Characterization of Bedrock for Geo-Environmental Site Assessment

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ABSTRACT
The City of Calgary and its immediate vicinity are underlain by a few metres to some 80 m of unconsolidated sediments overlying siltstone, sandstone and shale bedrock strata. In this geologic setting, it is quite common to begin a phase II environmental site investigation using auger drill rigs. One inherent problem with using auger rigs is that they can penetrate weathered bedrock and even some distance into intact bedrock without the logging technician always noticing the changes in stratigraphy. Consequently, monitoring wells have been installed with screens straddling the soil overburden and bedrock strata, potentially resulting in cross-contamination and improper assessment of hydraulic properties with exaggerated estimates of the vertical extent of impacts. To overcome this deficiency, boreholes can be advanced using diamond coring where bedrock is encountered. Diamond coring techniques permit better characterization of the bedrock with respect to fracturing and discontinuity by evaluating total core recovery and rock quality designation (RQD). During diamond coring, the borehole is usually cased thus minimizing potential vertical cross-contamination. Downhole geophysical methods can provide additional indicators for stratigraphic changes and enable the proper location of screen intervals for monitoring wells. Two case histories will be presented to illustrate the use of diamond coring drilling and downhole geophysical methods in the subsurface investigation and remediation process.

RÉSUMÉ
La ville de Calgary et ses environs proches reposent sur une couche de sédiments inconsolidés d'environ 80 m d'épaisseur, eux même sur un substratum rocheux de siltstone, grès et schiste. A cause de cette séquence géologique il est courant de commencer une Etude Environnementale de Site de Phase II en utilisant une foreuse à tarière. Un problème inhérent à l'utilisation de ce type de foreuse c'est que le substratum rocheux, altéré ou non, peut être atteint sans que le technicien en charge du log géologique ne s'aperçoive du changement de stratigraphie. En conséquence des puits de contrôle ont été installés avec leur section crépinée à cheval entre les sédiments inconsolidés et le substratum rocheux, pouvant potentiellement mener à une contamination croisée. Ce type d'installation peut également conduire à une estimation erronée des propriétés hydrauliques ainsi qu'à une estimation exagérée de l'étendue verticale de la pollution. Pour parer à cette faiblesse, le trou de sonde peut être avancé en utilisant une foreuse à diamant lorsqu'un substratum rocheux est présent. Lors de l'utilisation d'une foreuse à diamant le trou de sonde est généralement tubé afin de minimiser les risques de contamination croisée. Les méthodes géophysiques en puits, telles la mesure de conductivité électrique ou la diagraphie gamma (log gamma naturel) peuvent fournir des informations complémentaires au niveau des changements stratigraphiques et permettent un choix approprié de l'intervalle à crépiner pour les puits de contrôle. Deux exemples vont être présentés afin d'illustrer l'utilisation d'une foreuse à diamant ainsi que les méthodes géophysiques pour l'investigation de subsurface ainsi que pour la remédiation de site.

1 INTRODUCTION

The City of Calgary and its immediate vicinity is underlain by a few metres to 80 m of unconsolidated sediments overlying sandstone and shale of the Paleocene Paskapoo and Porcupine Hills formations (Obsborn and Rajewicz 1998). In this geologic setting, it is quite common to begin a phase II environmental site investigation using auger drill rigs due to their versatility and ease of access to sites. However, when bedrock (weathered or intact) is encountered, auger drilling is not capable of providing adequate stratigraphic resolution to locate the maximum depth of impact or to position the screen interval of monitoring wells.

This paper will first discuss the commonly used drilling methods used in the Calgary area. Differences between auger drilling and bedrock coring techniques will be illustrated using boreholes advanced in two unidentified sites in the Calgary area and their effects on remedial actions are then discussed.

2 PHASE II INVESTIGATION AT TWO ALBERTA SITES

Both sites used in this paper are former service stations. Figures 1 and 2 show the site plans with borehole locations for the sites, named as Site A and Site B, respectively.

At Site A, the soil profile consists of silts and clays to an approximate depth of 9.0 m below grade surface (bgs) followed by sandstone and shale bedrock of the Porcupine Hills Formations to at least 22.9 m bgs, the maximum depth drilled. Site B is underlain by a surficial layer of silt (Quaternary till) to approximately 1.7 m bgs. Below this overburden is a bedrock stratum consisting of cross-bedded siltstone, sandstone and shale of the

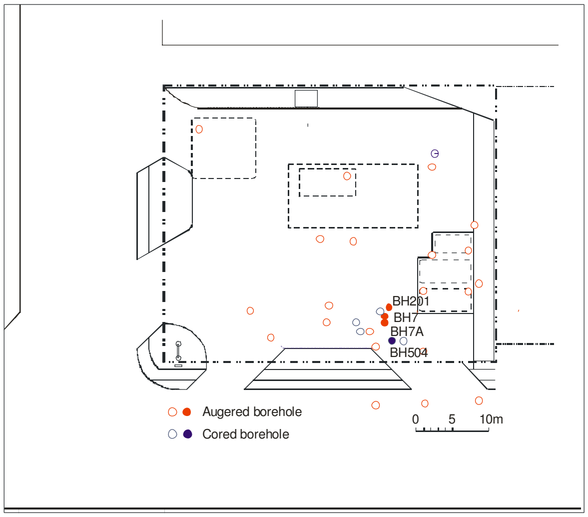

Figure 1. Site Plan – Site A

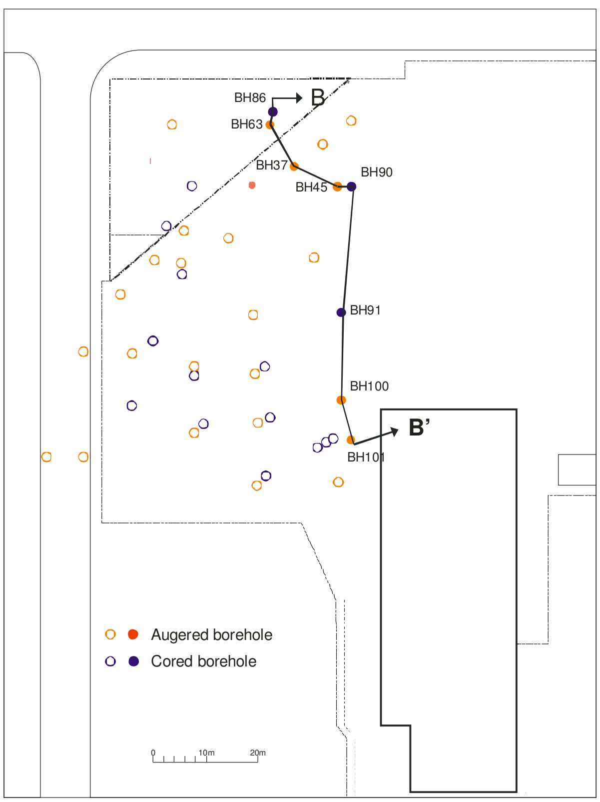

Figure 2. Site Plan – Site B

Porcupine Hills formation.

2.1 Common Drilling Methods for Phase II Environmental Site Investigations

Table 1 summarizes the common drilling methods used in south and central Alberta for Phase II environmental site investigations (ESAs). The table is compiled based on the authors' personal experience in drilling for environmental site investigations. The drilling method is usually selected according to local geology, size and depth of the borehole, the local availability of equipment and the available expertize. For an initial drilling exercise without prior geologic data, several references such as Meyboom (1961), Moran (1986) and Osborn and Rajewicz (1998), provide valuable preliminary geologic data for sites around Calgary. In general, the drilling method selected should advance the borehole at an acceptable rate, minimize soil smearing and allow for the collection of depth-specific soil samples and should not use drilling mud. Augers and direct push are applicable in soils up to fine gravel in size; hammer and air-rotary rigs are useful in gravels and boulders; and diamond coring and air-rotary drilling are employed in bedrocks. Sonic drilling is well suited for gravelly sites in Calgary; however, at present, sonic rigs are not readily available south of Fort McMurray. In this paper, discussion is limited to auger and diamond core drilling since these are the methods used at the two sites presented in this paper.

Solid-stem augers (SSAs) usually have the highest availability and the lowest cost among the methods presented in Table 1. The equipment is relatively mobile and drilling is completed without the use of drilling fluids. The major disadvantages associated with SSAs are that the boreholes are limited to depths not exceeding 15 m (50 ft); they can only provide disturbed grab samples; the soil cuttings may ride up through the augers resulting in inaccurate sample depth; they generate cuttings that require proper disposal and the borehole remains uncased during drilling (thus higher potential for cross-contamination). Ideally, SSAs are best used in exploratory drilling (or stratigraphic screening) due to its economy and accessibility. When using SSAs, it is not recommended to collect soil samples using Shelby tubes or split spoons; these procedures will involve removing the auger strings from the borehole and potentially cause cross-contamination and borehole wall instability.

Hollow-stem augers (HSAs) have higher availability and lower cost than many other methods described in Table 1. The equipment is relatively mobile and drilling is completed moderately fast without the use of drilling fluids. The hollow stem allows soil samples to be collected using Shelby tubes, split-spoon samplers or continuous core samplers. It also enables a monitoring well to be installed through a cased opening. Shelby tubes can provide nearly undisturbed samples in cohesive materials and soft formations (Shuter and Teasdale 1989). The disadvantages of HSAs include that the boreholes are limited to depths of about 15 m (50 ft), they generate drill cuttings that require disposal, and the high potential of cross-contamination through an uncased borehole wall. In addition, special procedures

Table 1. Common Drilling Methods Used in South and Central Alberta

Drill Type	Soil Type								Max. Depth	Can Install Monitoring Well
	Clay	Silt	Sand	Fine Gravel	Coarse Gravel	Boulder	Weathered Bedrock	Bedrock		
Auger: Hand	○	○	○	⦿	●	●	●	●	~ 10' (3 m)	yes[c]
Auger: Hollow Stem	○	○	○	○	**O**	●	○	●	~ 50' [a] (15 m)	yes[b]
Auger: Solid Stem	○	○	○	○	●	●	○	●	~ 50' [a] (15 m)	yes[c]
Coring - Diamond Bit	●	●	●	●	●	⦿	○	○	> 50' (15m)	possible
Direct Push (with Percussion Hammer)	○	○	○	○	**O**	●	●	●	~ 25' (7.5m) - without hammer; ~ 35' (10.5 m) - with hammer	possible with prepack
Hammer	●	●	⦿	⦿	○	○	**O**	**O**	> 50' (15 m)	yes
Rotary	○	○	○	○	○	○	○	○	> 50' (15 m)	yes
Sonic [d]	○	○	○	○	○	⦿	⦿	**O**	> 50' (15 m)	yes

Notes:
[a] depth will be shallower if chassis weighs less than 1.5 tonnes
[b] may have difficulties installing in flowing sands
[c] may be limited by sidewall stability
[d] at present, sonic drills are not readily available in Alberta south of Fort McMurray

Legend for Applicability

○ common practice
⦿ possible
O very difficult
● not common practice

may be required when installing a monitoring well in flowing sands.

Diamond coring is usually carried out using rotary drilling rigs equipped with double-tube core-barrels enabling the recovery of continuous samples (cores) using air or clean water as the drilling fluid. Cuttings are immediately pulled into the core barrel, thus minimizing erosion along the borehole and resulting in minimal contamination by overlying borehole material (Sterrett and Hanna 2007, Campbell and Lehr 1973). Rock cores are usually either 1⅞"(47.6 mm) or 1½" (38.1 mm) in diameter; they are also identified as NQ and HQ cores, respectively, by the drilling industry. Coring is usually only used in rock formations; hence, other drilling methods are using to advance a borehole through the overburden. In cobbles or gravels, either Odex or rotary drilling is used and the borehole is cased. Odex drilling is commonly used to drive a 5½" (140 mm) diameter casing through gravelly overburden; while rotary drilling with a B57 rig is used to set a 3½" (89 mm) diameter casing through silts and clays and seal it into bedrock. Core drilling can provide a good record of subsurface stratigraphy and fracture distribution within each core run. However, coring drilling is more expensive and time-consuming compared to the other drilling methods listed in Table 1.

3 AUGER DRILLING AND CORING COMPARED

One inherent problem with using auger rigs is that they can penetrate weathered bedrock and even some distance into intact bedrock without the logging personnel always noticing the changes in stratigraphy. Consequently, monitoring wells have been installed with screens straddling unconsolidated formation and bedrock strata, potentially resulting in cross-contamination and improper assessment hydraulic properties with

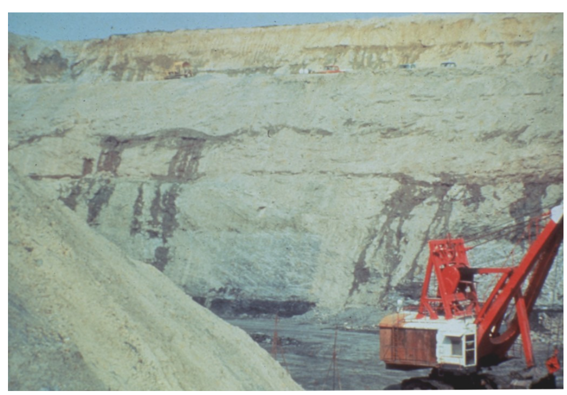

Figure 3. Seepage from Upper Aquifer Materials on an Excavation Face
(Photo compliment of Dr. Tim Kimmis, Midwest GeoSciences Group)

exaggerated estimates of the vertical extent of impacts as illustrated in the following discussion.

3.1 Potential Cross-Contamination

As an uncased borehole is being advanced through a formation consists of alternating strata of aquifer (water-bearing) and aquitard (non-water-bearing) materials, it is possible for impacted groundwater in an upper aquifer to travel down the borehole wall and cross contaminate the underlying materials. Figure 3 shows an excavation face exposing two water-bearing layers and the associated groundwater seepage. An uncased borehole advanced through these two layers will provide a vertical communication pathway from the top to the bottom layer.

3.2 Stratigraphic Identification

Stratigraphic data obtained by SSA drilling and diamond coring are illustrated in this section using various boreholes advanced in the two sites previously described.

Figure 4 summarizes the borehole data obtained at boreholes BH7, BH7A, BH201 and BH504 drilled in Site A. Boreholes BH7, BH7A and BH201 were advanced using SSAs while borehole BH504 was advanced using SSAs (in the overburden) and diamond coring (in bedrock). These boreholes were located within 3 m of each other (see Figure 1).

As illustrated in Figure 4, logs from BH7, BH7A and BH201, when compared to the core log of BH504, show that the logging technicians likely have identified ground up sandstone as sand in boreholes BH7 and BH201 and as siltstone in BH7A. In addition, the occurrence of clay in Borehole BH201 is not supported by BH7 or BH7A, located within 2 m. Figure 5 shows the sandstone cuttings obtained from auger drilling. The angular fragments help to indicate that the borehole has been advanced into sandstone bedrock. Another possible indicator is the rate of borehole advancement and the difficulty in drilling. Hence, communication with the drillers is an important step during subsurface investigations. Moreover, field soil identification should be adequately backed up using laboratory grain size analyses.

Rock quality designations (RQDs) for BH504 are also shown on Figure 4. They indicate that the sandstone formation and the upper shale formation are weathered and fractured while the shale formation is relatively unfractured below 18.2 m from grade. The relatively unfractured state was confirmed by a bail test a hydraulic conductivity of about 1.6×10^{-9} m/s.

Although not used for this site, RQD data can also be used to estimate in situ effective porosity (Liu and Brady 1999) and the degree of jointing (Palmstrom 2005). Effective porosity is one of the key parameters controlling contaminant transport in geologic formations through the inhalation and groundwater pathways. Alberta Environment has not provided any guidance to estimate this parameter for risk assessment calculations for bedrock sites (AENV 2009). Although Liu and Brady (1999) were originally written to address the leaching process for mineral recovery in a porous medium, the mathematics described is equally applicable to contaminant transport. They proposed to estimate the

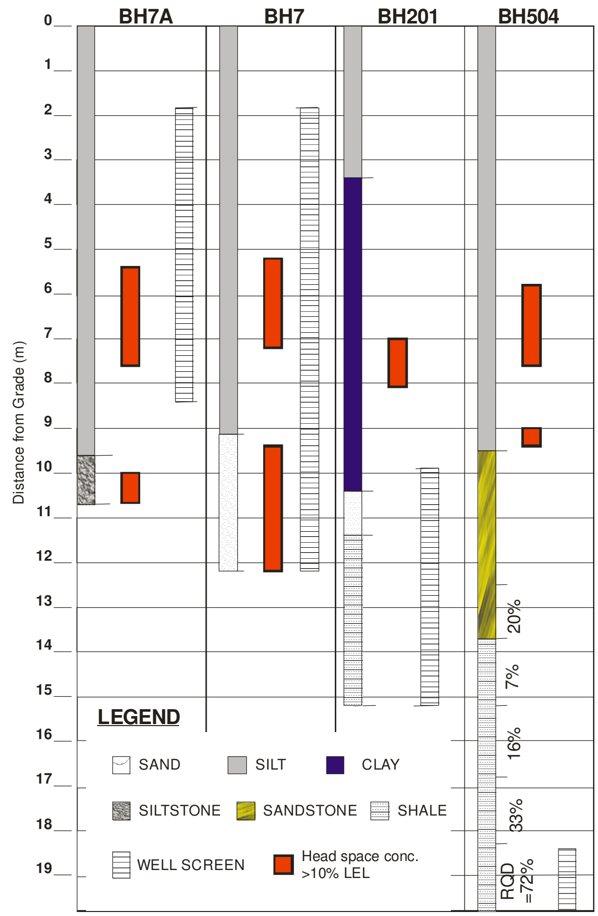

Figure 4. Summary of Borehole Data from Selected Boreholes at Site A.

Figure 5. Sandstone Cuttings from Auger Drilling

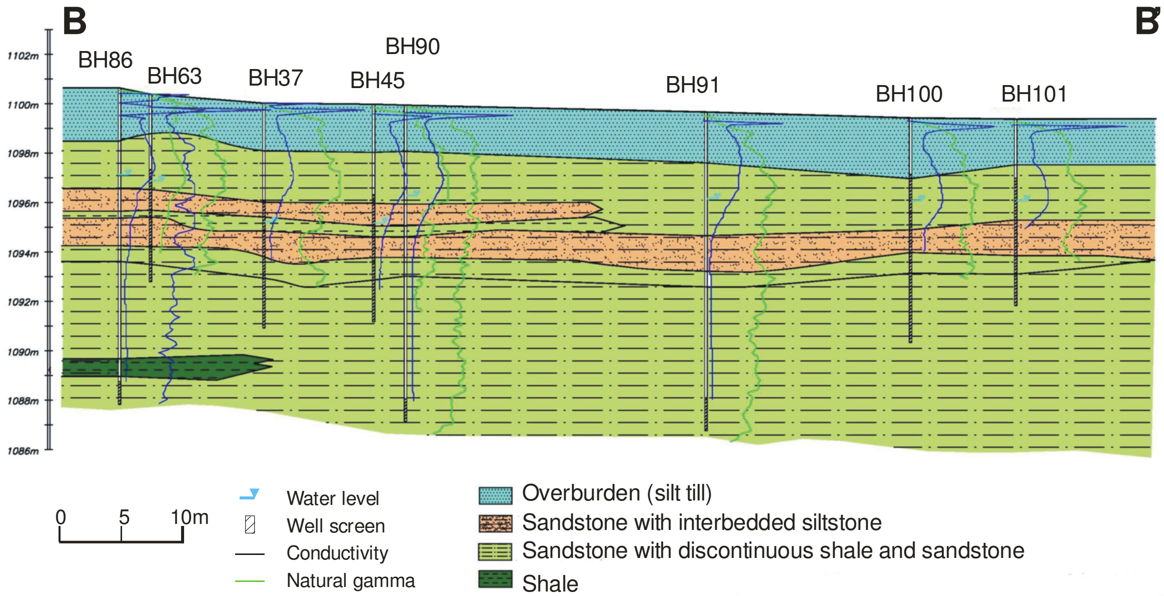

Figure 6. Stratigraphic Cross-Section A-A' at Site B Showing Conductivity and Natural Gamma Logs.

effective porosity for a specific length of core using hydraulic conductivity and the value of RQD.

It should also be noted that in BH7 and BH7A, higher headspace vapour concentrations were detected in two separate zones. Since the groundwater table was located around 7 m bgs, it is possible that the samples from the lower zone might have been cross-contaminated.

Figure 6 presents a geologic cross-section, Section B-B', for Site B. The cross-section was developed using diamond coring logs, SSA borehole logs, together with down-hole geophysical logging using a conductivity probe and a natural gamma probe. The cored boreholes include BH86, BH90, and BH91. Bedrock lithology was determined primarily used coring data. Poor to fair RQD values were observed for most of the siltstone and/or sandstone formations to an approximate depth of 7.5 m bgs. The low RQD values indicate a high degree of weathering and fracturing of these units and thus potential groundwater transport pathways. Fair to good RQD values were measured below 7.5 m predominantly in the sandstone and interbedded siltstones.

Downhole geophysical logging, including conductivity and natural gamma emission, was used to refine stratigraphic correlations within and between boreholes in order to:

- map conductivity contrasts;
- permit hydraulic and chemical characterization of the conductive fracture network;
- understand bedding distribution and to correlate fracture network between boreholes; and,
- aid in the design of a zone-specific groundwater level monitoring network.

Natural gamma logging was conducted to measure the natural radioactivity (gamma ray) emitted by the surrounding geologic formation. Higher measured values in units of counts per seconds reflect higher clay content (shale) of the surrounding bedrock formation (Keys 1990). This technique can be used to refine stratigraphic correlations and to delineate changes in lithology. The natural gamma log was recorded at intervals of 0.025 m through the 50 mm (2 in) PVC casing. The natural gamma emission counts ranged from 0 to 200 per second. Values of 50 counts per second to 130 counts per second are typical of sandstone and 100 to 220 counts are typical of shale. Under most subsurface conditions, about 90% of natural gamma radiation detected probably originates from materials within 15 cm to 30 cm (6 in to 12 in) of the borehole wall.

EM39 logging was conducted to evaluate the stratigraphic variation of the formations by measuring the electrical conductivity of the pore liquids within a zone of 0.25 m to 1.25 m adjacent to the borehole wall. The electrical conductivity values measured ranged from 0 to 50 mS/m. In general, a higher conductivity value would indicate higher clay contents (Schulmeister et al. 2003) or water-wet pathways. However, conductivity readings can be affected by other factors such as mineralogy and pore-water chemistry. Natural gamma count is another useful tool that for distinguishing between shale and sandstone (Keys 1990).

Geophysical and logging data can further be validated by in situ hydraulic testing such as bail or slug tests. Using depth-specific screens installed in boreholes cored into bedrock and bail tests, it was possible to determine the most conductive fracture network appears to be located between 5.5 m and 7.2 m below grade within the fractured sandstone with interbedded siltstone and shale layers.

4 CONCLUSIONS

At Site A and Site B, more precise stratigraphic definition is achieved using bedrock coring techniques. While SSA drilling offers economic operations and easy accessibility and is a useful tool for exploratory drilling, it is not capable of providing accurate geologic data for bedrock (weathered or intact) sites. To achieve reliable distinction between sand and sandstone, or silt and shale or silt stone, much is dependent on the logging technician's experience and expertise. SSA drilling may also cause cross contamination from an upper aquifer to a lower aquifer. When sufficient lengths of cores are recovered, rock coring offers a reliable method to obtain a visual and physical representation of the subsurface geologic formations. In addition, both SSA and coring can be enhanced by downhole geophysical logging, which can help to distinguish between clays and silts and sands, and map water-bearing zones. Coring, since it is carried out in a cased hole, is capable to provide more precise vertical delineation of contaminations. In order to properly identify water-bearing zones, the vertical extent of contamination, and potential contaminant transport pathways, monitoring wells with proper screen intervals are required. Data from Site A also point out that field logging should be backed adequately up by an appropriate number of laboratory grain size analyses.

ACKNOWLEDGEMENTS

The writers would like to thank Ms. Aurore Kurc for her French translation of the abstract. Portion of this work was carried out under the Scientific Research and Experimental Development (SR&ED) program.

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