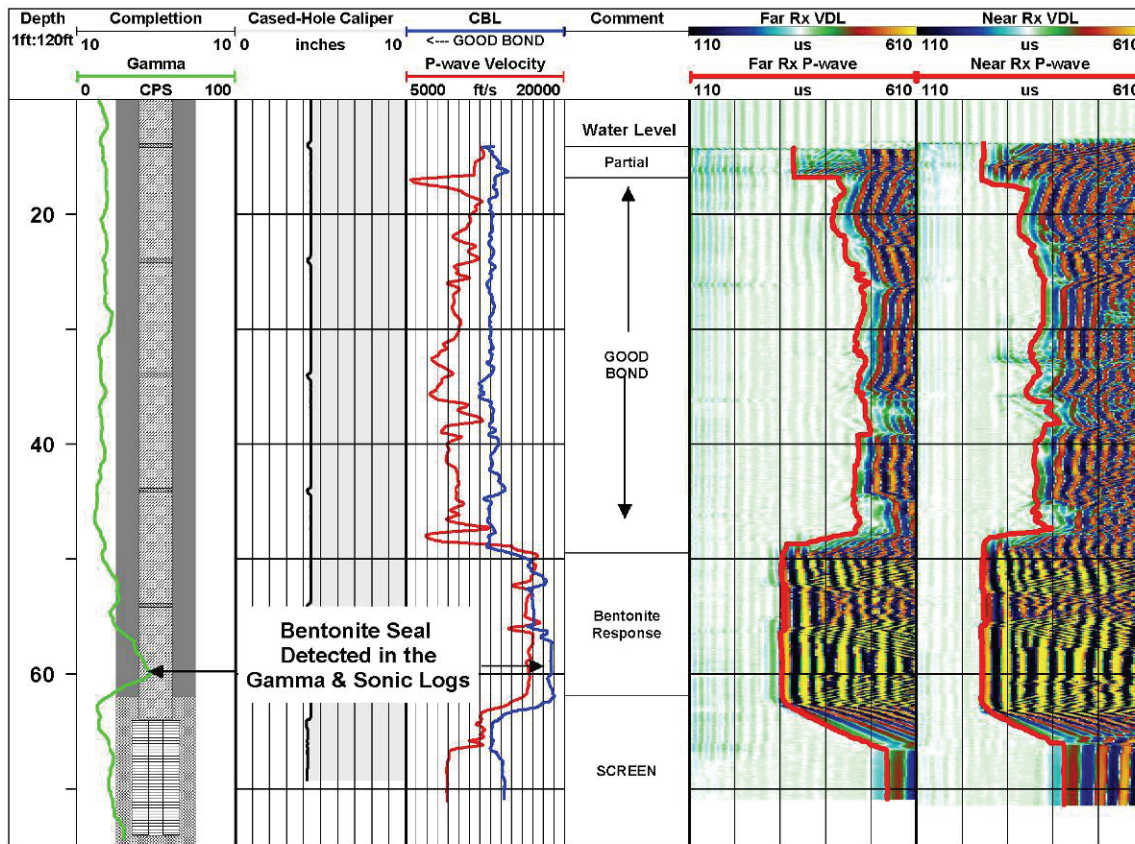


Figure 6.6-3: Example of good casing bond seen in geophysical logs. (Golder Associates)

The key log features evident on Figure 6.6-3 indicative of a good casing bond are:

- CBL amplitude log shows consistently lower values, not like the free-pipe case;
- VDL does not exhibit a “ringing” character indicative of free-pipe, or unbonded casing;
- Casing joints are not visible in the VDL;
- Caliper log confirms the casing joints;
- Velocity log is in the range expected for the formation;
- VDL exhibits the “ringing” character indicative of free-pipe over the bentonite seal;
- Bentonite seal is confirmed by the gamma log;
- CBL amplitude and velocity log indicate the bentonite seal; and
- the screen signature is apparent in the VDL.

The gamma log can sometimes be used to identify the bentonite seal above casing screens through both steel and PVC casing; however, not all bentonite has a gamma signature. The induction log will always identify the bentonite seal, but the induction log can only be used through PVC casing.

6.6.2 Density Methods

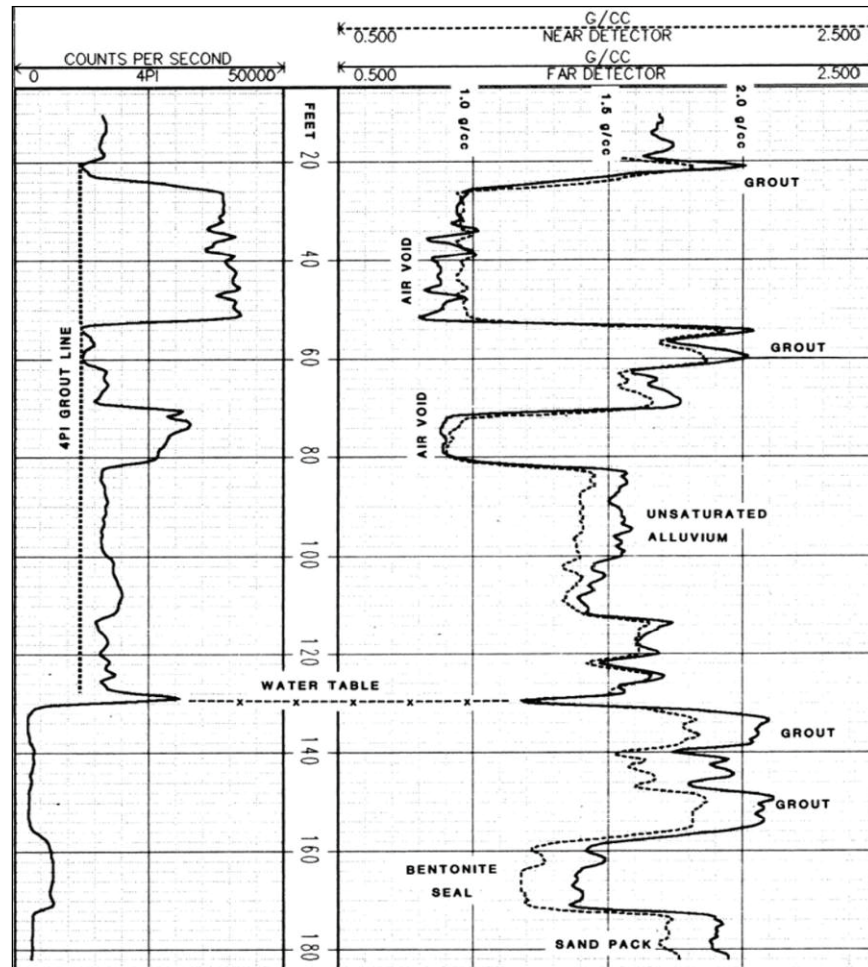


Figure 6.6-4: Example of density log used to evaluate well construction. (RE Crowder Consulting, LLC)

Active source density logs have been proven to be a useful tool for well construction evaluation. The absence of cement behind the casing will appear as a low density zone, and the bentonite seal can also be identified (Figure 6.6-4). Also, the density tool can be run above the water table for information about well construction where sonic tools cannot be employed. (Yearsley et al, 1991).

6.6.3 Acoustic Televiwer and Camera Methods

The ALT ABI40 full-waveform acoustic televiwer (ATV) has an optional casing inspection mode that allows this tool to detect echoes from the inner wall and the outer wall of steel casing. This data can be used to calculate the amount of inner corrosion, outer corrosion, and remaining casing thickness. The tool can also be used to gather information about the presence and absence of cement and the quality of cement bond, as shown on Figure 6.6-5 (Deltombe et al, 2004).

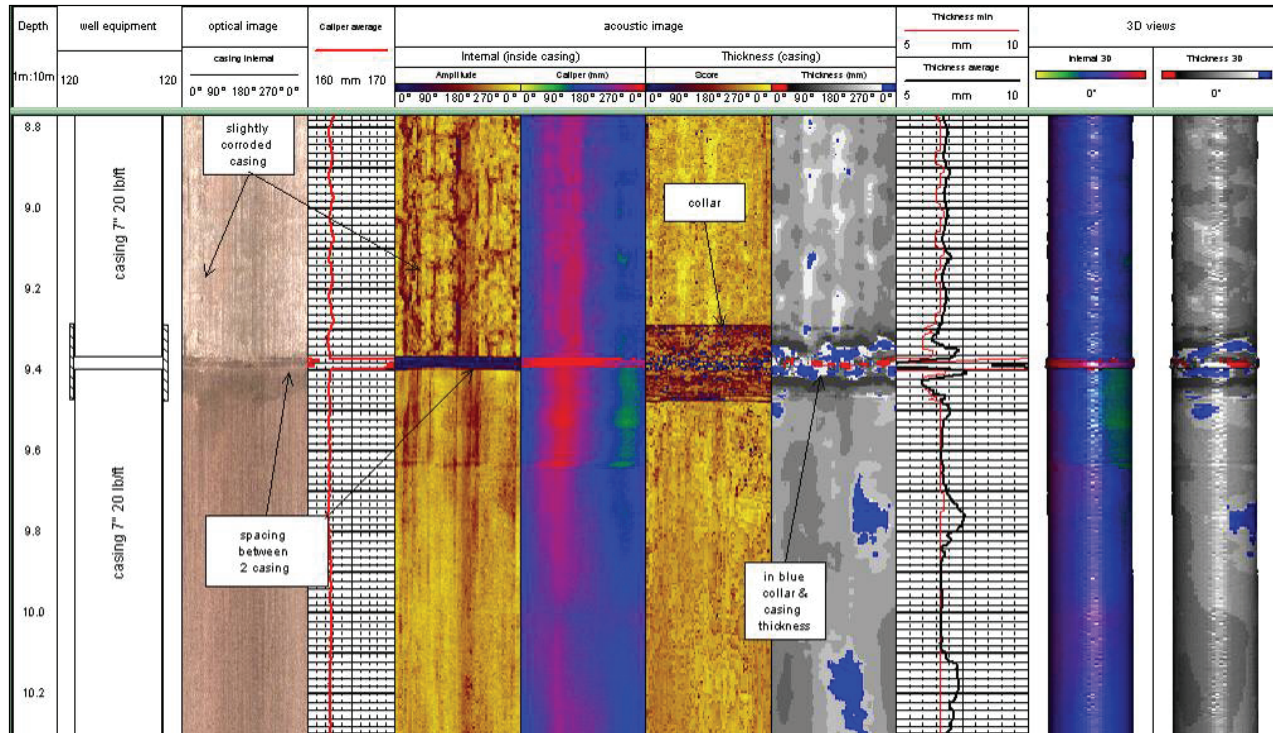


Figure 6.6-5: Example of casing inspection using an ALT ABI40 acoustic televiewer (Mount Sopris Instrument Co.)

Additionally, borehole video systems (color and black and white) are commonly used in well inspections, primarily to check casings, casing joints and well screens for damage and to confirm placement. Optical televiewers can also be used for this application.

7. CASE STUDIES

In addition to the applications provided in Chapter 6, the case studies presented in this chapter demonstrate the effectiveness of borehole geophysical methods for site characterization studies. We present the following nine case studies related to potential nuclear repository sites, underground research facilities and large civil works:

- Crystalline Rock Environments
 - Forsmark Site, Sweden
 - Granitic Rock, Czech Republic
 - Üveghuta Site, Hungary
 - Water Tunnel No. 3, New York, USA
 - Sellafield Site, UK
 - AECL Underground Research Laboratory, Manitoba, Canada
- Sedimentary Rock Environments
 - Zürcher Weinland Site, Switzerland
 - Michigan Technological University (MTU) Test Site, Michigan, USA
 - Detroit River International Crossing (DRIC), Ontario, Canada

The Forsmark site, Sweden's preferred location for a deep geological repository, is situated in Precambrian aged crystalline rock. There has been an extensive borehole geophysical programme carried out at Forsmark under the overall direction of SKB.

From the Czech Republic, borehole geophysics investigations of the Podlesí granite are presented. The site, located in western Bohemia, is under preliminary consideration for a nuclear repository.

The Üveghuta Site is located near the village of Bátaapáti, in southern Hungary. This site is considered for low- and intermediate-level radioactive waste disposal in a granite body some 300 m below surface, and has been investigated using borehole geophysics.

New York City's Water Tunnel No. 3 is among the most complex engineering projects in the world today. Numerous boreholes have been drilled and geophysically logged in crystalline rock on the southern part of Manhattan Island in order to assess fractured rock quality and dewatering requirements.

During the 1990's a very advanced borehole geophysics campaign was carried out at the Sellafield site in the UK, where the crystalline rock is overlain by approximately 400 m of sedimentary rock.

The AECL Underground Research Laboratory (URL) in Manitoba, Canada was designed to provide a full-scale laboratory in which to simulate the conditions of a deep geological repository in Canadian Shield rocks. Although the geophysical logging conducted in support of this project was performed more than 20 years ago, the geophysical techniques provide insights that are still applicable today.

In Switzerland, NAGRA has investigated the Opalinus Clay as a potential host rock for a deep geological repository at the Zürcher Weinland site. Extensive geophysical testing was

completed in the Benken borehole to correlate the sedimentary rock strata to a large-scale, 3D seismic survey completed across the entire study area.

Michigan Technological University (MTU) operates a borehole seismic test site in the Michigan Basin designed specifically for the testing of borehole seismic imaging methods. The site has played a major role in the development of the vertical seismic profiling (VSP) method, the cross-well seismic tomography and cross-well seismic reflection methods as well as the reverse vertical seismic profiling (RVSP) technique.

An extensive geotechnical/geophysical investigation was undertaken on the Canadian side of the Detroit River International Crossing (DRIC) site in Windsor, Canada, to determine the zone of influence of past solution salt mining activities on the location and design of proposed bridge foundations. Both borehole geophysical logging and cross-hole seismic reflection played a critical role in the investigations.

7.1 Crystalline Rock Environments

7.1.1 Forsmark Site, Sweden

Introduction

SKB has carried out extensive geoscientific characterization studies at the Forsmark and Laxemar sites in Sweden. Both sites are situated in crystalline bedrock. This section describes the key borehole geophysical methods that have been used at the Forsmark site (Figure 7.1-1) as part of the site investigations.

Forsmark is located in the Paleoproterozoic bedrock in the Fennoscandian Shield. The bedrock geology of the site is dominated by granitic rocks which intruded the area at around 1.8 Ga (Hermansson et al., 2008). A major component of the study is the determination and imaging of fractures or lineations that control the movement of groundwater. The investigations at Forsmark have involved extensive drilling and borehole geophysical logging, including thirteen deep cored boreholes (800 to 1000 m), ten vertical and inclined shorter cored boreholes (100 to 600 m) and 38 percussion drilled boreholes (down to a maximum of 200 m).

Borehole Geophysical Surveys

A typical borehole logging suite at Forsmark such as the one used at borehole KFM12A (Mattsson, 2007) includes: normal resistivity, magnetic susceptibility, fluid temperature and fluid resistivity, natural gamma, compensated gamma density, caliper, sonic and acoustic televiewer.

The objective of the investigation at this particular borehole was to measure changes in physical properties of the bedrock around and in the boreholes (rock types, fracture frequency or zones of localized deformation). These data were used to develop the interpretive logs shown on Figure 7.1-2: magnetic susceptibility, gamma radiation, silicate density and fracture frequency.

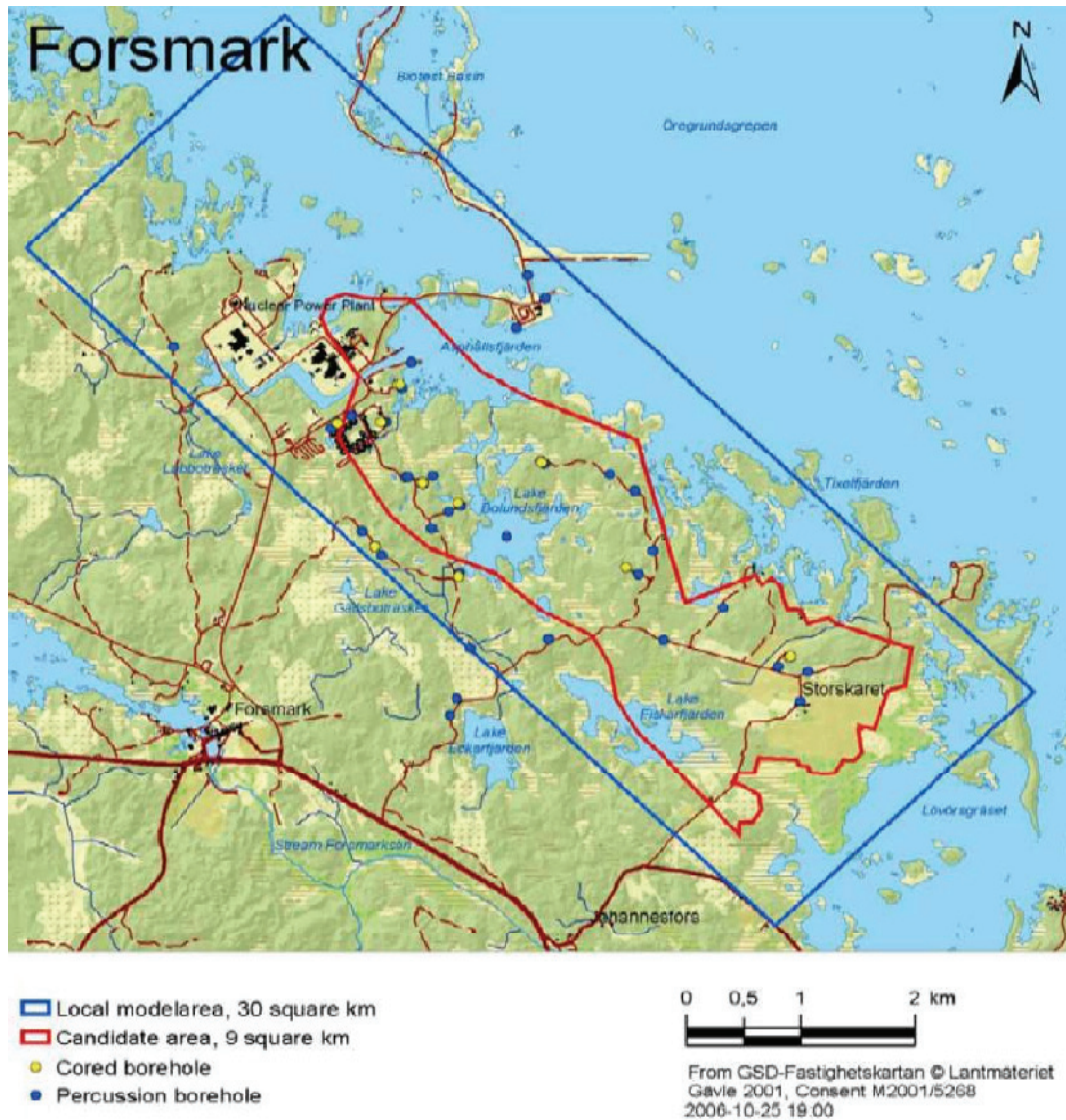


Figure 7.1-1: The Forsmark site showing the location of key cored and percussion drilled boreholes. (SKB)

At this particular borehole, geophysical logs indicated an unusually high level of fracturing compared to the majority of the boreholes in the Forsmark area (Mattson, 2007). The increase in fracture frequency observed within the first half of the borehole (60-370 m) was associated with a decrease in magnetic susceptibility and an increase in porosity. The lower half, down to 600 m, had a low fracture frequency. The largest fracture zone (possible deformation zone) observed between 212 and 251 m was associated with significant geophysical anomalies such as low magnetic susceptibility, P-wave velocity, resistivity and density.

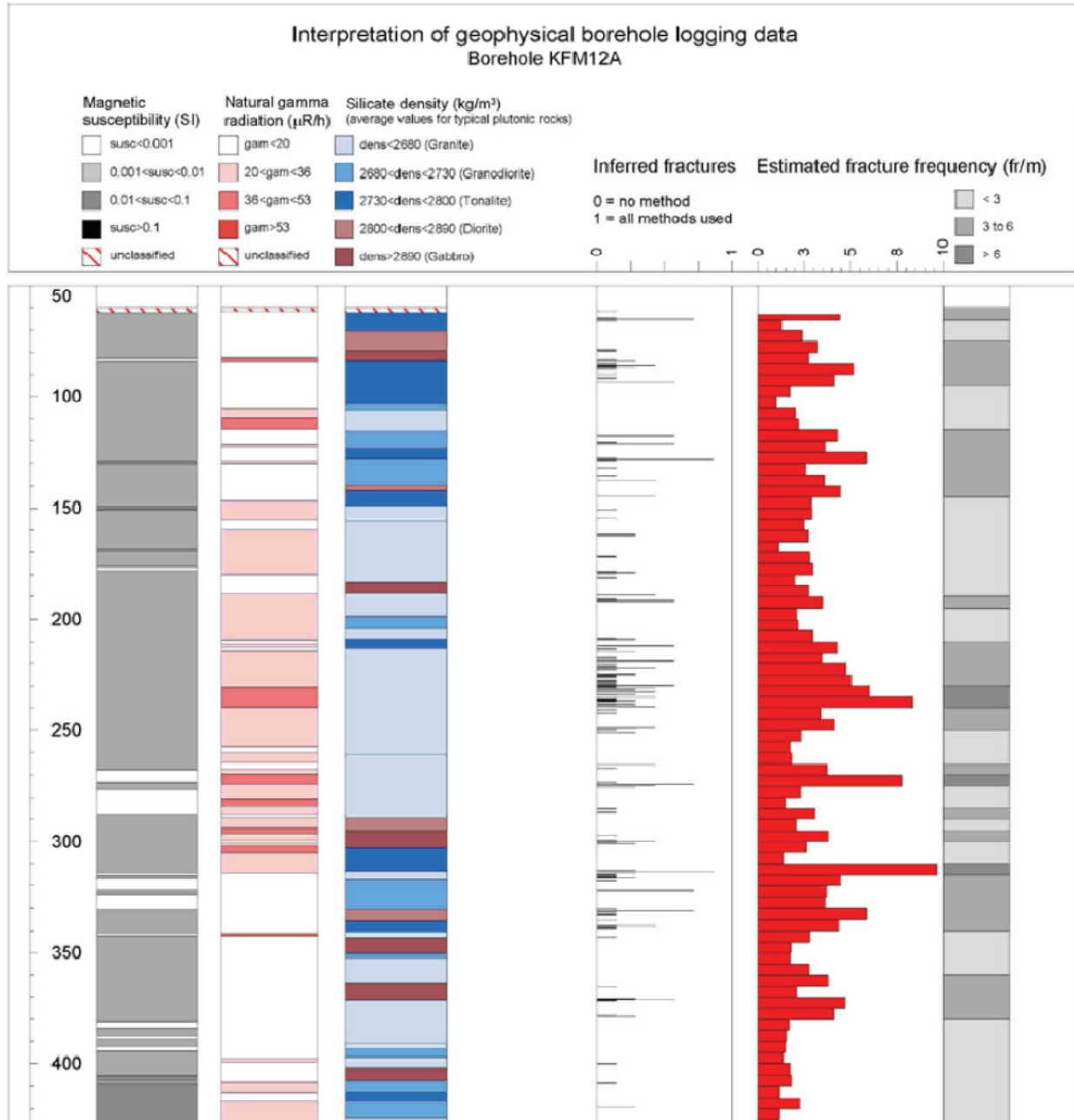


Figure 7.1-2: Interpretive geophysical logs for KFM12A Forsmark, Sweden. (Mattsson, 2007)

Borehole radar has also been used quite extensively at Forsmark to provide a high resolution image of fractures in the bedrock around the borehole. Data quality has generally been satisfactory except in some zones where the electric conductivity of the borehole fluid was high (Gustafsson and Gustafsson, 2009).

Difference flow logging was performed to identify water-conductive fractures and to determine the transmissivity and the hydraulic head in certain borehole sections. In support of this technique, and to get greater understanding of the hydrogeochemical condition, pumping tests, single point resistance of the borehole wall as well as electric conductivity of the borehole water

were measured in a few boreholes (Jönsson and Ludvigson, 2006; Väisäsvaara and Pekkanen, 2007). Results show that all the measurable flow anomalies were located above 30 m. Most of the inflows were supported by electrical conductivity and temperature measurements (Jönsson and Ludvigson, 2006).

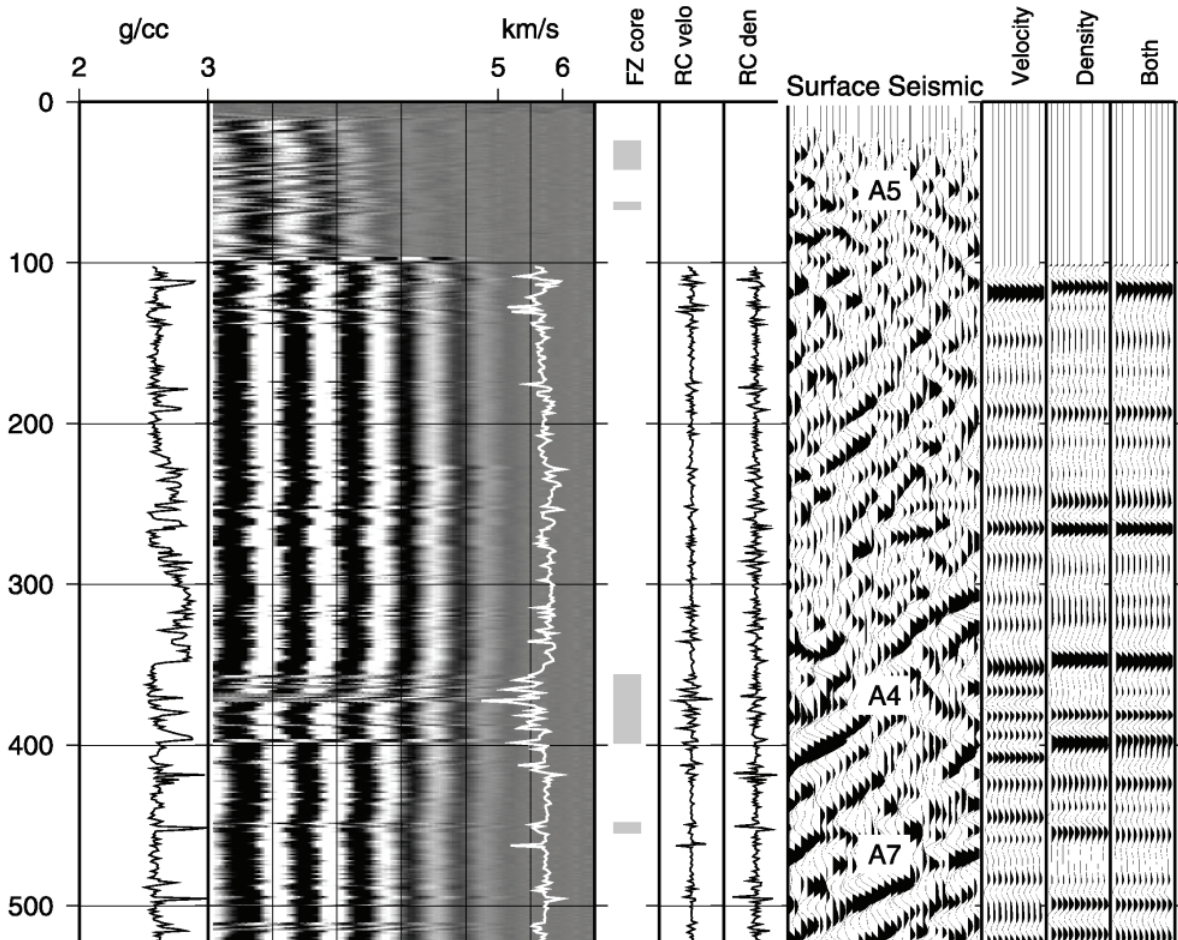


Figure 7.1-3: Density and sonic logs from the KFM03A borehole compared to the migrated seismic section and synthetic seismograms. (Juhlin and Stephens, 2006)

Vertical Seismic Profiling (VSP) was performed in select boreholes to correlate to surface seismic data. VSP as well as surface seismic reflection were able to image gently dipping reflections that have been interpreted as hydraulically conductive fracture zones (Juhlin, 2007; Juhlin and Stephens, 2006). Observations between core holes and density/sonic logs in Figure 7.1-3 indicate that high-density bodies characterize the presence of amphibolites while low-velocity zones are associated with open fractures (Juhlin and Stephens, 2006).

Although amphibolites may be locally highly reflective, the prominent seismic reflections have been interpreted as fracture zones. This is based on correlation between the location and the orientation of seismic reflectors and fractures observed in borehole KFM03A, and the lack of large amphibolite bodies mapped at the surface (Juhlin and Stephens, 2006). In Figure 7.1-3, compression wave sonic velocity is plotted on top of the full waveform sonic seismograms from the near receiver. Shaded portions in the FZ core panel indicate where the major deformation zones in the core have been identified. Reflection coefficients (RC) have been calculated using only the sonic and only the density log, to allow a comparison of the importance of the contrasts

in these two parameters. They are plotted on a scale ranging from -0.1 to 0.1 (from Juhlin and Stephens, 2006).

The borehole breakout technique has been used at Forsmark to determine the orientation of horizontal stresses, to correlate breakouts with observed drilling parameters, and to investigate the influence of lithology and structures on stress orientation. The analysis was completed with the aid of the acoustic televiewer (Lawani, 2007). Overcoring stress measurements were also conducted using the 3D Borre probe in a few boreholes. Despite some drill rig problems, the measurements were relatively successful.

7.1.2 Granitic Rock, Czech Republic

Introduction

In 2003, preliminary site characterization studies for a nuclear repository were initiated at six sites in the Czech Republic, following a wide geological assessment. The six selected sites were mainly chosen for their promising geology with low degree of fracturing and alteration zones, low flow velocity and hydraulic conductivity indicating the presence of very old groundwater, and the lack of potential mineral deposits. All these sites are located in the granitic crystalline rock of the Bohemian Massif.

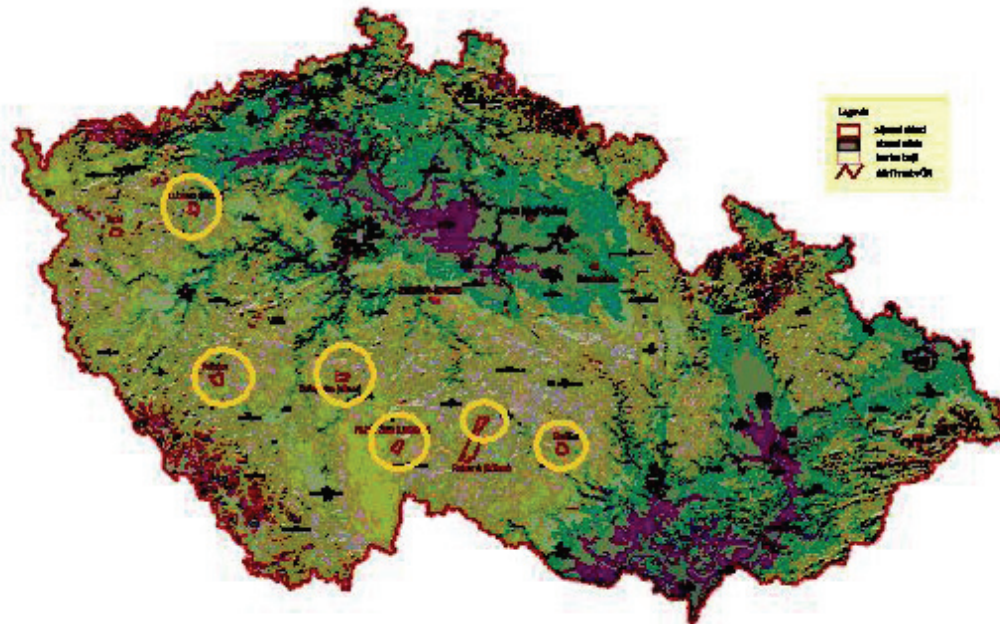


Figure 7.1-4: Map showing locations of the six selected sites: (1) Lubenec-Blatno, (2) Pacejov Nadrazi, (3) Bozejovice-Vlksice, (4) Lodherov, (5) Rohozna, (6) Budisov. (McPhar Geosurveys Ltd., 2004)

The Czech Republic is now planning on selecting two candidate sites for the construction of a deep geological repository by the year 2015.

Borehole Geophysical Surveys

Good examples of the borehole geophysical logging techniques used in the Czech programme are provided in Zilahi-Sebess and Szongoth (2002) and in Lukes (2005) for boreholes PTP-3 and PTP-4A. Both boreholes are situated in the Podlesí granite, located in western Bohemia and consisting mainly of albite-protolithoionite-topaz granite (stock granite).

Borehole PTP-3 was logged in 2002 using acoustic televiewer (ATV), full waveform sonic, resistivity, caliper and heat pulse flowmeter. This study was specifically designed to investigate the fracture (fissure) system in the rock. Partial results of their investigation are presented on Figure 7.1-5, which shows fractures (open and total) from the ATV and resistivity logs.

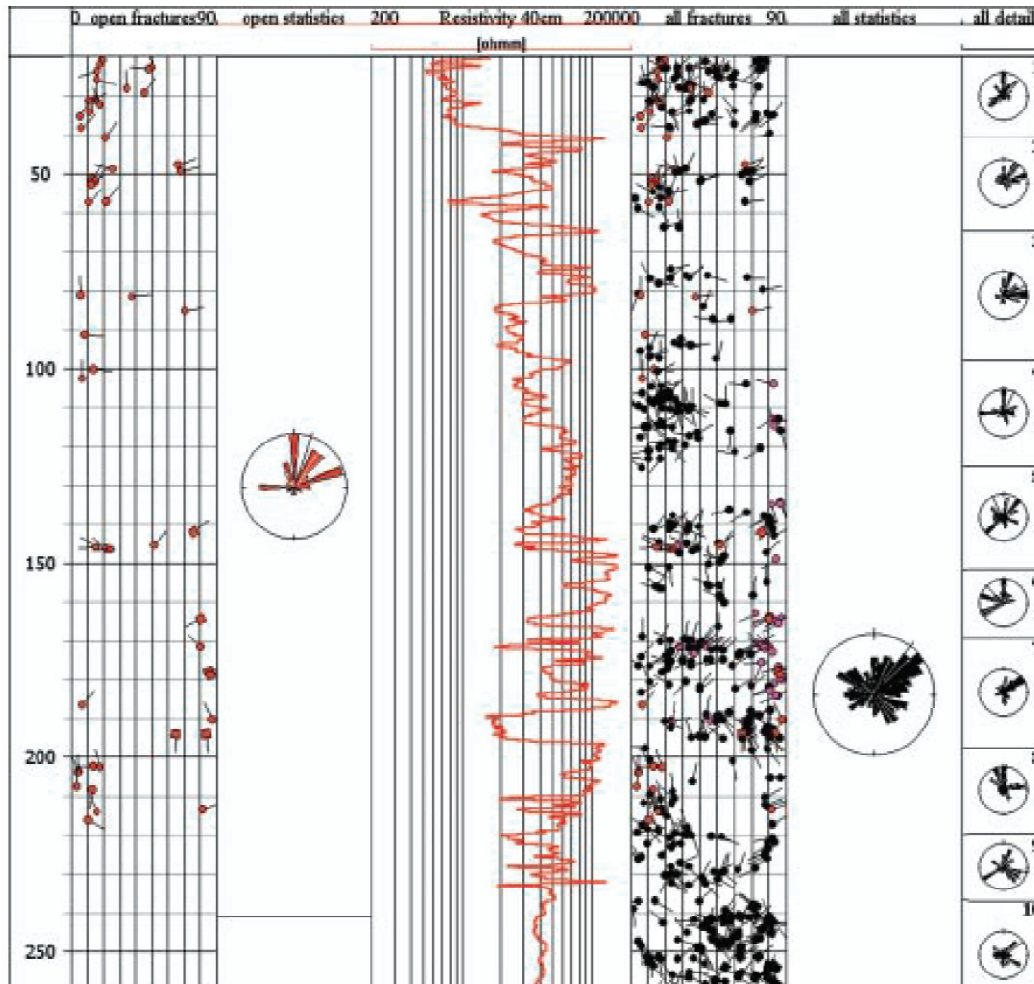


Figure 7.1-5: Resistivity and acoustic televiewer results for PTP-3. (Zilahi-Sebess and Szongoth, 2002)

The combination of these logging techniques provided valuable information on the orientation, distribution and geometry of the fractures, geologic boundaries, aplite and quartz veins, and on foliation, alteration, and infillings (Dobeš, 2005).

Boreholes PTP-3 and PTP-4A were again logged in 2005 for natural gamma, neutron, gamma density, electrical resistivity and fluid resistivity with a tracer, to further assess fracturing in hard granitic rocks and to evaluate the hydrogeological properties of the boreholes (Lukes, 2005). An example correlation between the logs from these boreholes is presented on Figure 7.1-5.

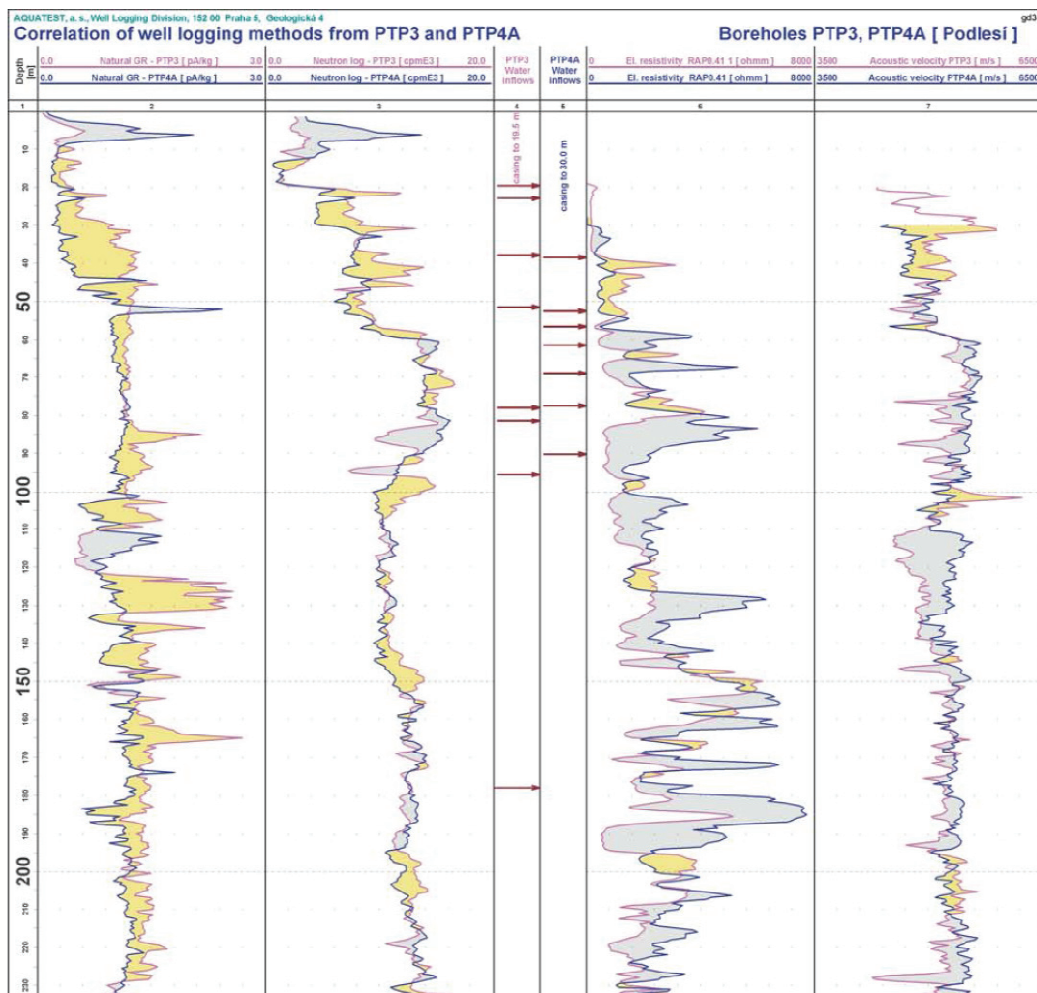


Figure 7.1-6: Correlation of gamma, neutron, resistivity and acoustic logs from PTP-3 and PTP-4A. (Lukes, 2005)

7.1.3 Üveghuta Site, Hungary

Introduction

The Üveghuta site is located near the village of Bátaapáti, in southern Hungary (Figure 7-1.7). This site is considered for low- and intermediate-level radioactive waste. The proposed repository will be located at a depth of approximately 300 m below surface within the Moragy granite formation. The granite body is overlain by 40 to 60 m of thick Pleistocene loess (Balla, Z., 2004; Vertesy et al, 2004).

Borehole Geophysical Surveys

From 1997 to 2002, approximately 30 deep boreholes have been drilled and geophysically logged at the site. These logging methods included: resistivity, magnetic susceptibility, density, gamma ray, neutron porosity, sonic, caliper, temperature, differential temperature, and deviation measurements. Non-routine geophysical techniques were also implemented in some of the boreholes including: heat pulse flow meter (HPFM), acoustic televiewer, full waveform sonic, borehole radar, borehole seismic reflection, cross-hole tomography, and VSP.



Figure 7.1-7: The Üveghuta site in southern Hungary. (GeoEye Inc.)

From the above techniques, resistivity and sonic were considered the most useful to characterize fracture intensity and the acoustic televiewer images provided the basic data set for the tectonic evaluation and the discrete fracture network (DFN) modelling.

Acoustic televiewer data indicated large variability in the fracture density within the study area with a high degree of fractures near the surface. A number of fault zones have been identified in deep boreholes within the site and in deep and shallow boreholes in the area around the site (Balla, 2004). The natural gamma logs assisted in differentiating rock types.

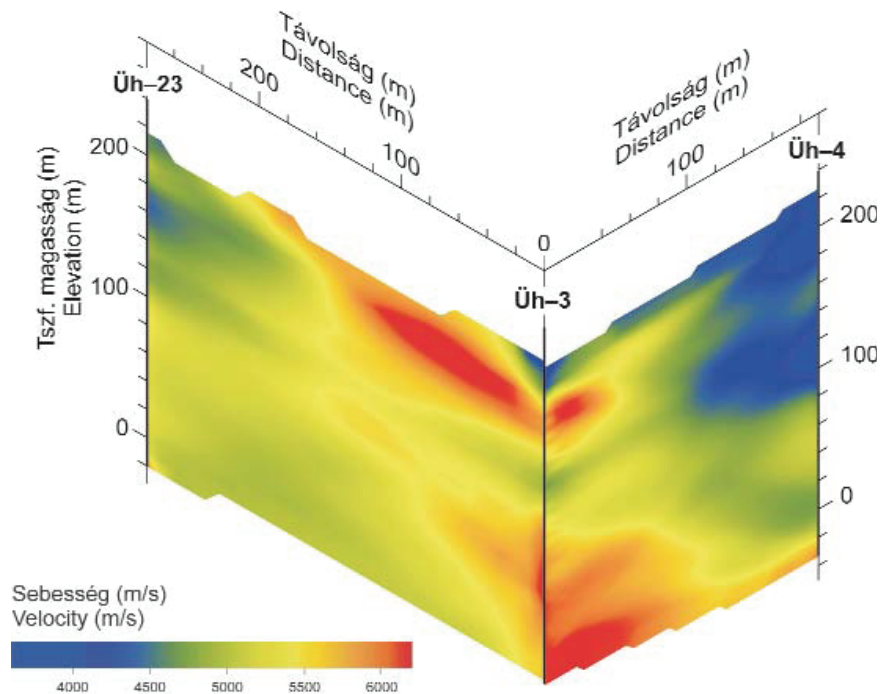


Figure 7.1-8: Cross-hole tomography results. (Toros et al, 2004)

High sensitivity temperature logs together with the HPFM provided extremely useful information about inflows. HPFM was performed only in vertical boreholes within the bedrock (Szongoth et al, 2004).

Borehole seismic (SH) reflection and cross-hole seismic tomography were jointly interpreted to provide important information regarding structures between the boreholes (Figure 7.1-8). The zones of low velocity were observed to correlate to zones of higher permeability (Toros et al, 2004).

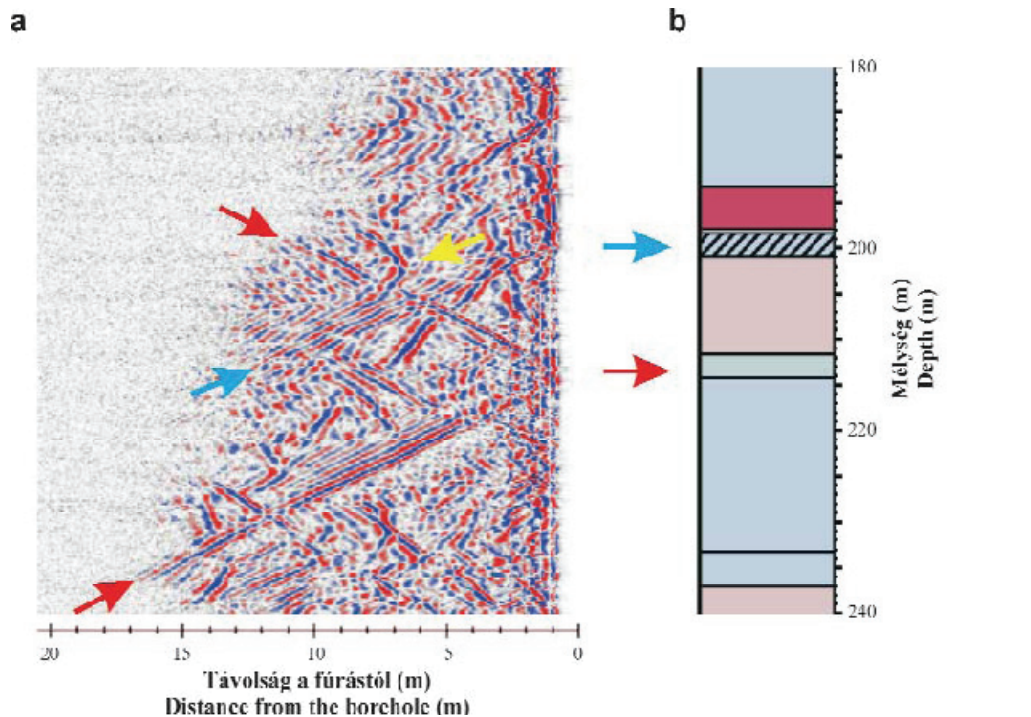


Figure 7.1-9: (a) A borehole radar section showing reflections correlated to (b) rock unit contacts. (Toros et al, 2004)

Borehole radar measurements were done only in a few boreholes and observed radar reflections within the granite suggested the presence of fractures and changes in the granite material (Figure 7.1-9). A lower depth of penetration (10 m) is observed in the upper part of the image, while in the lower part within the more compact granite a penetration of 17 metres is shown. Fractured zones and changes within the granite may have generated the observed reflections. Diffractions caused by heterogeneities (fractures, fissures, rock interfaces) can also be observed. Cross-hole tomography and radar measurements were not as effective as hoped (Golder Associates Hungary, personal communication).

7.1.4 Water Tunnel No. 3, New York, USA

Introduction

New York City Water Tunnel No. 3 is the largest capital construction project in New York City's history and among the most complex engineering projects in the world today. It is intended to provide the City with a critical third connection to its Upstate New York water supply system.

The tunnel will eventually be about 100 km long. Construction on the tunnel (Stage 1) began in 1970 and will not be completed until at least 2020 (Stage 4). The Manhattan section (Stage 2) is currently under construction and will be 3.0 m in diameter and extend for 14 km (Figure 7.1-10). The site is underlain by unconsolidated deposits ranging from 0.3 to 76 m thick overlying crystalline bedrock comprised of schist, marble, gneiss and granodiorite. The hydrogeologic evaluation of the bedrock began in 1988, and included a variety of borehole geophysical techniques.

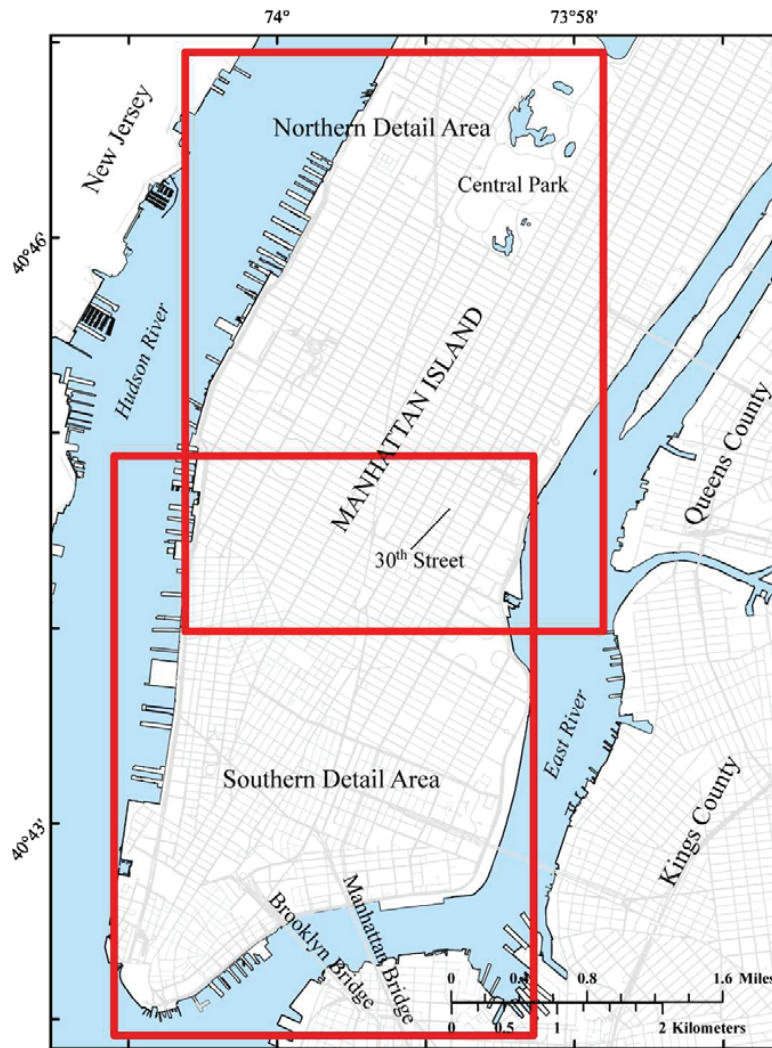


Figure 7.1-10: Location of the study area, Manhattan Island, New York. (Stumm et al, 2007)

Borehole Geophysical Surveys

A total of 64 boreholes were drilled on the southern part of Manhattan Island and many were geophysically logged (Stumm et al, 2007). The objectives of the borehole investigation were to provide information regarding the distribution and the orientation of fractures, the characterization of transmissive fracture zones, and the imaging of structures away from the borehole (up to 30 m away).

A typical example from the logging campaign is that of the Crescent Street borehole, which is a deep borehole (250 m) located in northern Queens County, New York (Stumm et al, 2001). The suite of geophysical logs acquired included: natural gamma, spontaneous potential (SP), single-point resistance, borehole radar, acoustic and optical televiewer, electromagnetic induction and focused electromagnetic induction (Figure 7.1-11).

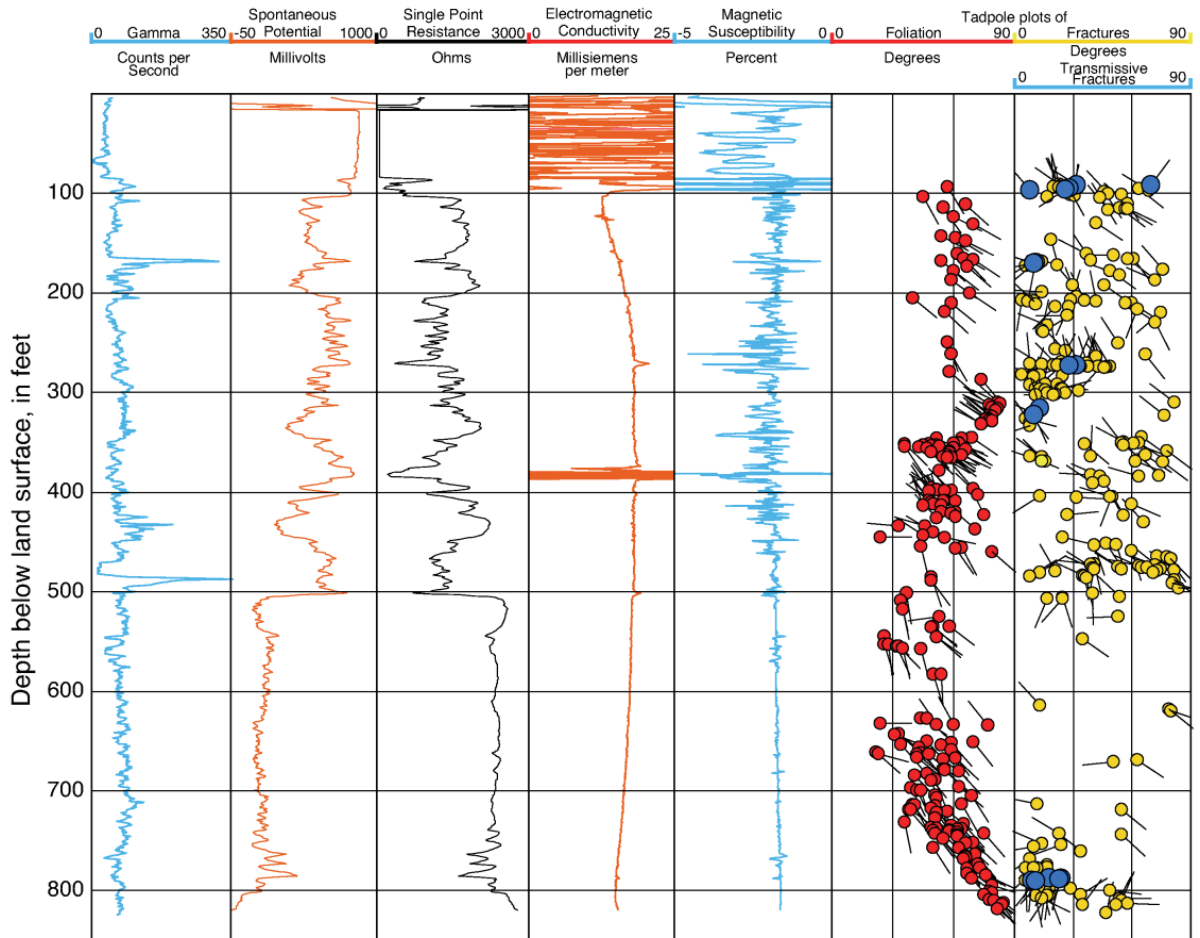


Figure 7.1-11: Geophysical log suite acquired at the Crescent Street borehole. (Stumm et al, 2001)

Variations in the gamma log indicated either the presence of clay minerals within transmissive fractures (high counts) or the presence of an amphibolite sequence (low counts). Increases in SP log voltages were found to be indicative of fractures while SPR and OTV provided information about rock mineralogy and conductive material indicative of filled fractures. The conductivity log showed a gradual increase with depth followed by a gradual decrease indicating a change in rock composition.

OTV and ATV data indicated that the bedrock was moderately fractured with a few highly fractured zones present. The tadpoles plots of the fractures and foliation determined using both the ATV and OTV logs illustrate a change in dip angle and azimuth of the fractures with depth (Stumm et al., 2001).

One of the innovative logging techniques used in this project (at that time) was a 60 MHz directional borehole radar system. This technique was able to image the presence of radar reflectors that would crosscut below the maximum depth of the borehole (Figure 7.1-12). Excavation of the tunnel beneath the borehole found dipping fractures consistent in orientation, location and character with the presence of the radar reflections. These fractures were found to be either mineralized (massive sulphide) or filled with water.

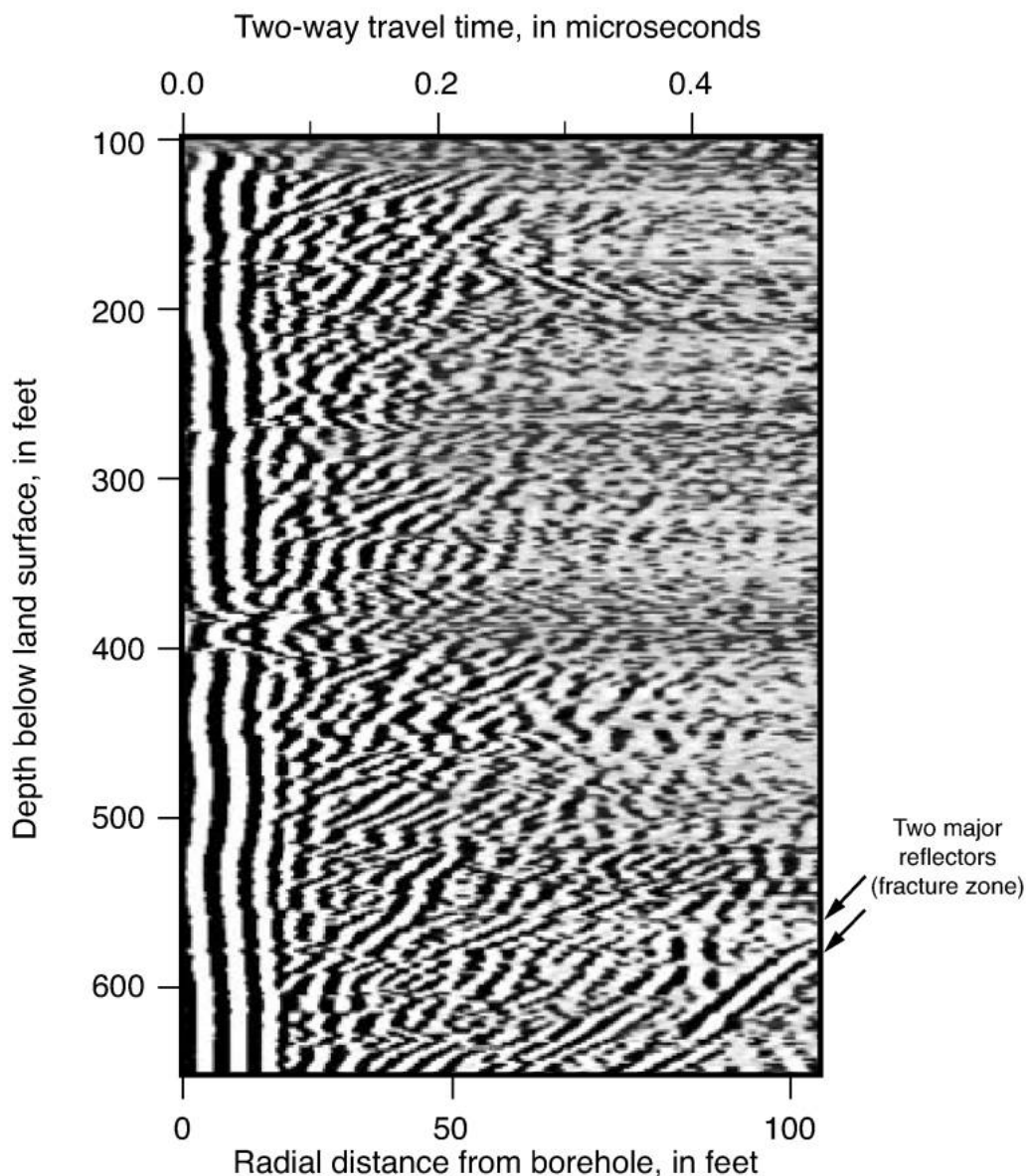


Figure 7.1-12: Image from the directional radar. (Stumm et al, 2001)

Data from borehole fluid temperature and resistivity, differential temperature, and HPFM along with water level data were acquired to provide information on the hydraulic characteristics of the bedrock. HPFM data collected under pumping and non-pumping conditions revealed the presence of several transmissive fracture zones. Sharp changes in the water-temperature log also revealed the movement of groundwater through fractures.

Mechanical and acoustic caliper and magnetic susceptibility logs together with others (e.g. OTV) and core analysis were used to provide information on the lithology of the bedrock. The borehole deviation log provided information on the borehole's angle and direction, important information to get the true depth of the borehole.

7.1.5 Sellafield Site, UK

Introduction

In the United Kingdom, investigations for a nuclear repository were initiated at two sites: Dounreay and Sellafield. Both sites are a crystalline basement host rock beneath a sedimentary sequence, which at Sellafield is approximately described as 400 m of sandstone. Similar investigation programmes were conducted at both sites but through time the focus switched to the Sellafield site (Figure 7.1-13). Detailed investigations took place in two areas of the site: the Potential Repository Zone (PRZ) and proposed underground laboratory. The proposed repository host rock at Sellafield is within the Borrowdale Volcanic Group, a sequence of volcanic rocks of mid-Ordovician age.

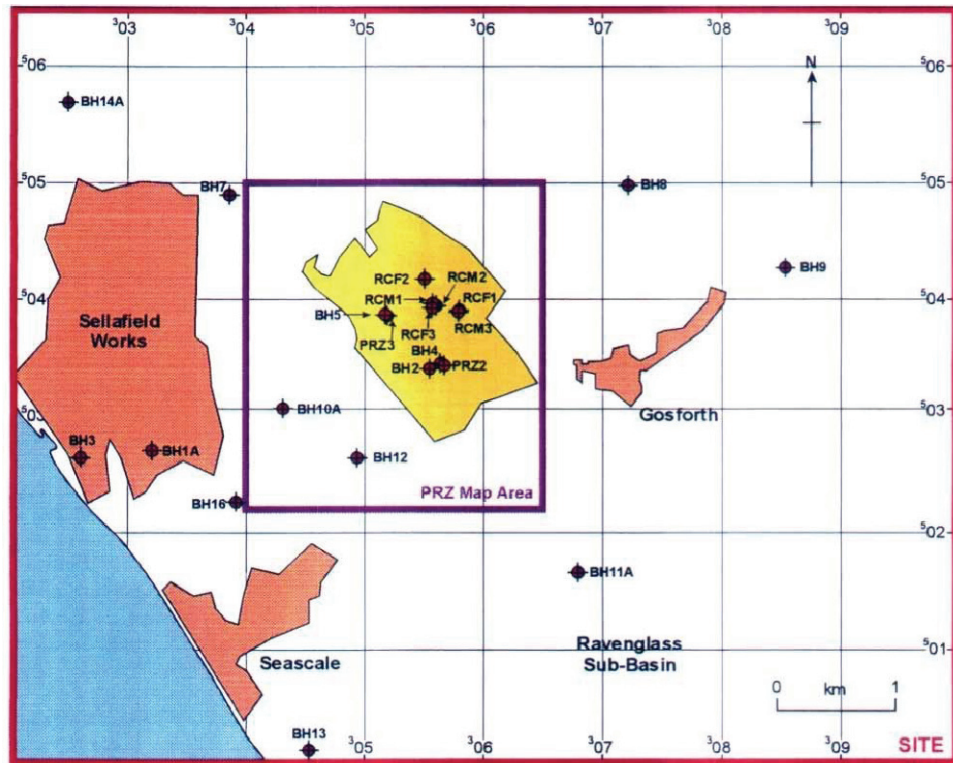


Figure 7.1-13: Schematic location of the potential repository zone (PRZ) and the Nirex boreholes within the Sellafield site. (Gunning et al, 1997)

Detailed investigations were conducted in an area immediately around the potential repository site of approximately 50 km².

Borehole Geophysical Surveys

Geophysical logging was conducted in all of the boreholes during drilling; the log suite evolved through time as new logging tools became available. For example, at the start of the investigations, a Formation Microscanner was run, replaced later by a more advanced Fullbore Formation Micro Imager. A summary of the geophysical logging programme can be found in the paper by Gunning et al (1997). The logging suite generically included:

Electric – Guard and induction logs were used to measure formation resistivity and estimate the depth of mud invasion into the formation from drilling. The latter was important when designing subsequent groundwater sampling programmes.

Natural Gamma – Used for stratigraphic correlation and petrophysical interpretation (clay content).

Neutron Porosity – Used for stratigraphic correlation and petrophysical interpretation (porosity).

Gamma Density – Used for stratigraphic correlation and petrophysical interpretation (bulk density). These included compensated gamma-density and litho-density (photoelectric) logging tools.

Sonic – Compression and shear wave sonic data were combined with density measurements to estimate elastic moduli. Additionally, the tube wave data were used to identify fractures and provide an indication of fracture width and extent.

Image logs – Resistivity based tools were used to determine the location of fractures and their dip and dip direction and conduct structural interpretations. The results were also used to locate test intervals and seating of packers for hydrogeologic testing. Image logs included Formation Micro-scanner; Fullbore Formation Micro-imager and testing of an Azimuthal Resistivity Imager. An acoustic televiewer was also used in some boreholes.

Borehole Orientation – Both a stand-alone gyroscope and accelerometers / magnetometers built into the imaging tools were used to survey borehole orientation.

Caliper / Dip Meter – Used multi-arm caliper devices and dip-meters which were utilized to determine dip of strata based on an interpretation of the diameter of the borehole.

NMR – This log was used in conjunction with density / neutron logs for petrophysical interpretation.

Induction – Acquired in one borehole to determine formation conductivity prior to conducting a borehole radar test survey.

Additional geophysical logs were acquired in some boreholes during hydrogeologic testing. These logs were related to fluid flow in the borehole and included temperature / fluid conductivity, flow meter; and water quality (dissolved oxygen; conductivity; pH; and Eh).

Many of the boreholes were used to acquire VSPs. These surveys used a number of different geometries to acquire the necessary data. These included zero- and far-offset surveys, and walk-away surveys. The VSP data were used to correlate to surface seismic reflection data and through specialised processing to identify faults and fracture systems and determine their positions in 3D space.

A few of the boreholes were used to conduct cross-hole seismic tomography experiments to determine the velocity of the rock mass between the boreholes and to interpret structure.

The borehole radar method was tested at one location. The results indicated that the conditions were not favourable for the methodology, since the rock was too conductive to achieve useable radar penetration into the formation.

7.1.6 AECL Underground Research Laboratory, Manitoba, Canada

Introduction

The AECL URL project was designed to provide a full-scale laboratory in which to simulate the conditions of a deep geological repository (Paillet, 1991; Davison et al, 1982). Although the geophysical logging conducted in support of this project was performed more than 20 years ago, the geophysical techniques were being developed specifically for the characterization of crystalline rocks and they provide useful insights that are still applicable today.

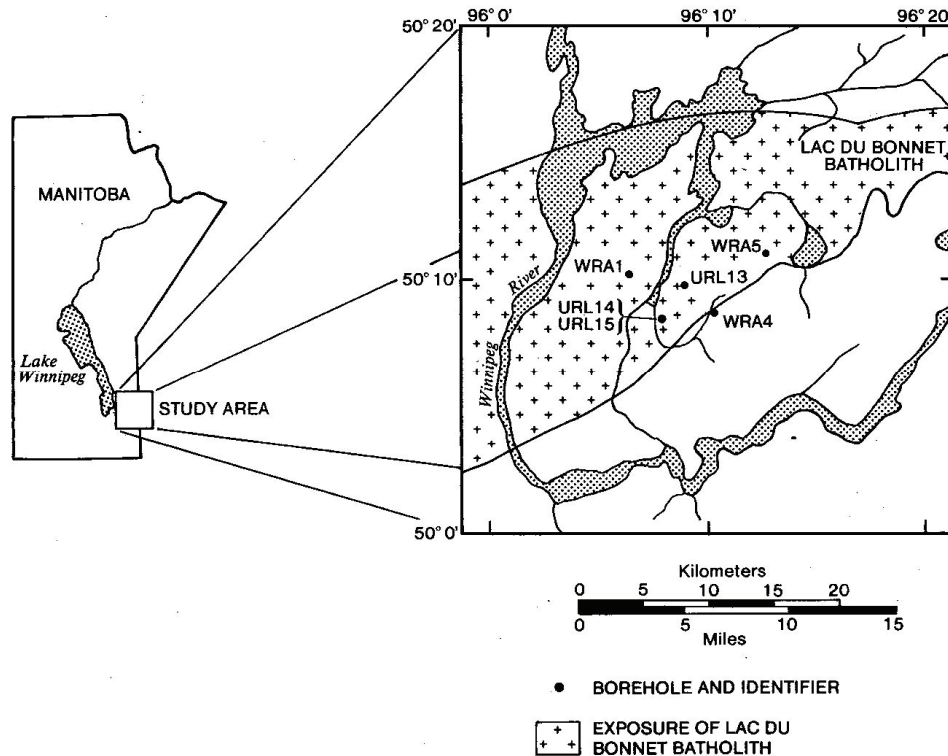


Figure 7.1-14: The Lac Du Bonnet batholith and URL site, including the URL-14/15 pair.

The URL site is located in southeastern Manitoba (Figure 7.1-14) and is situated in an intrusive granitic rock body: the Lac Du Bonnet Batholith, with relatively sparse fracture density in exposed bedrock outcrops, and relatively homogeneous and isotropic mineral fabric.

Borehole Geophysical Surveys

Initial exploration boreholes were used to provide a generalized representation of fracture distribution and orientation as a function of depth and distance from contacts with the surrounding gneiss (Davison et al, 1982; Davison, 1984). Geophysical well logs were compared to detailed descriptions of core properties and fracture distributions along boreholes were compared to indications from high-resolution surface seismic soundings (Paillet, 1991, 1993a). The combined data sets indicated a sparsely fractured rock mass with a series of eastward dipping, subhorizontal fracture zones (Figure 7.1-15). Very few if any permeable fractures were identified in the intervals between the intensely fractured zones. The fracture zones, in contrast, were found to be highly permeable, although the permeability varied significantly among boreholes. The URL tunnel shaft site was selected so that an underground test area could be

constructed in one of the unfractured intervals between the large-scale, subhorizontal fracture zones.

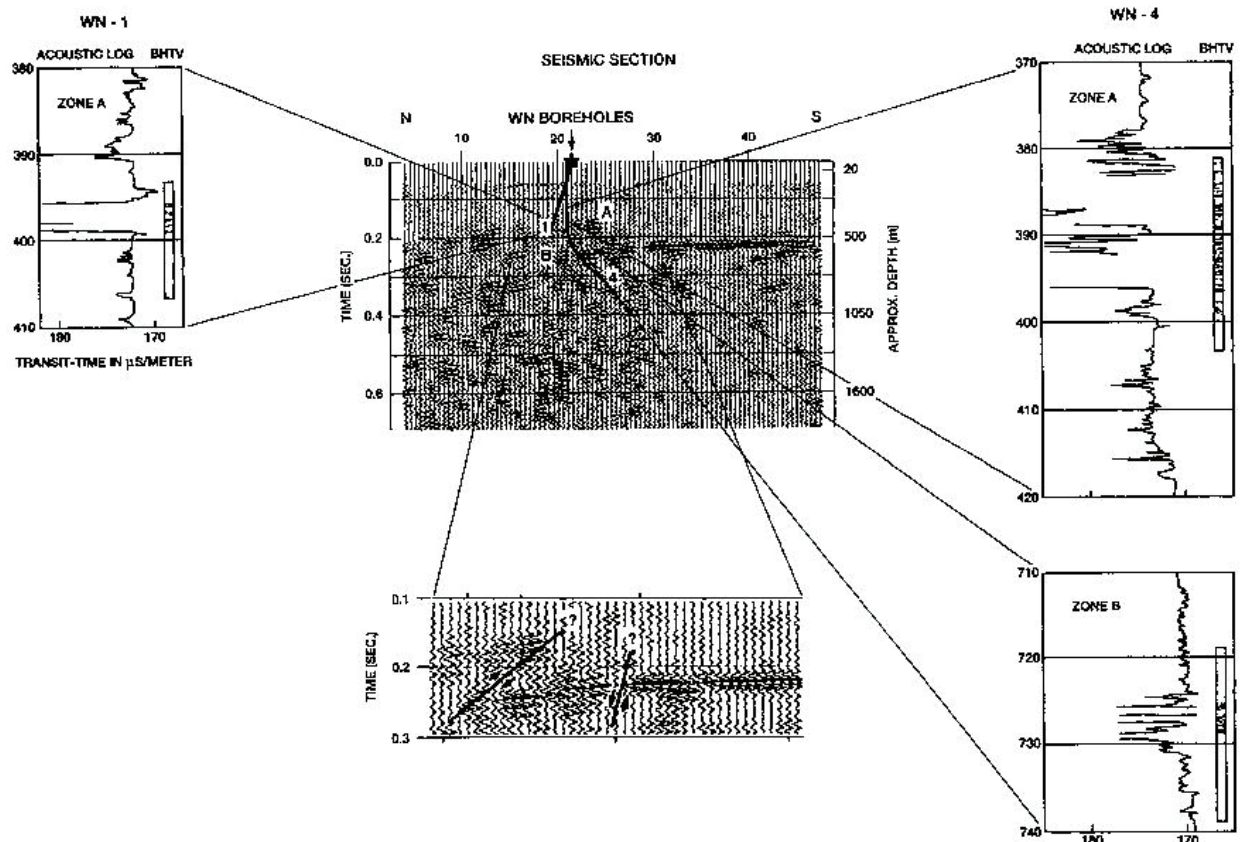


Figure 7.1-15: Sonic log characterization of the width of one of the large-scale, eastward dipping fracture zones at the URL site, where that zone intersects two of the early exploratory boreholes drilled as part of the site selection process.

Borehole logs were used in all of the initial boreholes drilled to sample properties of the Lac Du Bonnet Batholith (Paillet, 1988; 1989). Most boreholes were drilled at approximately 20 degrees from vertical so that a scribe on the downward side of the core barrel would provide orientation for the core samples. The suite of logs used in these boreholes consisted of caliper, natural gamma, fluid column temperature and resistivity, single-point resistivity, acoustic full-waveform and acoustic televiewer logs. Long and short normal resistivity logs were run in larger diameter boreholes when available.

Nuclear source logs (density and neutron porosity) were not run because AECL had specifically requested that sources not be used on this project. Density logs were assumed to provide little useful information except for the indirect indication of borehole enlargement in fractured intervals. Neutron logging might have been used as a method for assessing the degree of alteration in the vicinity of fracture zones (Nelson et al, 1983; Long et al, 1996). Televiewer logs were recorded in analog form (Polaroid photographs of oscilloscope images) throughout this project (Paillet et al, 1985). Heat-pulse flow meter logs were run in boreholes after 1985, when that technology became available (Hess, 1986).

The off-vertical boreholes provided complications in running the logs because the probes could be hung up on the rough edges of the major fracture zones. This problem would not be severe

in modern drilling projects where orientated core can be obtained in vertical boreholes, but would still be an issue in boreholes drilled off vertical to intercept near-vertical fractures and lithologic contacts. The mechanical caliper log would not function at all in the deviated boreholes because the weight of the probe body compressed the spring-loaded arms. Useful caliper logs were obtained by removing two of the three arms and the boreholes logged with the probe body sliding along the downhill side of the borehole. This produced a single-arm caliper log giving a useful indication of major fractures and other borehole conditions. Caliper logs remain useful today as a safe way of confirming stability in newly-drilled boreholes, and single-arm caliper logs may be required whenever boreholes are deliberately deviated in order to provide an effective sampling of fracture populations. Using centralizers to maintain the tools position in the borehole can facilitate use of multi-arm caliper logs in inclined boreholes.

In evaluating the borehole information, the most useful information came from the combination of caliper and televiewer logs (Paillet, 1991). The correlation of the two logs verified depth information. This was important because the tight bowsprings and narrow borehole diameter often induced depth error by cable slippage on the measuring wheel. The televiewer logs provide a detailed sample of strike, dip, and relative aperture of each fracture (Paillet, 1988). This information was compared to core observations (Figure 7.1-16).

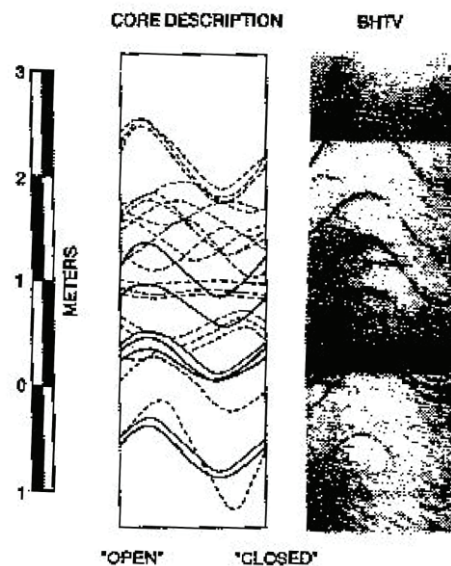


Figure 7.1-16: Comparison of borehole televiewer log with a reconstruction of fractures as given by the core description.

The core descriptions indicated fractures were “open” whenever passages between infilling minerals could be identified. The primary discrepancy between televiewer and log interpretation and core description occurred in the case of fractures that appeared open on the televiewer log but were not described as open on core (Paillet et al, 1985). This was attributed to the effects of drilling in eroding infilling minerals or altered rock adjacent to fracture faces. The televiewer was of critical importance in filling in the information from core intervals where there was some lack of recovery, including fracture zones where core was described as “rubble”. The televiewer logs indicated the orientation and distribution of the altered fractures within the interval, as well as the exact thickness of the interval.

Another application of the televiwer log was in the detection of borehole wall breakouts in some of the boreholes, which closely correlated with core diskings (Paillet, 1989). Breakouts are stress induced failures of the borehole wall induced by the presence of strongly non-isotropic stresses, and core diskings is also associated with abnormal stress in situ (Paillet and Kim, 1987). These were attributed to stress concentrations in the vicinity of large-scale asperities in the fracture zones that locally increased the in situ stress in the rock around the borehole. This was a useful and unique contribution from geophysical logs in confirming a model where ancient thrust faults have been re-activated by the modern continental stress regime.

Acoustic logs were run with a slim, high-frequency probe using a piezoelectric source transducer with a center-band frequency of 34 kHz (Paillet, 1980; 1983; Paillet and White, 1982). The acoustic log indicated the homogeneity of the granitic batholith in intervals of unfractured rock, with $V_p = 5.6$ km/s and $V_s = 3.5$ km/s. V_p measurements were so precise and consistent that the slight increase in V_p with depth attributed to lithostatic loading could be easily recognized (White, 1983). The full waveform logs were used to provide a further qualitative assessment of rock quality. Seismic propagation across fractured intervals provided a great disruption of the otherwise consistent waveforms (Paillet, 1980; 1985; Paillet and Cheng, 1991). This assessment of rock quality was represented by plotting waveforms alongside other logs in composite presentations. A more quantitative relation between fractures and waveform logs was explored by correlating various measures of waveform amplitude with fracture size (inferred from other logs or core descriptions) and fracture transmissivity (derived by straddle packer hydraulic testing) (Davison et al, 1982; Paillet, 1983). For the 34 kHz waveforms, the best representation was the amplitude in a window corresponding to the Stoneley (tube) wave mode, where amplitude logs could be correlated directly with the measured transmissivity of the interval between acoustic source and receiver. The amplitude deficit was computed by summing the differences in the average amplitude in the Stoneley wave window and the amplitude in a similar window computed from waveforms in adjacent unfractured rock.

One important result from this analysis was the observation that fracture orientation did not appear to influence the relationship between attenuation and transmissivity (Tang and Cheng, 1989; Paillet, 1981). Even when near-vertical fractures intersected the borehole over distances several times greater than source to receiver spacing in the acoustic probe, the attenuation (amplitude deficit) was evenly spread along the length of the fracture in the log computations. Although the amplitude of Stoneley waves was attenuated by the presence of permeable fractures, there was no consistent reflection of the Stoneley wave energy as predicted by Hornby et al (1989). This was attributed to the irregularity of the fracture faces which acted to disperse short-wavelength waves rather than produce a coherent reflection. This assumption was investigated by logging at a lower source frequency of 5 kHz where longer wavelengths might result in more coherent reflections. Under these conditions, a coherent reflection could be recognized, and the amplitude of the reflection related to fracture aperture as described for models of idealized planar fractures in the geophysical literature (Paillet, 1989; Paillet and Cheng, 1991).

The heat pulse flow meter became available after 1986 and was used on a number of boreholes drilled to characterize hydraulic conditions around the URL excavation (Hess, 1986). Recent borehole flow models were not available for quantitative interpretation of high-resolution flow logs, but flow meter results were presented as qualitative indications of hydraulically active fractures and fracture zones (Paillet, 1988; 1989; Hess, 1986). In many situations, the flow profile under ambient or pumping conditions indicated the specific fracture associated with inflow in a fracture zone.

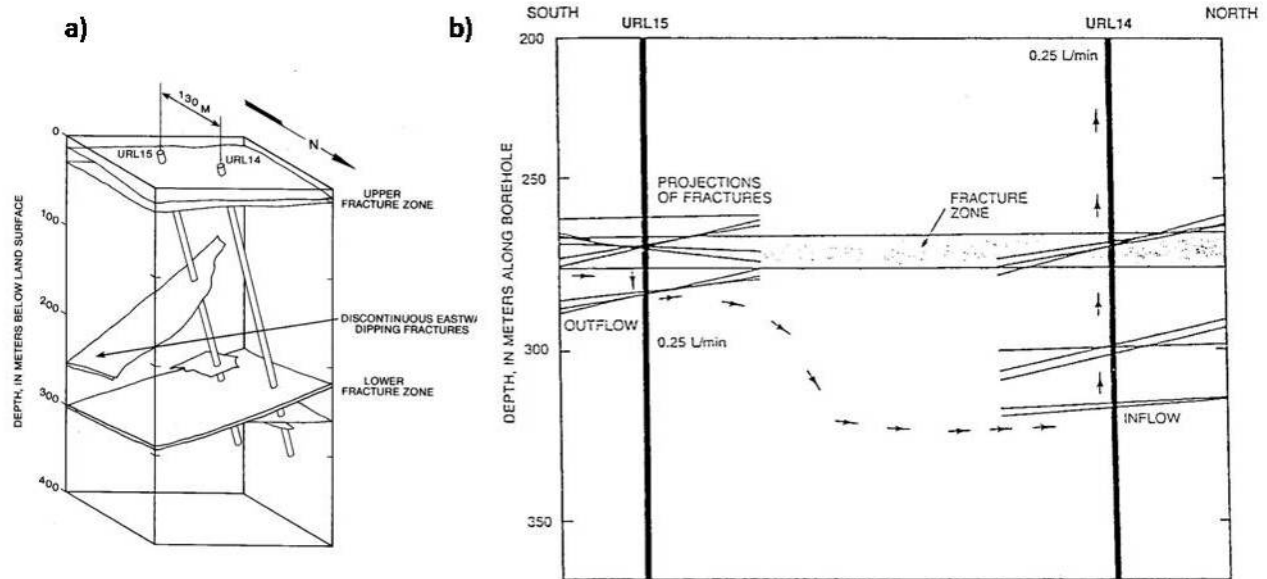


Figure 7.1-17: a) Schematic illustration of URL-14 and URL-15 intersecting a major subhorizontal fracture zone in the vicinity of the URL ; and b) Borehole flow profiles in URL-14 and URL-15 under steady pumping.

In Figure 7.1-17a two nearby boreholes intersected one of the subhorizontal fracture zones near the URL shaft. Although logs for both boreholes indicated a thick interval of fractured and altered rock, there was a great difference in the apparent transmissivity of the zones (Figure 5.1-17b). Borehole URL-15 produced flow with negligible drawdown, whereas borehole URL-14 produced about 0.25 l/min with several tens of meters of drawdown. None of this inflow was found to come from the fracture zone in URL-14, and all of the flow stimulated in URL-15 exited by way of similar minor fractures below the zone. The inflow in URL-14 was likewise associated with minor, relatively unaltered fractures slightly below the fracture zone (Paillet, 1993b). This is consistent with the “pull-apart” model of the fracture zones, where reactivated stresses have opened up permeable sections between large-scale asperities, while the fracture zone has been compressed in the vicinity of asperities forcing flow through fractures on the flanks of the main zone.

7.2 Sedimentary Rock Environments

7.2.1 Zürcher Weinland Site, Switzerland

Introduction

In 1994, NAGRA started investigating the Opalinus Clay as a potential host rock for a deep geological repository with the Zürcher Weinland as a potential site (Figure 7.2-1). The Opalinus Clay is a moderately overconsolidated marine claystone formation from the middle Jurassic. The site lies within one of the most seismically quiet areas of Switzerland which is not under significant compressive stress.

The site characterization included surface geophysics with primarily a large 3D seismic campaign (Birkhäuser et al., 2001) as well as borehole geophysics with an exploratory borehole referred to as the Benken borehole (NAGRA, 2001).

Borehole Geophysical Surveys

The “Benken” borehole, as indicated by its name, is located in the community of Benken in Canton Zurich (Figure 7.2-1). The borehole was drilled in 1998/99 to a depth of 1007 metres. The Benken borehole was drilled through the entire Mesozoic sediment sequence and stopped in the crystalline basement composed of gneiss.



Figure 7.2-1: Location map showing the Zürcher Weinland site with the Benken borehole, Switzerland. (NEA, 2003)

Figure 7.2-2 shows a geological cross-section through the area at the Benken borehole. From the surface to the bottom, the borehole encountered 68 m of unconsolidated sediments, 131 m of tertiary deposits and a 784.3 m thick Mesozoic sequence. The thickness of the Opalinus Clay is about 113 m with its top surface located at a depth of about 540 m. The primary objectives of the Benken borehole were to get geological data for the Opalinus Clay and surrounding rock formations and to calibrate borehole data with seismic images.

The geological data included various information on the sedimentary sequence such as thickness, bedding, lithological and mineralogical composition, geometry and characteristics of the fracture and fault systems, mechanical properties of the Opalinus Clay, stress field and temperature conditions of the formation, hydraulic properties in aquifers, and hydrogeology of deep groundwater (NAGRA, 2001).

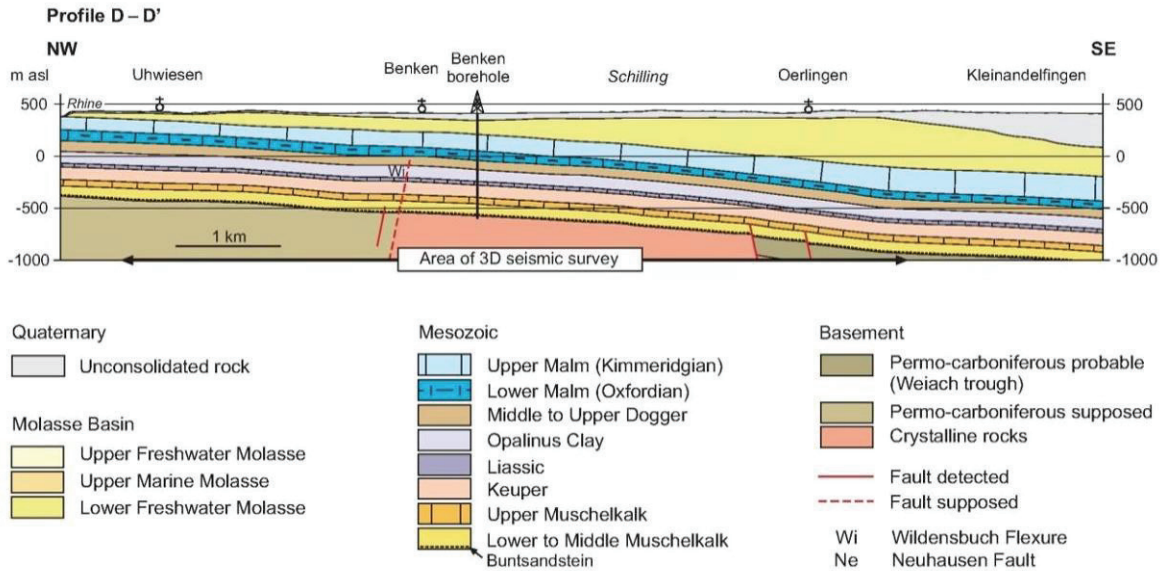


Figure 7.2-2: Geological cross-section through the potential siting area showing the location of the Benken borehole. (NEA, 2003)

Seismic measurement in this deep borehole involved the use of check-shot and walk-away VSP techniques (Figure 7.2-3). The check-shot method is used to provide a corrected sonic log. This check-shot corrected sonic log is in turn used to produce a synthetic seismogram for surface seismic correlation purposes. VSP was successfully carried out to tie the 3D seismic data to the borehole data. Results from the seismic borehole techniques provided an image of the seismic reflectors near the borehole allowing calibration of the 3D seismic data as well as lateral extrapolation of the borehole results over the study area (NAGRA, 2001).

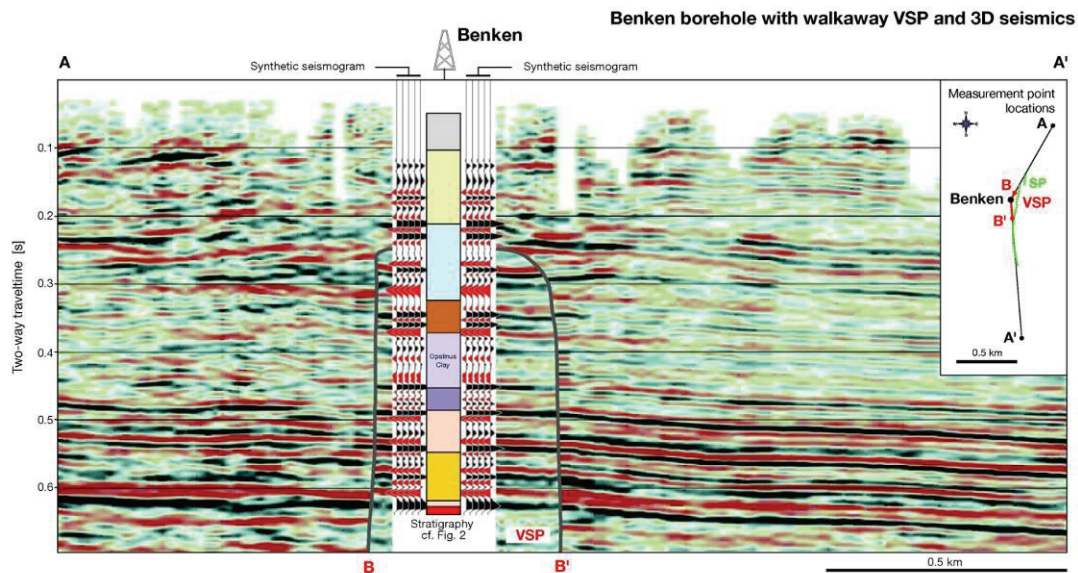


Figure 7.2-3: VSP and synthetic seismogram spliced into the 3D seismic line along a particular profile. (NAGRA, 2000)

Geophysical logging in the Benken borehole involved a wide range of standard and non-standard probes including natural gamma, caliper, compensated neutron, SP, sonic, electric (guard), litho-density and NMR.

High resolution imaging tools (resistivity and sonic) were utilized for structural logging to improve information on the orientation of features, to detect hydraulic fractures and to orient the borehole core.

Results show that the Opalinus Clay formation is thick with an homogeneous lithology and very low hydraulic conductivity. The geological units above and below the clay layer also have low hydraulic conductivity and borehole investigations in the Opalinus Clay have shown that hydraulic conductivity of fault zones is similar to the hydraulic conductivity of intact rock when the rock overburden is greater than 200 m (Gautschi, 2001). Borehole geophysics using a range of probes provided a detailed understanding of the lithology, the spatial orientation of the geological formations, fractures and heterogeneities.

7.2.2 Michigan Technological University (MTU) Test Site, Michigan, USA

Introduction

Michigan Technological University (MTU) operates a borehole seismic test site in the Michigan Basin designed specifically for the testing of borehole seismic imaging methods. The seismic imaging object (a producing reef) is situated between two deep boreholes (Figure 7.2-4). The boreholes were intentionally drilled outside the reef such that a full cross-section of the reef would fall within the image plane. The reef is a special imaging object because it is a closed feature that is porous, permeable, and has produced nearly 1 million barrels of oil over the past 30 years.

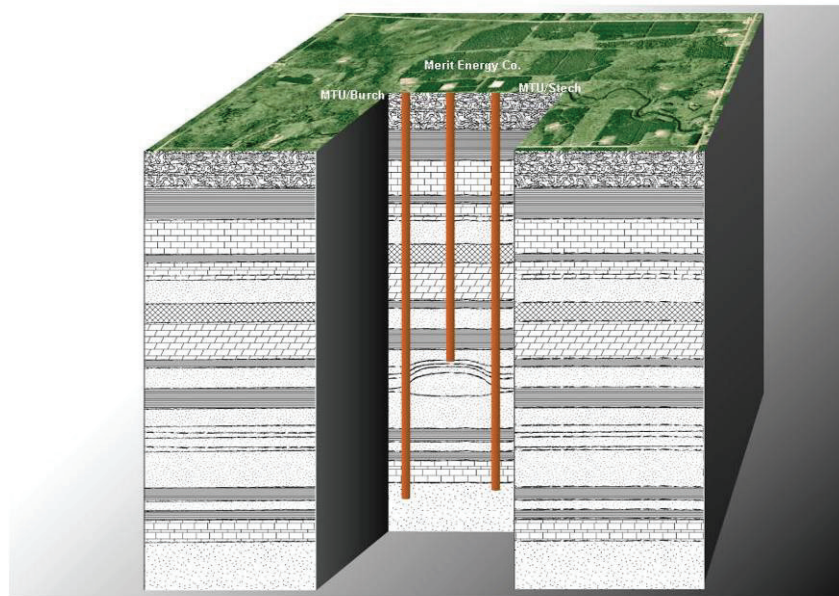


Figure 7.2-4: Michigan Technological University's two research boreholes (MTU/Burch and MTU/Stech) with respect to the seismic imaging object (reef) and the producing well.

The test site has been in operation since 1983 when it was first established by the Massachusetts Institute of Technology (MIT) as a part of an industry research consortium in its Earth Resources Laboratory (ERL). The site has played a major role in the development of the

vertical seismic profiling (VSP) method, the cross-well seismic tomography and cross-well seismic reflection methods as well as the reverse vertical seismic profiling (RVSP) technique. The geological structure of the site is given on Figure 7.2-5.

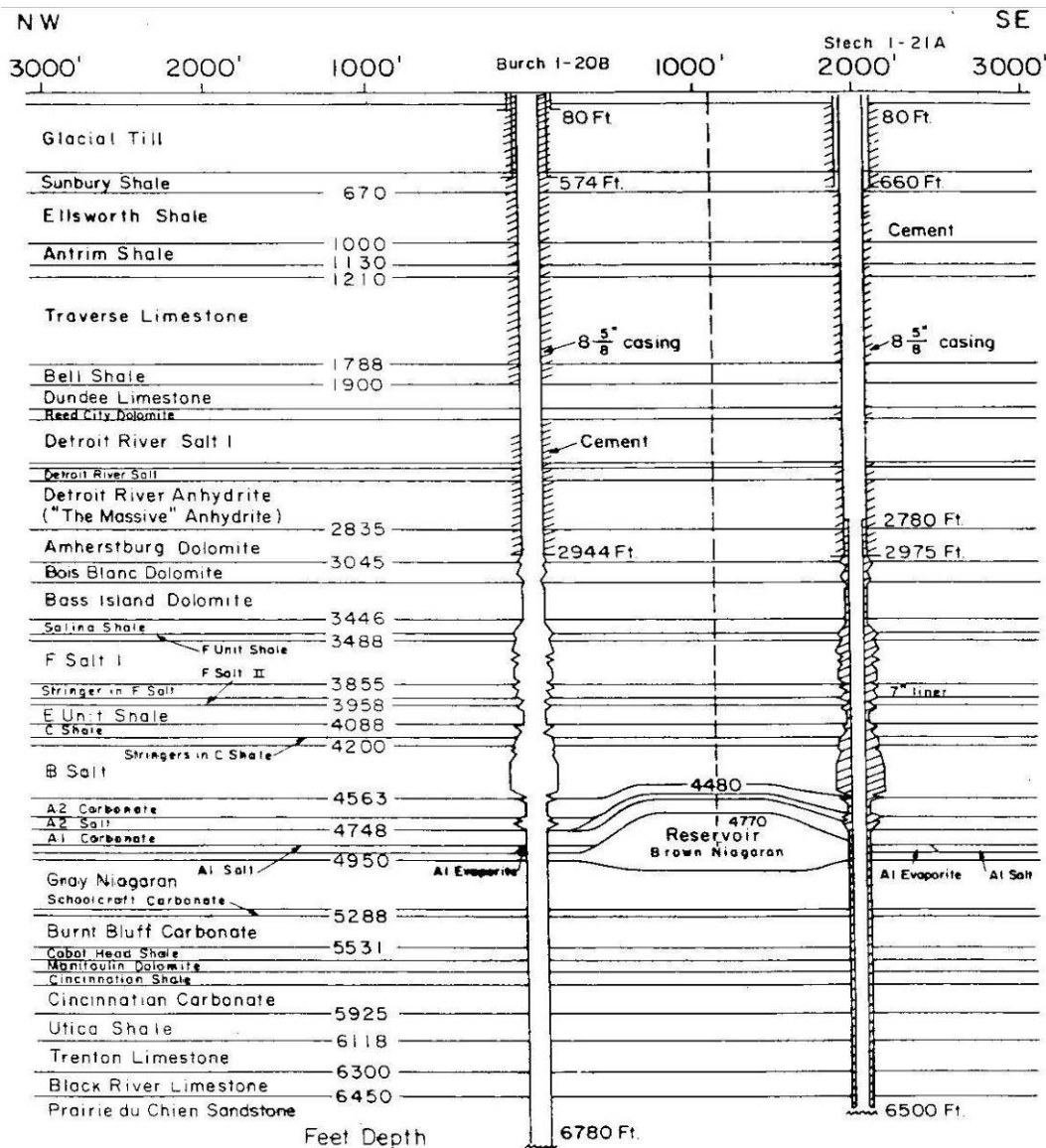


Figure 7.2-5: Geologic cross-section at the MTU test site.

Borehole Geophysical Surveys

Over the four year time period from 1983 to 1987 seventeen (17) VSPs were shot into the MIT/Burch borehole using three different kinds of sources (vertical vibrators, horizontal vibrators, and tilted airguns OmniPulse), and source locations ranging from zero offset out to 1,800 m. Early VSP processing was simply a VSP to CDP (common depth point) transformation (i.e. "stretching-of-traces") processing followed by the simple observation of the known seismic imaging object (reef) in the several VSP images. In Figure 7.2-6 the actual reef is still not visible, but the B-Salt/A2 Carbonate interface is imaged.

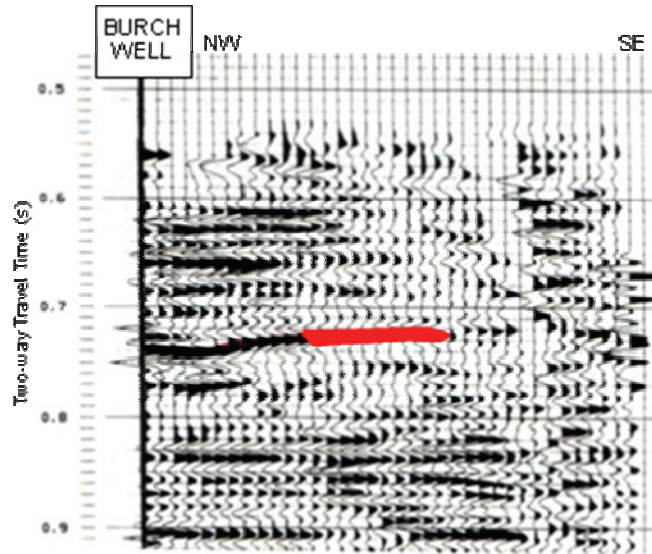


Figure 7.2-6: Image of reef (red) as seen by VSP to CDP transform processing of data acquired in the Burch borehole, MTU site.

Converted SV waves (SV – vertical plane shear waves from compression waves) from a well-known set of interfaces (B Salt to A1/A2 Carbonate series) were observed at reef level. Figure 7.2-7 showed a strong, tuned, SV event converted from the first arrival P waves at a depth of approximately 1,400 m (4,700 ft) that confirmed the presence of a large “notch” in the reef that was observed on the surface seismic images. Although VSP was not successful to image the reef, important information around the reef is obtained.

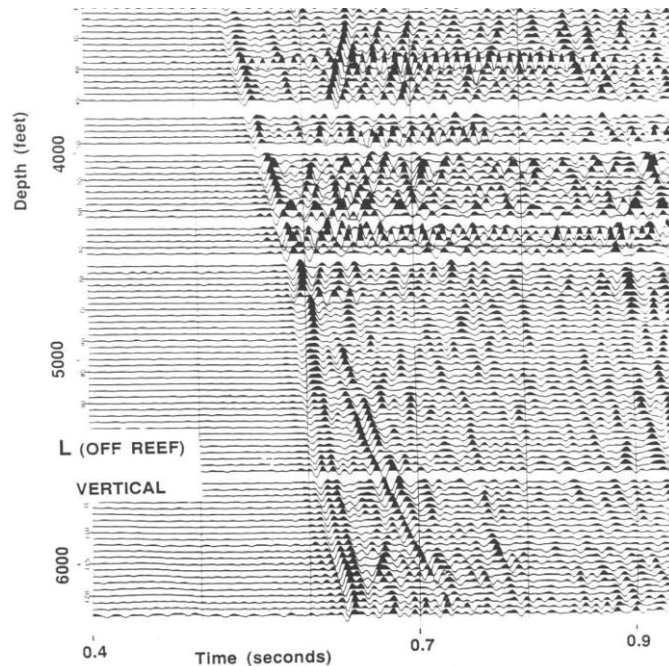


Figure 7.2-7: Example of raw plot of offset (1,800 m) VSP data, MTU site.

The comparison of the VSP images of the reef to cross-well images had to wait until the mid 1990's. Two boreholes were, obviously, required and they had to be relatively close together.

In 1990, MIT found an abandoned hole that had missed the reef on the side opposite the Burch borehole. This borehole, referred to as the Stech borehole, was re-drilled. The two boreholes did not intersect the reef allowing the entire reef to stand inside the image plane (Figure 7.2-8).

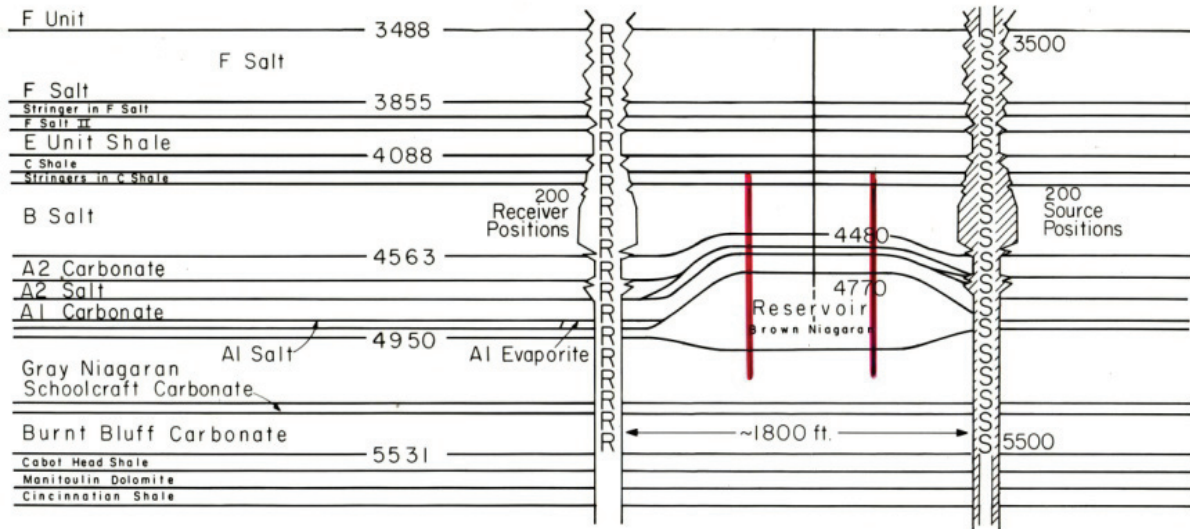


Figure 7.2-8: Cross-section of the test site showing the source locations (S) and receiver locations (R) used in cross-well tomography and cross-well reflection research.

In cross-well seismic imaging, the ray paths do not pass through the surface weathering layer, therefore these data should display higher frequency content than the VSP. Glacial till covers the test site and low attenuation (high Q) carbonate formations make up a major portion of the structure. Therefore cross-well data should display a major increase in frequency content over VSP and surface seismic data. Full wave form acoustic logs in the source and receiver holes have been used as supplementary data.

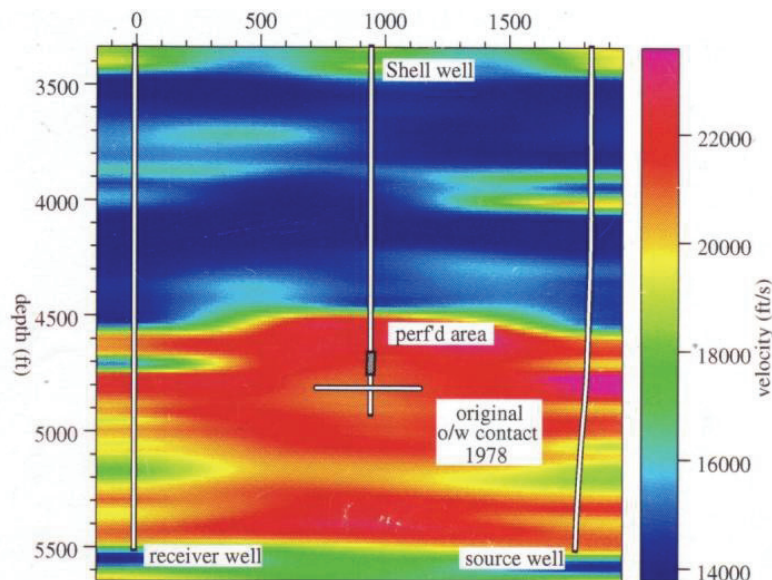


Figure 7.2-9: Tomographic image of the reef and nearby formations above and below the reef, MTU site.

The cross-well data used to produce the tomographic image in Figure 7.2-9 was acquired in 1990 and 1991 in the 1,000Hz frequency band using only two piezoelectric receivers in the Burch hole and two piezoelectric sources in the Stech borehole. A weak low velocity zone was the only new information about the interior of the reef.

Compression wave velocities at the test site range from approximately 2,900 m/s (Bell Shale) to 6,700 m/s. (A1 Carbonate). Cross-well reflection imaging produced a more detailed image. The reef is characterized by an “empty” zone identified by the red velocity streak running through it (Figure 7.2-10). Several small details inside the reef are now seen.

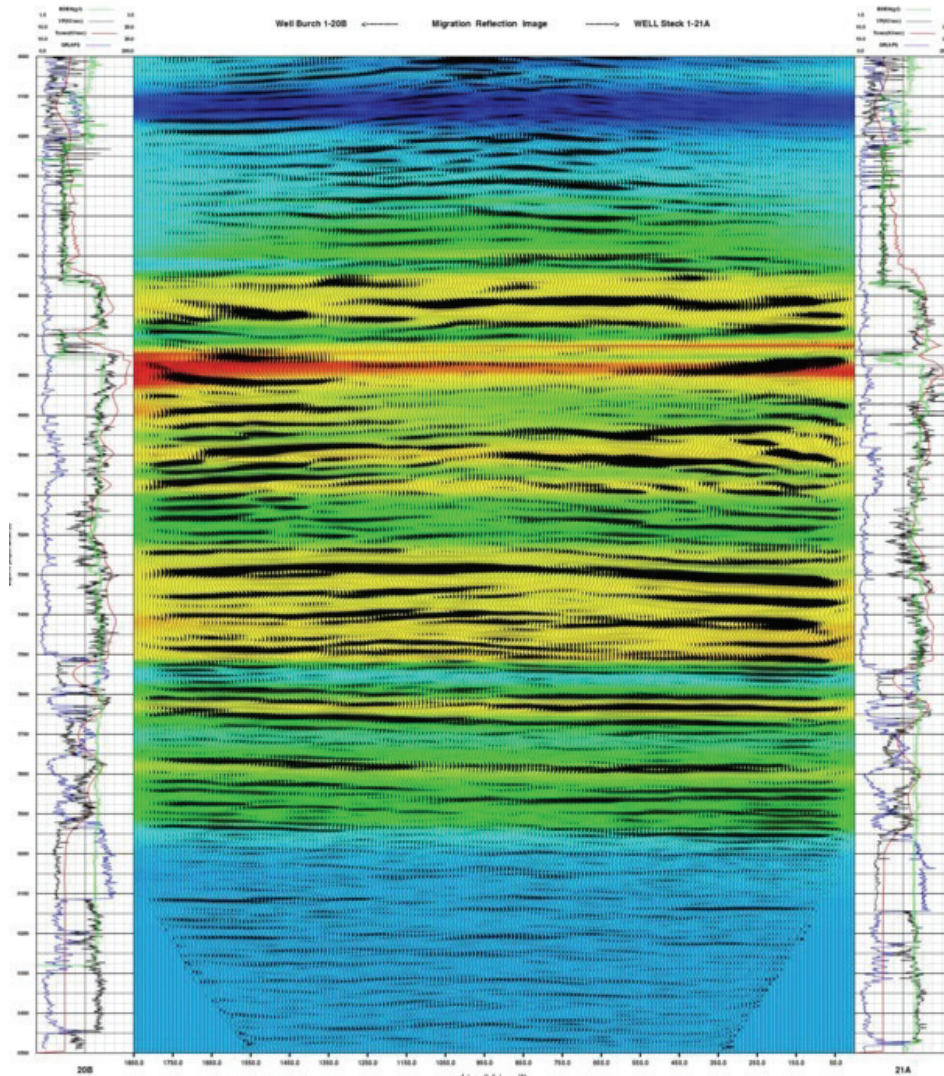


Figure 7.2-10: Cross-well reflection image of the reservoir. The background is a layer constrained tomographic of P wave velocities at the MTU site.

To achieve a 3-D image using the VSP technique one can distribute many sources on the earth's surface or one can reverse the method by placing the source in the borehole while distributing receivers on the surface (reverse vertical seismic profiling (RVSP)). The resulting RVSP image as shown on Figure 7.2-11 shows the higher resolution achieved with the higher frequency content.

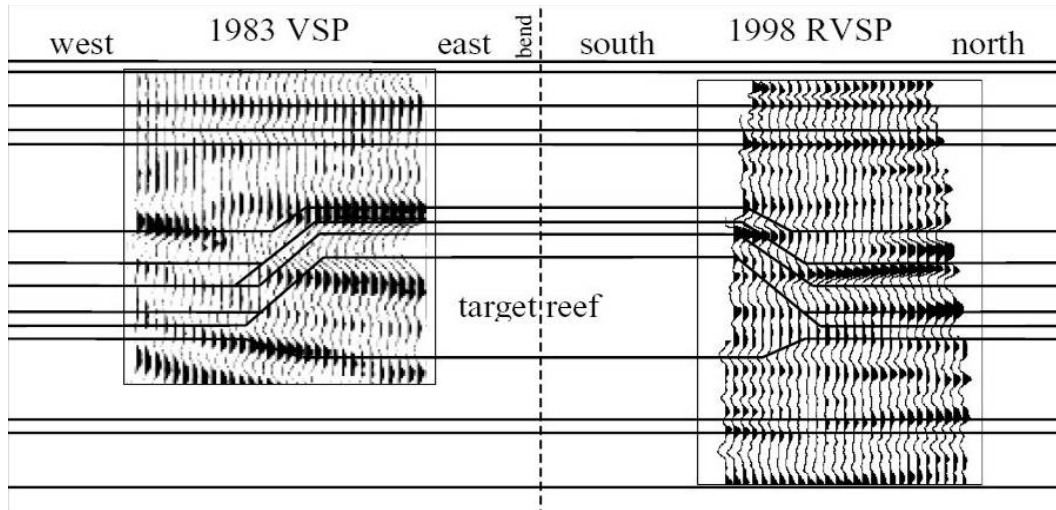


Figure 7.2-11: Comparison of a conventional VSP image and a RVSP image. The higher frequency content of the RVSP data is apparent in the quality of the RVSP image.

An independent verification on the seismic images was obtained using borehole gravity measurements in the Burch borehole. The gravity measurements (Figure 7.2-12) revealed that the thickness of the reef material was underestimated by about 15 m.

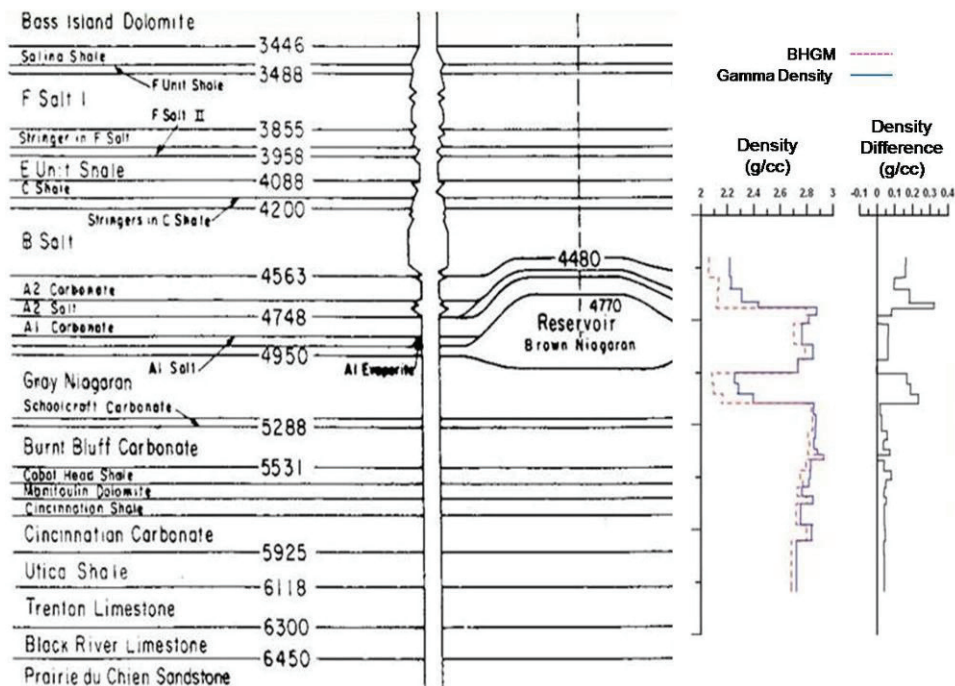


Figure 7.2-12: BHGM measurements made in the Burch borehole, MTU site.

7.2.3 Detroit River International Crossing (DRIC), Ontario, Canada

Introduction

In 2006, the search for a new highway crossing of the Detroit River between Ontario and Michigan (Detroit River International Crossing – DRIC) led to three possible sites for a new bridge. However, the sites were located near a former solution salt mine (Figure 7.2-13). The solution mining activities had taken place since 1902 and a sink hole had opened up in the mid-

1950's that was 8 m deep and 100 m in diameter. The mining had taken place at a depth of 300 to 450 m below ground surface in the Salina Fm (Figure 7.2-13). Given this past history, an extensive geotechnical investigation was undertaken from 2006 to 2008 on behalf of the Ontario Ministry of Transportation on the Canadian side of the crossing. The question to be answered was "how close is too close?" or more definitively – what would be the zone of influence of the solution mining with respect to locating and designing the bridge foundations?

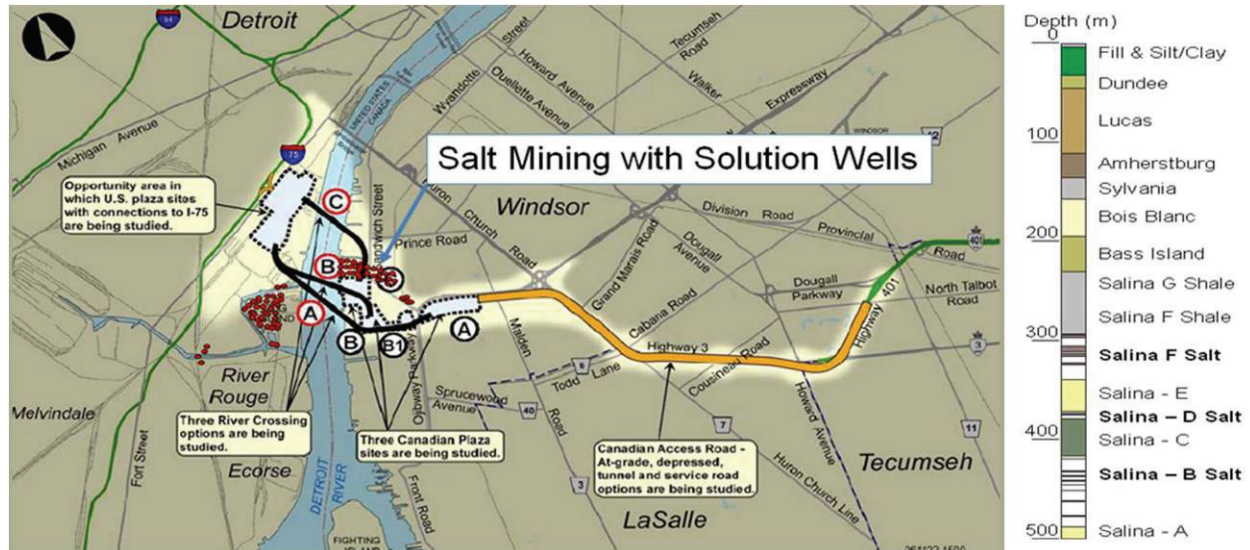


Figure 7.2-13: Location and generalized stratigraphy, DRIC project site, Windsor, Ontario.

Twelve boreholes were completed to a depth of 500 m that included the overburden (30 metres) and Palaeozoic bedrock from Dundee Fm (Middle Devonian) to almost the base of the Salina Fm (Upper Silurian). Of the 12 boreholes drilled, only one was cored to the full depth of drilling (and another to approximately 300 m) mainly due to extremely difficult drilling conditions. As such, a heavy reliance was placed on borehole geophysics in this investigation.

Borehole Geophysical Surveys

The overall purpose of the investigation was to locate and infer the lateral extension of voids due to solution mining activities. The investigation on the Canadian side of the crossing included 2D and 3D surface seismic reflection surveys, the drilling of 12 boreholes to a depth of 500 m, borehole geophysical logging (natural gamma, apparent conductivity, acoustic televiewer, full wave form sonic and caliper), cross-well seismic imaging, synthesis and interpretation of the hydrogeological and geotechnical data and modelling to assess the vertical and lateral extent that solution mining and the sinkhole collapse may have influenced the rock mass.

Stratigraphic and structural data were derived from the natural gamma, apparent conductivity and acoustic televiewer logs. The sonic logs were used to provide measurements of compression and shear wave velocity, engineering properties, acoustic porosity and, in combination with the acoustic televiewer data, apparent rock hardness and apparent density. It was determined during the planning stage of the project that active source nuclear logs (neutron porosity, gamma-density and photoelectric effect) were not to be used due to the poor ground conditions.

The natural gamma and apparent conductivity logs were first correlated to the cored boreholes and then used to correlate stratigraphy across the site in the remaining 10 boreholes. Based on

these logs, it was possible to identify marker horizons and measure depth with a high degree of accuracy. The natural gamma logs in particular, were matched virtually peak-for-peak, trough-for-trough between the various boreholes (Figure 7.2-14).

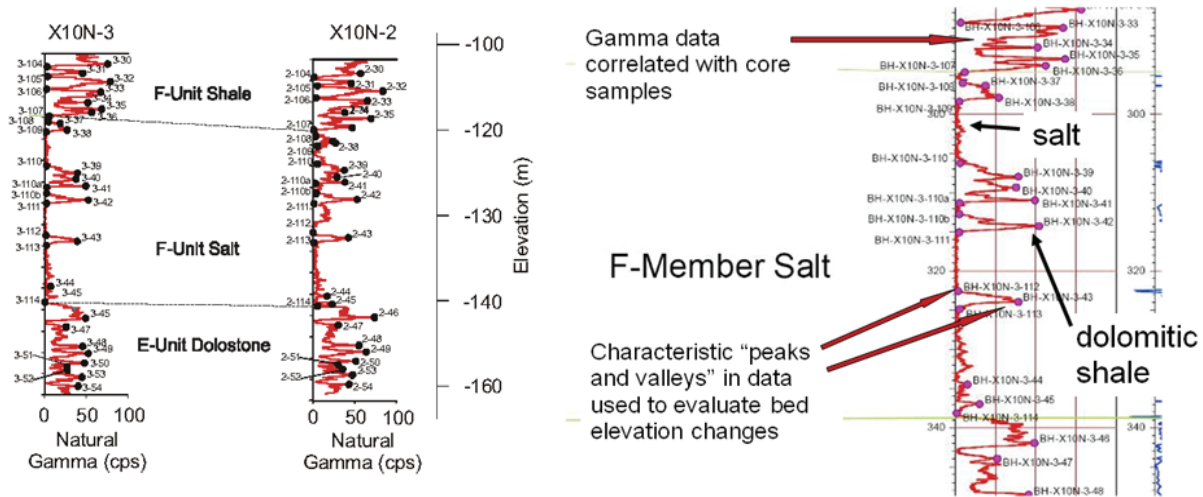


Figure 7.2-14: Natural gamma log correlations, DRIC site. (Golder Associates)

The acoustic televiewer logs were analyzed for structure including major, minor and partially open fractures (Figure 7.2-15). With reference to Figure 7.2-15, the optical televiewer log was collected in one borehole (BH 10N-2) where fluid exchange between the formation and the borehole provided clear conditions for the “visual” log. The fracture histogram was generated from analysis of the acoustic televiewer data.

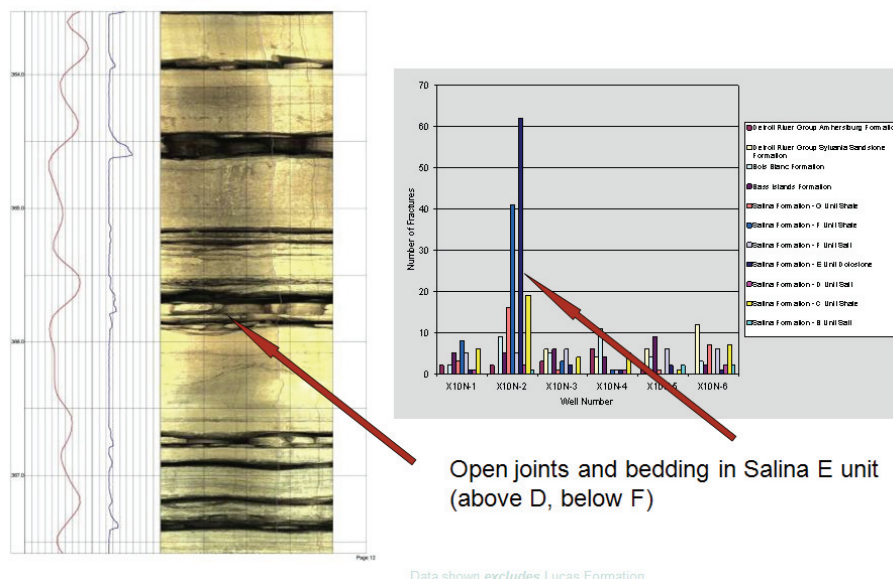


Figure 7.2-15: Optical Televiewer Data Example and Fracture Histogram. (Golder Associates)

The analysis indicated that fracturing was, for the most part, associated with bedding partings and vertical fractures, where present, were constrained to short intervals within more brittle rock

layers. As expected, the borehole with the highest degree of fracturing (BH10N-2) was the closest to the portion of the site where solution mining activities were conducted.

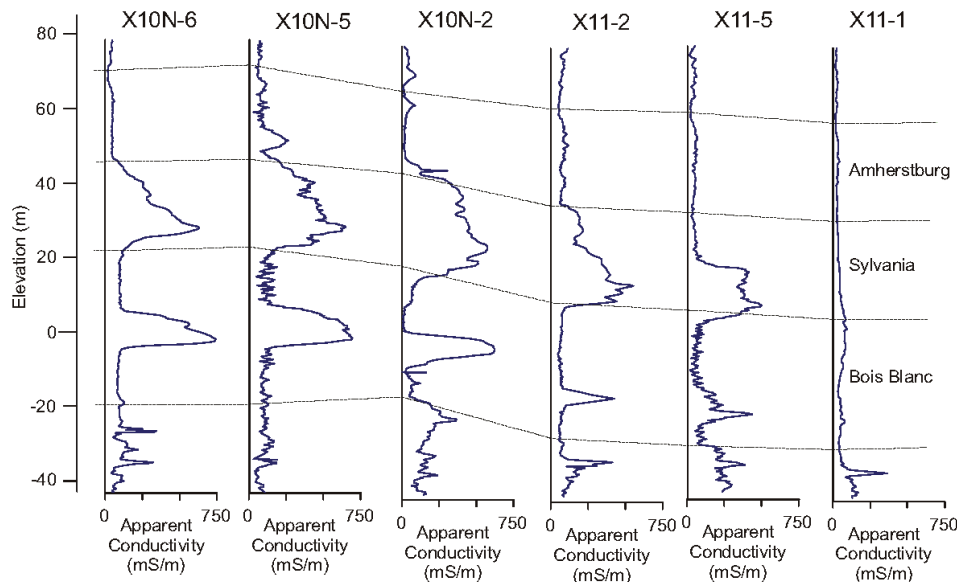


Figure 7.2-16: Apparent conductivity logs in the Sylvania and Bois Blanc Formations, DRIC site. (Golder Associates)

Apparent conductivity data also helped to define the limit of disruption in the stratigraphy above the solution-mined openings deeper in the section. Zones of anomalous high apparent conductivity were measured in the Sylvania and Bois Blanc Formations (Figure 7.2-16). On Figure 7.2-16, the logs are generally arranged from south to north (left to right) spanning the solution mining area. Boreholes X10N-2 and X11-2 are closest to the former solution mining site.

It was clear from comparison to other logs (caliper, natural gamma and acoustic televiewer) that these changes were not related to changes in borehole diameter, drilling fluids (fresh water used in this horizon), or variability in porosity. The measured apparent conductivity through these zones was greater or less depending on proximity of each borehole to the brine field. It is probable that long-term problems with broken, repaired and poorly abandoned brine wells, as well as potential aquifer mixing during the sinkhole collapse event, resulted in permeation and migration of brine into these (permeable) formations.

Cross-hole seismic reflection imaging surveys were completed to generate 19 panels to investigate the stratigraphy between the boreholes at the site. This seismic imaging in combination with modelling and borehole geophysical logging provided the basis for defining the limits of the structure deformation in the bedrock associated with the solution mining. Figure 7.2-17 shows a cross-well seismic reflection image from an area of the site removed from the solution mining. The reflectors are clear, flat and continuous between the boreholes. Figure 7.2-18 shows a cross-well seismic reflection image where the borehole pair straddled a zone of solution mining. Here the reflectors are weak and variably dipping across the section.

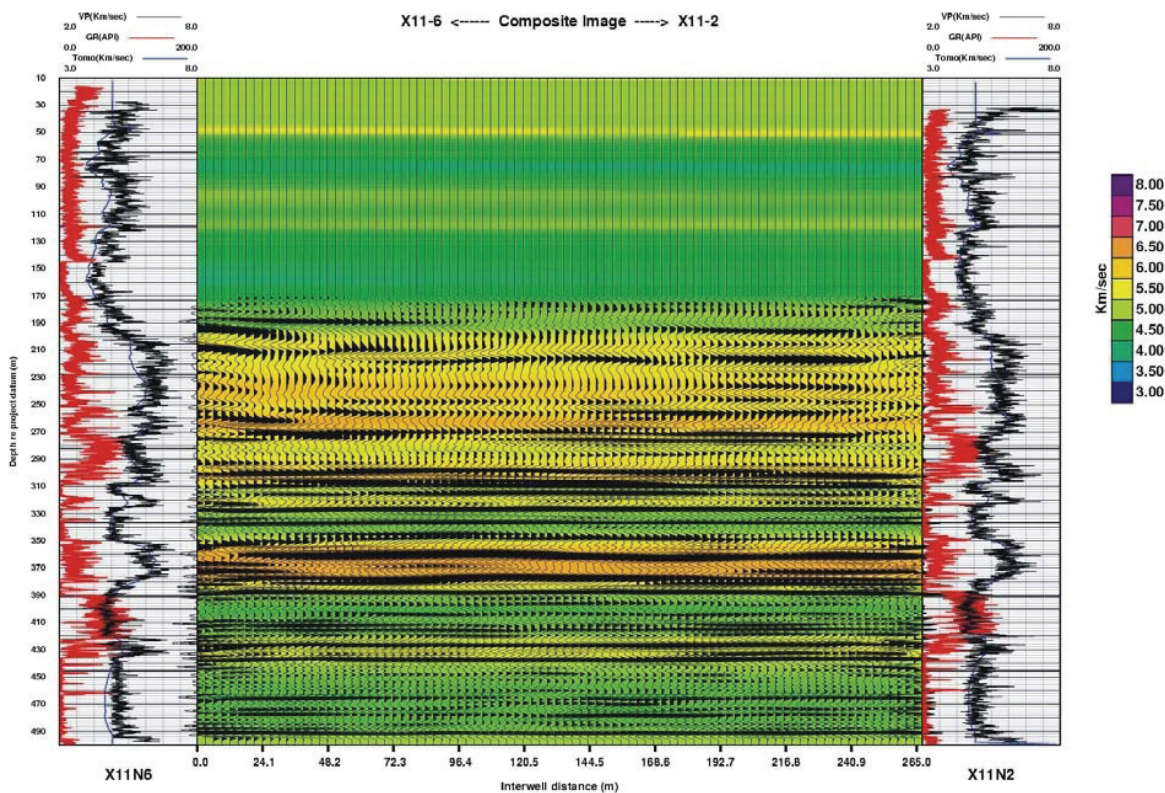


Figure 7.2-17: Cross-hole seismic reflection and borehole geophysics results in undisturbed ground, DRIC site. (Z-Seis Reservoir Imaging and Golder Associates)

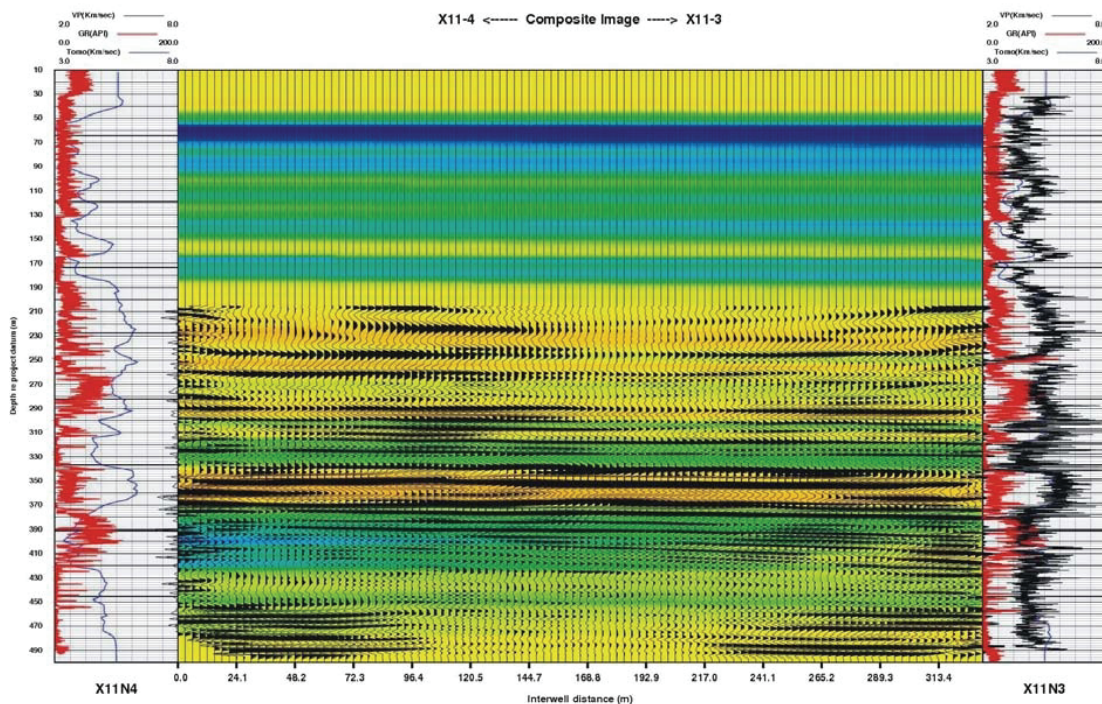


Figure 7.2-18: Cross-hole seismic reflection and borehole geophysics results in disturbed ground, DRIC site. (Z-Seis Reservoir Imaging and Golder Associates)

On the left side, Figure 7.2-19 shows the results of numerical modelling bedrock subsidence into a 2-dimensional hypothetical cavity with a wedge-shaped edge. The numerical modelling was completed with the UDEC (Itasca software, 2006 version) universal distinct element code. On the right side of the figure is an enhanced version of the seismic data shown on Figure 7.2-18, to highlight the seismic response in the lower data gap along with a re-interpretation. The central dipping feature is interpreted to be a structural distortion due to collapse into the plane of the cross section. The seismic interpretation was invaluable in supporting the numerical simulation of the solution mining collapse.

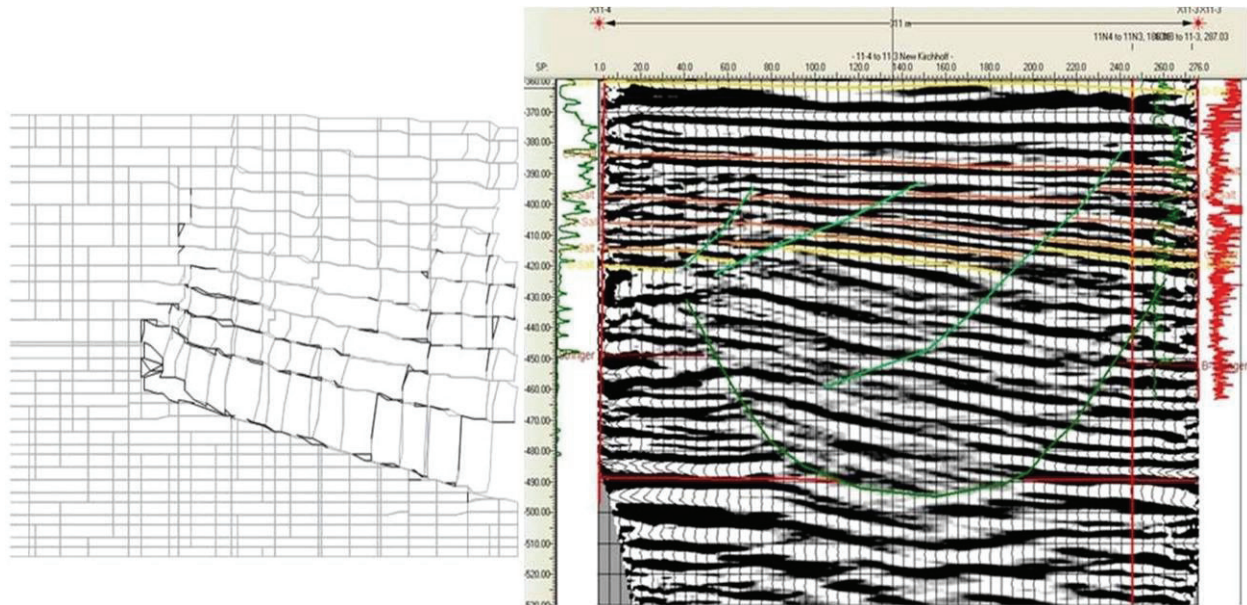


Figure 7.2-19: Bedrock Numerical Model and Enhanced Seismic Profile, DRIC site. (Z-Seis Reservoir Imaging)

In summary, the combination of the borehole geophysical data together with the cross-well seismic data and numerical modelling provided considerable insight to the subsurface structure at this site and provided a basis for establishing limits on the zone of influence of the solution mining with respect to locating and designing the bridge foundations. Modelling support and the borehole geophysical data were vital aids in interpretation of the data.

7.3 Summary

This section summarizes the borehole geophysical methods and approaches to site characterization as seen in the various case histories, the applicability of the methods to the Canadian programme for both sedimentary and crystalline host rock environments, and some of the key lessons learned.

7.3.1 Approaches to Date

Borehole-based geophysical methods have been an integral part of virtually all deep bedrock investigations and especially for all of the repository studies to date. These investigations, such as the work for the AECL URL Project, have helped to drive the development of new geophysical technologies and applications. The geophysical methods used have generally been directed at characterization of the geological and hydrogeological properties and to a lesser degree, the engineering properties of the host rock environment.

In general terms, there have been two approaches for deciding on the suite of borehole geophysical methods: run the entire tool box of geophysical methods versus run a set of tools for specific purposes only. The acquisition of geophysical log data is relatively inexpensive, so it can be argued that it is prudent to acquire all the data possible. For the most part, this has been the approach to date in repository studies – all methods are applied, including prototype methods that are experimental in nature. Examples of this would include work at the AECL URL and Sweden's Forsmark site.

By contrast, in other heavy civil applications such as the DRIC bridge foundation investigation or No. 3 Tunnel investigation, time and budget constraints are such that specific technologies are selected to address specific project requirements.

Borehole geophysical methods are very technology driven and as such, technologies will evolve and improve over the lifespan of a repository project. The specific technologies used in the borehole geophysical programs at several sites, including Sellafield and Forsmark, evolved over time. For example, optical televiewer technology did not exist a decade ago; today, optical televiewers are routinely used in geotechnical investigations for most underground mining and engineering works.

The most successful borehole geophysical programs have been those that were developed in close conjunction with the overall investigation programme for the site, and in particular from a logistics perspective, close conjunction with the drilling and hydrogeologic testing programs. On occasion, the requirement for specific types of borehole-based geophysical data will drive the drilling program, as there will be certain requirements for the boreholes including diameter, depth and separation between boreholes. As well, the use of borehole geophysics in percussion or rotary drilled holes can result in significant savings over an investigation programme based solely on cored borehole drilling.

Advancements in the application of borehole based geophysical methods have been accomplished through collaboration with other repository research groups, sharing ideas and best practices and through strong, long-term working relationships with universities, other scientific organizations and equipment manufacturers and service companies. There are many good examples of close collaboration between nuclear waste management agencies, universities and scientific organizations such as the collaboration with SKB and Uppsala University in Sweden and the work completed at the AECL URL site with contributions by the research staff on site, the Geological Survey of Canada, the USGS, the USACOE and equipment developers.

7.3.2 Best Practices – Sedimentary Rock

The range of borehole geophysical techniques available to investigate sedimentary rocks is vast and the state-of-science of their application is sophisticated. There are techniques to characterize virtually all aspects of the rock, including: stratigraphy, lithology, hydrogeology, rock properties and fluid properties.

Techniques in a typical geophysical log suite, such as the logs acquired at the Benken borehole include: gamma, caliper, compensated neutron, sonic, electric, litho-density, NMR and high resolution (resistivity and sonic) imaging tools. This is similar to the suite used by Nirex at Sellafield (sedimentary rocks overlying a crystalline host rock). It should be noted that some logging tools used for sedimentary rock environments require larger diameter boreholes (15 to

30 cm), but the tools can often be run in multi-tool strings and can be run down to depths in excess of 2,000 m.

Sedimentary rocks are stratified and generally horizontally layered or shallow dipping . Individual units and formations generally have distinctive log signatures for one or more of the logging tools. Marker beds can therefore be identified and followed from borehole to borehole and from this, large-scale structure can be inferred by interpolation between boreholes. Further, if the stratigraphy within the area of a site investigation can be demonstrated to be laterally uniform or if large scale structures can be delineated, then it may be possible, with a reasonable degree of certainty, to apply small scale measurements made in the borehole to the larger context of the site. This can yield great insight into the geology and hydrogeology of a site –two of the most common targets of a borehole investigation.

Also important in a sedimentary rock environment, as demonstrated at the Benken borehole, is the use of VSP surveys to tie the subsurface geology to surface seismic reflection data. VSP surveys in the Benken borehole were critical in the interpretation of the 3D surface seismic data set, which forms the basis of the geological characterization of this site.

Additionally, techniques like cross-hole seismic reflection can also be used in sedimentary rocks to obtain very high resolution images of the subsurface where such detail is required, as demonstrated at the DRIC site.

The flow logging techniques used to measure fracture flow and the televiewer imaging techniques used to identify fractures in a borehole are considered to be less applicable to porous sedimentary rock environments where fluid movement can also occur through the rock matrix.

7.3.3 Best Practices – Crystalline Rock

The borehole based wireline techniques most widely applied to crystalline rock sites were tools that provide information on rock type and rock properties (gamma, electric, litho-density, magnetic susceptibility), fractures and their orientation (calipers, televewers, dipmeters), and fracture flow and hydraulics (flow meters, fluid resistivity and temperature). These tools are typically designed so that they can be run in smaller diameter (< 15cm) cored or percussion boreholes.

Perhaps the most important application of borehole geophysics at crystalline rock sites is the characterization of the fractures and the fracture flow system. Fracture data from televewers is often used as the basis for the development of discrete fracture network (DFN) models, which are in turn used to complete the hydrogeologic characterization of the site.

Cross-hole seismic methods in crystalline rock have generally been focussed on tomography using first arrivals. VSP reflection methods were developed in the 1990's for use at crystalline rock sites in Finland and Sweden with success (e.g. Enescu, N., Cosma, C. and Balu, L. 2007), although the techniques are highly specialized and not widely practiced. There have been recent advances in interpretive processing, such as the use of coherency analysis in automated interpretation (fault strand picking) of seismic data, which could improve the applicability of borehole seismic methods to crystalline rocks.

7.3.4 Case Studies – Lessons Learned

Borehole geophysics has played an integral part in the characterization of both sedimentary and crystalline rock sites. Virtually all borehole geophysical tools were found to be applicable to both sedimentary and crystalline rocks, although the importance of one tool versus the other does vary with the application.

In general terms, there have been two approaches for deciding on the suite of borehole geophysical methods: run a full suite of geophysical methods (Table 6.0-1) versus run a set of tools for specific purposes only. In repository studies, investigators have been inclined to run a more complete suite of logs, as well as push to the limits of the state-of-science.

Borehole geophysical methods are very technology driven and as such, technologies will evolve and improve over the lifespan of a repository project. The specific technologies used in the borehole geophysical programs at several sites evolved over time.

The most successful borehole geophysical programs have been those that were developed in close conjunction with the overall investigation programme for the site, and in particular from a logistics perspective, close conjunction with the drilling and hydrogeologic testing programs. The use of borehole geophysics in percussion or rotary drilled holes can result in significant savings over an investigation programme based solely on cored borehole drilling.

A quality assurance and quality control (QA/QC) plan has to be developed prior to initiating any field investigations and this plan has to be sufficiently robust so as to meet the standards required to support the safety assessment for the repository.

Collaboration with other repository research groups, universities, government agencies and service providers is or should be an essential part of developing a sound programme of investigation – certainly this is true for borehole geophysics. There are numerous techniques that can be applied with new ones being developed every couple of years. This collaboration should extend beyond the planning stage as these investigations can take years and there is great potential for the technology to advance during the lifetime of an investigation. Also, it is expected that there should be opportunities for repository investigators to collaborate with service providers for equipment and programme design and development and testing of new technologies.

8. CONCLUSIONS

This report presents a discussion of borehole geophysical tools and techniques that could be applied to the characterization of deep geological repository candidate sites. The techniques considered include wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and NMR logs), flow logging tools (impeller, heat pulse, electromagnetic, and fluid tracking), seismic methods (sonic and full waveform, tomography, reflection and VSP), borehole radar, borehole TDEM and cross-hole EM. The report provides guidance on the benefits that specific techniques may provide along with some constraints. Borehole geophysical techniques are heavily reliant on technology and as such, techniques will evolve and improve during the life span of a repository investigation.

Typical borehole geophysical applications are presented in this report, including the determination of lithology and stratigraphy, physical properties, rock structure and hydrogeologic properties, as well as in situ stress investigations, and well inspections. Nine case histories are presented and discussed, including crystalline and sedimentary rock environments from project sites in Europe and North America. The project sites presented include nuclear repository sites, underground test sites and heavy civil works.

Details on the accuracy and resolution of each method are provided. These are guidelines as they are dependent on many investigation specific factors, including geology, target geometry, intrinsic properties of the formations and the condition and nature of the borehole (i.e. diameter, rugosity, stability, fluid level).

A successful borehole geophysical programme is one that is developed in close conjunction with the overall investigation programme for the site, and in particular from a logistics perspective, in close conjunction with the drilling and hydrogeologic testing programs. The use of borehole geophysics in percussion or rotary drilled holes can result in significant savings over an investigation programme based solely on cored borehole drilling.

Borehole geophysics has played an integral part in the characterization of both sedimentary and crystalline rock sites in every nuclear repository program. Borehole geophysical data are one of the primary inputs to the development of the site geosphere model. Virtually all borehole geophysical tools were found to be applicable to both sedimentary and crystalline rocks, although the importance of one tool versus the other does vary with the application.

Canada is very well positioned to apply borehole-based geophysical methods in these types of geoscientific and ground engineering studies. There are a number of well established consulting and service provider companies with the expertise and equipment inventory to complete these types of surveys.

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