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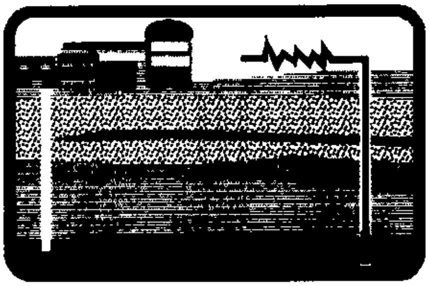

URBAN GEOLOGY 4.
Urban Geophysics in the Kitchener-Waterloo Region

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SUMMARY

During the past decade, the geophysical methods of well logging, and borehole and surface seismic reflection have been adapted and applied to the delineation of overburden aquifers in the Regional Municipality of Waterloo of southern Ontario. We present here an overview of the methodologies that have been developed for this purpose at the University of Waterloo. Some examples are presented, and future research directions for this area of geophysics are discussed.

RÉSUMÉ

Au cours de la dernière décennie les méthodes d'études géophysiques de diagraphie de même que celles de la séismique réflection en surface et dans les puits de forage ont été adaptées et utilisées pour faire le relevé des aquifères existants au sein des roches meubles, dans la région de la municipalité régionale de Waterloo, dans le sud de l'Ontario. Nous présentons un aperçu des méthodologies qui ont été développées à ce propos à l'*University of Waterloo*. Certains exemples sont décrits, et l'on présente les orientations de recherche à venir dans ce champ d'activité de la géophysique.

INTRODUCTION

The Regional Municipality of Waterloo (RMW), situated 100 km southwest of Toronto, includes the cities of Waterloo, Kitchener and Cambridge. Its population of 387,000 is spread over an area of 1330 km^2. Like many communities, the RMW relies largely on overburden aquifers for its residential and industrial water requirements. Sustainable growth depends on securing and expanding this important resource. This growth could potentially degrade the quality of water if not managed properly.

To manage and protect the groundwater, a detailed understanding of the aquifer/aquitard system is required. Owing to the complexity of these overburden deposits, the lateral resolution required for this degree of understanding cannot be achieved cost-effectively with drilling alone. Geophysics has long been used successfully as a tool to image stratigraphy and assess reserves in the oil and gas industry. Significant progress has been made to adapt these methods to water resource investigations (Keys, 1989; Hunter *et al.*, 1989). Here we describe the progress of the geophysics group at the University of Waterloo in addressing the problems we encounter in the RMW, recognizing our dependence on developments within the larger research community.

GEOLOGICAL SETTING

Underlying the glacial sediments that make up the overburden in the RMW are the Silurian and Devonian shales and limestones of the Michigan Basin. These are the Bois Blanc, Bass Island, Salina and Guelph formations (Fig. 1).

Several layers of glacial sediments lie unconformably on these shales and limestones. They are less than 100,000 years in age and in some places exceed 100 m in thickness. Exposed at the surface are the Wentworth, Port Stanley, Tavistock and Maryhill tills as well as the Waterloo, Paris and Galt moraines. At depth, drilling encounters the Catfish Creek Till, as well as at least two pre-Catfish Creek tills (Karrow *et al.*, 1990b).

The exact extent and nature of these deposits is subject to continual refinement as information from each new borehole is acquired.

WELL LOGGING

Since our acquisition of a well-logging system in the early 1970s, the University of Waterloo has been routinely conducting the geophysical logging of boreholes as they are drilled in the RMW. A complete suite of geophysical logs (Fig. 2) typically consists of natural gamma, density (gamma-gamma), epithermal neutron, short/long normal resistivity, and conductivity responses. Since the early 1980s, all data have been collected in digital form, most recently by the computer interface hardware and the software system LOGGITT. A total of 15 cased boreholes are now available, throughout the RMW, for teaching and experimentation with geophysical logging. Many of these have continuous core for comparison with the geophysical data. These boreholes use a standard 7.5 cm schedule 40 PVC casing (Greenhouse and Pehme, 1986; Karrow *et al.*, 1990a).

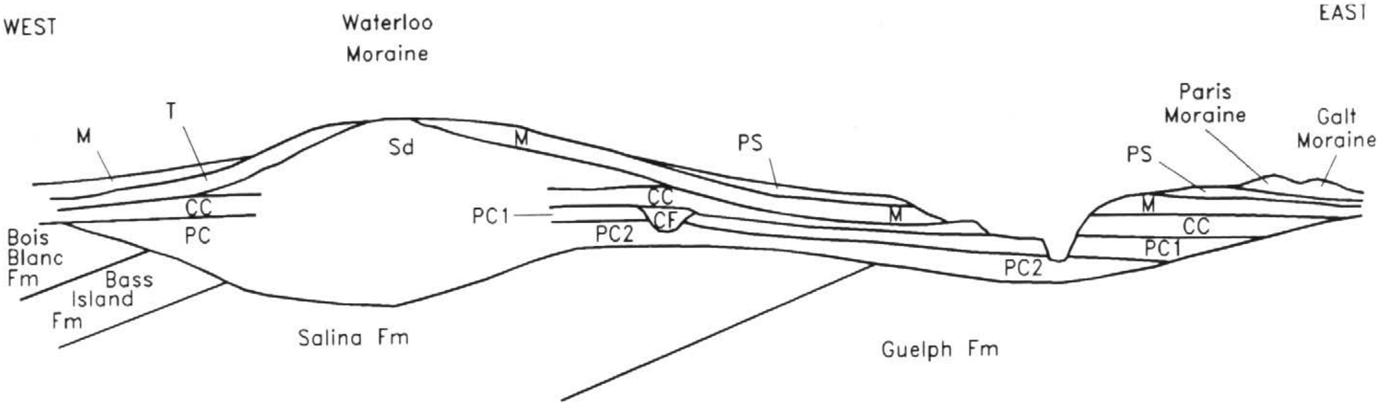
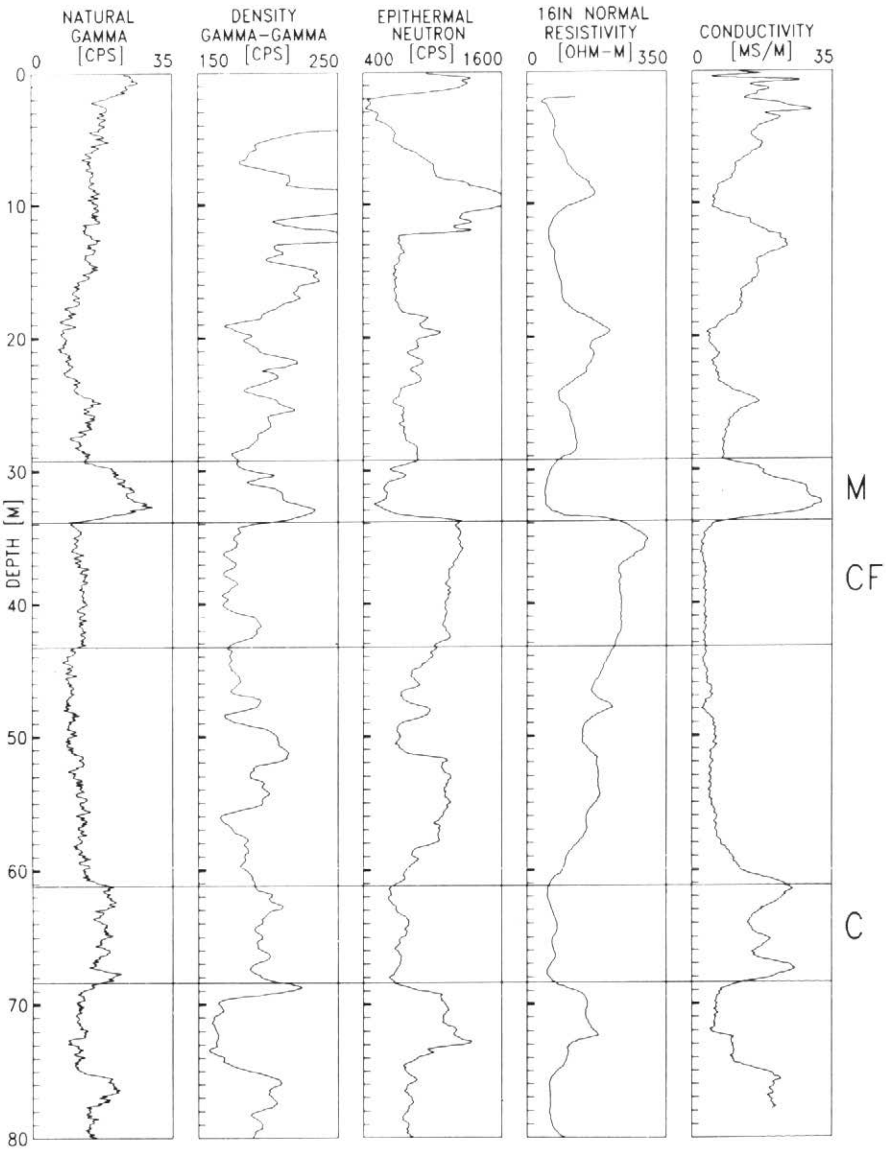


Figure 1 (above) *Cross-section of the RMW showing sequence of deposits (from Karrow* et al., *1990b). Symbols:* ***CC****, Catfish Creek Till;* ***CF****, Stream Channel Fill;* ***M****, Maryhill Till;* ***PC1****,* ***PC2****, Pre-Catfish Creek Tills;* ***PS****, Port Stanley Till;* ***Sd****, Sand;* ***T****, Tavistock Till;* ***W****, Wentworth Till.*

Figure 2 (right) *Geophysical log suite at the Mannheim 1-87 borehole. The Maryhill (****M****), Catfish Creek (****CF****) and Canning (****C****) tills are prominent horizons recognizable on the logs.*



Assessing Physical Properties of Quaternary Deposits: Calibration Pits

Pehme (1984) first undertook a methodical investigation of borehole geophysics as a cost-effective method of identifying Quaternary deposits in the RMW. As part of this study, he constructed a series of calibration pits (Fig. 3) to standardize tool detectors and to calibrate log responses for physical properties. From the data collected in these pits, empirical mathematical relationships were developed to convert gamma-gamma, neutron and natural gamma counts to bulk density, water content, and clay content in the standard cased RMW boreholes.

Automated Identification of Quaternary Deposits Using Cross-Plots and Principal Component Analysis

Using geophysical logs and continuous core data at four boreholes, Pehme (1984) constructed gamma-neutron and gamma-density log cross-plots to describe the geophysical responses of the common lithologies and stratigraphic units encountered. Figure 4 shows the gamma-neutron cross-plot distributions for core materials described as gravel, sand, silt and clay. Identification of the four lithological groups can be improved to some extent by including other logs, but considerable overlap still exists. Leask (1985), Kassenaar and Dusseault (1987) and Kassenaar (1989) describe attempts to develop objective lithology and stratigraphy recognition algorithms from the calibrated logs. Leask used cross-plots, while Kassenaar and Dusseault used principal component analysis. Although successful in some of their objectives, these methods have not yet proved practical.

Geophysical Log Catalogue

As understanding of log responses and their relationships to sediment texture and composition grew, so did the volume of logs available for interpretation. It soon became apparent that all of these logs, as well as others provided from local consultants, needed to be brought together into some kind of database if they were to be maintained for posterity and used collectively to unravel the RMW's stratigraphy. In 1988, greatly assisted by Dirk Kassenaar's development of the log analysis software VIEWLOG, the first Well Log Catalogue for the RMW was compiled by Schneider and Greenhouse (1989), containing data from 32 boreholes. The third edition was recently compiled by Schneider (1993), in a format suitable for inclusion in a regional database of geological information. It contains geophysical and geological data for 291 boreholes drilled and logged geophysically between 1959 and 1992 across the entire RMW.

The first catalogue provided several benefits. For example, a direct result of this compilation of all the data in one place was the recognition of a new regional marker horizon, the Canning Till. It is a silty clay till encountered below the Catfish Creek Till in the southern part of the RMW. Another benefit was the concept of electrofacies.

Electrofacies

Many of the logs, for example the gamma-neutron pair in Figure 2, suggest that there are a number of roughly repeatable sequences, or "electrofacies", throughout the RMW. Electrofacies are a common descriptor in sedimentary

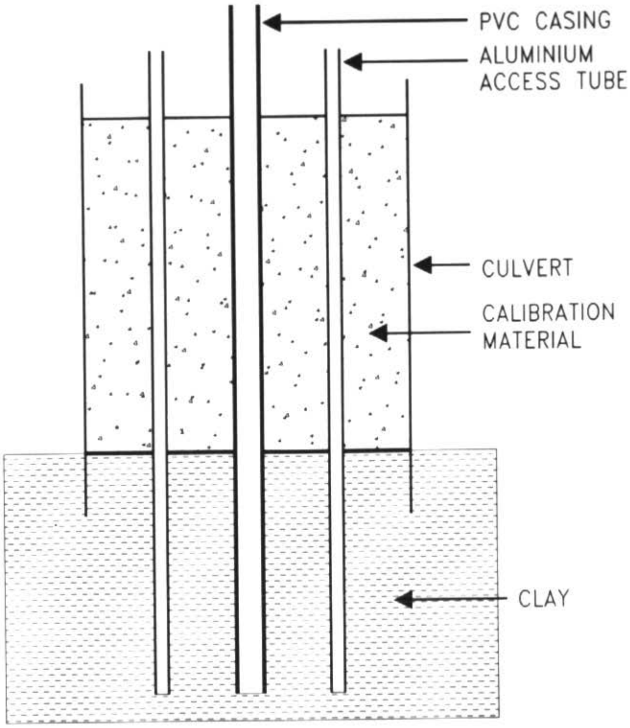


Figure 3 *Standard calibration pits for determination of physical properties. Pits were constructed from 90 cm diameter steel culverts and filled with various earth materials. The standard PVC casing and access tubes penetrate through into the Wentworth clay till below.*

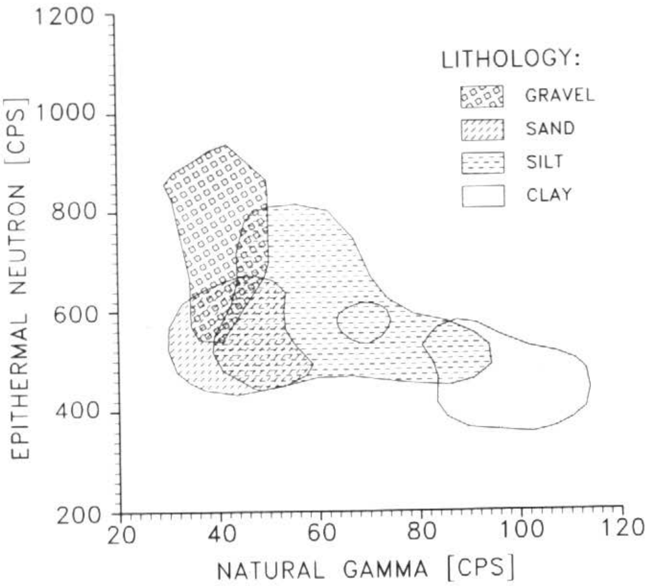


Figure 4 *Natural gamma* versus *neutron cross-plot showing lithology distributions, based on four boreholes in the RMW which were both geophysically logged and cored (adapted from Pehme, 1984).*

basin analysis. Doveton (1986) describes electrofacies as "collective associations of log responses which appear to typify certain zones and differentiate them from others." Eyles *et al.* (1985) have used similar concepts in dealing with Quaternary deposits in the Lake Ontario Basin.

Figure 5 shows our electrofacies subdivision of the section at Mannheim 1-87 (see also Fig. 2), which serves as a type-section for the southern part of the RMW. There is still debate as to whether these subdivisions are regional features, and whether they are, in fact, the manifestation of cyclic depositional processes such as the repeated advance and retreat of ice.

If validated, the electrofacies do imply a regional order that had not been previously recognized. In Figure 5, the sequences are compared to the generalized hydrostratigraphy. Of the sequences, II and III are most frequently encountered and are of principal importance to the hydrogeology. They suggest that the main aquifer system in the RMW is divided into two distinct zones, each with a coarser and/or mixed-grain-size top and a finer grained bottom. The top of each zone is generally characterized by higher neutron response (lower porosity) and lower gamma (lower clay content) response than the base of the zone.

At the surface, the Maryhill Drift is frequently encountered, which is glaciofluvial in origin and quite variable in composition. Either this drift or local till units comprise the top of sequence I. The bottom of sequence I is the clay-rich Maryhill Till, the top of II is the Catfish Creek Till, a silty gravel unit which is commonly cemented in places. The bottom of II, the Catfish Creek Drift, has a low neutron response, but no high gamma response, suggesting that it is a fine silt rather than a clay. The top of III has been described by Ross (1986) as a sand till with similarities to the Catfish Creek Till. It has thus been designated as a pre-Catfish Till or PC1. The bottom of III is identified with the Canning Till. Unit IV is presumed to be a second pre-Catfish Creek Till, designated PC2.

The geophysical logs are an essential part of a regional stratigraphic correlation. They help to establish a reference section for the RMW against which new data can be judged. For example, occasionally we drill into materials that, based on their geophysical logs, clearly have no equivalent in the majority of local boreholes. These anomalous materials are probably infill within channels that have been eroded through the standard units.

SEISMIC REFLECTION

The well logs provide detailed vertical resolution of the stratigraphy in the RMW. An inventory of the aquifer system also requires that the lateral varia-

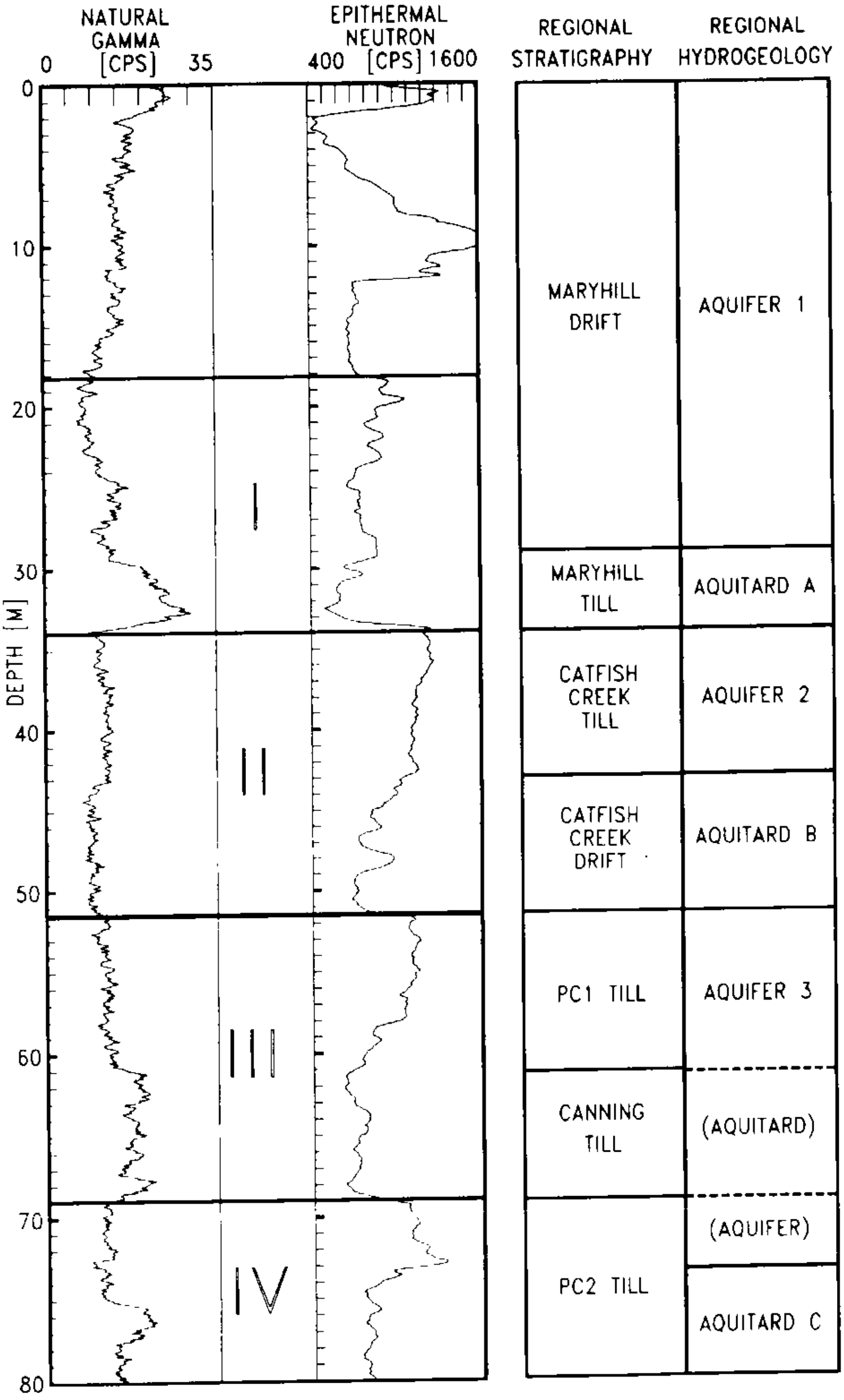


Figure 5 *Electrofacies classification at the Mannheim 1-87 borehole. Electrofacies are correlated to the aquifer classification system used by area hydrogeologists. Sequences I to III are characterized by downward decreasing neutron response and a fine grained (clay or silt) basal unit. See text for comments on the electrofacies/aquifer correlation.*

tions from borehole to borehole be mapped. A modified seismic reflection method for these urban environments is being developed for this purpose.

Seismic reflection has proved successful in the imaging of Quaternary deposits under certain conditions (*e.g.*, Hunter *et al.*, 1984). In an urbanized environment, there are a number of problems that must be overcome.

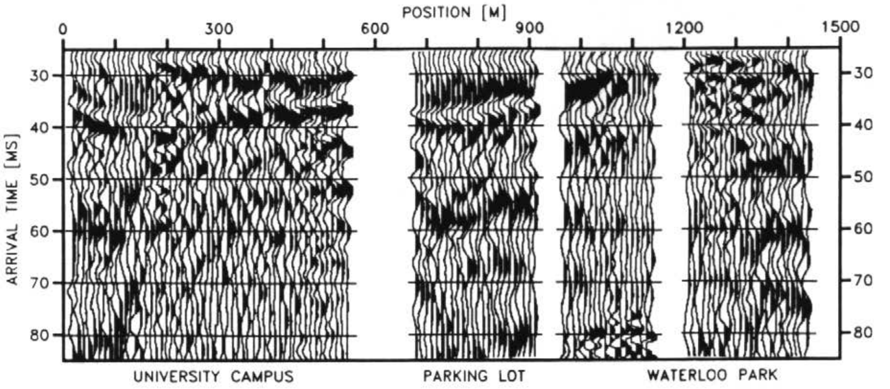


Figure 6 *This 30-metre common offset reflection record, obtained along railroad right-of-way near the University of Waterloo campus, demonstrates the typical poor resolution obtained using conventional field recording techniques. Cultural noise, nearsurface fill material and a relatively deep water table all contribute to the poor results obtained. Gaps are present where streets were crossed during the survey.*

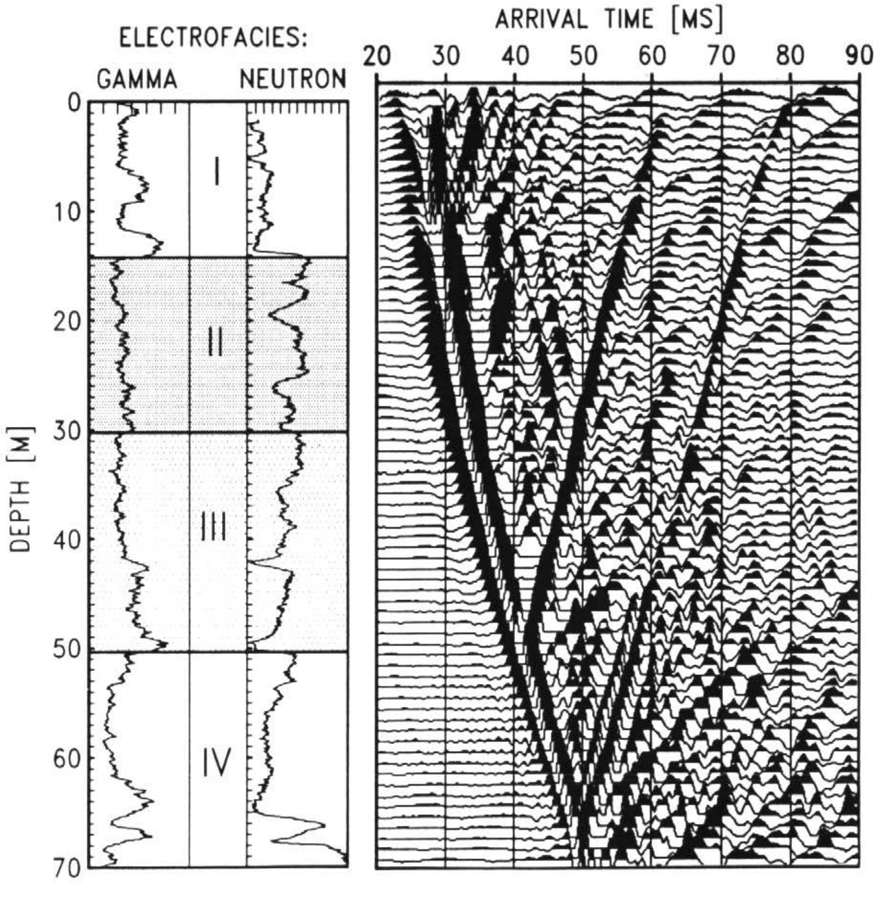


Figure 7 *A vertical seismic profile record at the Bauer-87 borehole. Seismic energy is seen to reflect upward from the bedrock (base of sequence IV), as well as from the III–IV,II–III (less obvious) and I–II boundaries. Note the multiples generated from the underside of some of these boundaries, and what appear to be upward travelling tube waves generated at the bedrock interface.*

Clear access routes between boreholes must be secured in order to conduct seismic reflection surveys. Vibrational noise from cultural features such as factories and traffic is superimposed on the seismograms, and must be dealt with. Energy loss due to near-surface fill, coarse-grained sediments, and an often thick unsaturated zone must be addressed. Scattered arrivals from buried cultural features such as sewer pipes must be recognized. Induced electrical signals from power lines must be filtered out. Finally, reflection events must be correlated to known stratigraphy from borehole data.

Early Applications of Seismic Reflection

Seismic reflection investigations at the University of Waterloo began with the acquisition of a high-resolution engineering seismograph in 1986. B.Sc. theses by Bloomer (1987), Spark (1988), Situm (1989), and Lockhard (1989) all contributed to our understanding of the problems that are faced. Figure 6 shows a common offset reflection record obtained along a railroad right-of-way through the city of Waterloo. The poor quality of the image — due primarily to the low average frequency of the recorded signals — is typical of what is obtained with conventional techniques in this area.

From these early seismic reflection investigations, it was concluded that while these methods showed great potential to deliver subsurface images of high resolution, to realize their full potential, the quality of field data as well as the sophistication of processing methods must be fundamentally improved.

Current Research

We are now addressing these concerns systematically. A project underway (Greenhouse *et al.*, 1991) is attempting to optimize each element of the seismic recording and processing procedure for the near-surface environment of glaciated regions such as southern Ontario. Seismic sources, receivers, recording equipment, recording method, and processing software are all being examined. Field parameters investigated include: seismic gun design; explosive mixture; geophone type and response bandwidth; and coupling to the ground and depth of burial of source and receiver. Two engineering seismographs, one with 12-bit recording resolution and the other with 18-bit floating-point recording resolution, have been used for these experiments and their features and effectiveness compared. Three seismic processing software packages have been used. Common offset and common mid-point survey methods are being compared for data quality and cost-effectiveness. Preliminary results are described by Lockhard (1992).

A New Seismic Energy Source

Currently under development is an alternative seismic energy source, similar in certain respects to the familiar "vibroseis" source of the oil industry and the borehole seismic source described by Wong *et al.* (1983). The source is a vibrating transducer consisting of a coil moving in a permanent magnetic field. The transducer is coupled to the ground by an auger attached to the moving coil. The coil is fed a "maximum length sequence" signal, a random but repeatable sequence of 16,000 pulses delivered over 8 seconds. The impulse response of the earth is calculated by cross correlation of the recorded geophone response with the generated input signal to the transducer. The attractiveness of this source is its ability to stack signals and its relatively broad band frequency output. Initial tests of this source have been very encouraging.

VERTICAL SEISMIC PROFILING

Vertical seismic profiling (VSP) of selected boreholes in the RMW has been used to correlate seismic reflection arrivals to geophysical electrofacies and core stratigraphy (Meleski, 1988; Greenhouse *et al.*, 1990). VSP data are collected by placing an array of hydrophones in a borehole and detonating a shotgun blast at a point on the surface, typically 20 m from the borehole. The resulting seismogram can be used to determine seismic velocity as a function of depth and to identify the origin of seismic reflections observed at the surface.

A good example at the Bauer-87 borehole is shown in Figure 7. Neutron and gamma logs, and the interpreted electrofacies I through IV, are shown for comparison. The first or direct arrivals at the downhole geophone form a gently curving event, moving downward from left to right, that defines the seismic P-wave velocity. Reflections are evident as events moving upward from left to right and originating where the direct arrival intersects the reflector depth. Reflected arrivals that reach the near-surface geophone at 81 milliseconds (ms) and 63 ms are particularly strong and represent reflections from the bedrock and the top of sequence IV, respectively. Weaker reflected events reach the surface at approximately 38 ms and perhaps 34 ms. A weak reflected event may perhaps also originate on the II–III boundary. Downward moving events arriving later are probably multiples, and appear to originate from the intersection of upward moving reflections with stratigraphic boundaries. The low angle upward moving event originating at the bedrock is thought to be a tube wave, a slowly propagating mode which is confined to the borehole casing.

Not all the VSPs we record are of

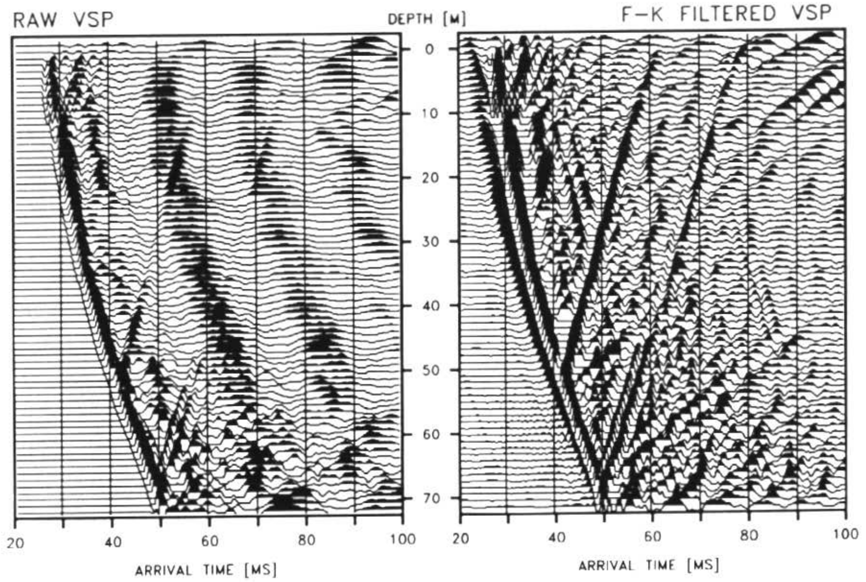


Figure 8 *F-K filtering used for VSP processing. This technique not only enhances high frequencies in the record, but also enhances the upgoing events while supressing the downgoing events. This example was recorded near the Bauer-87 borehole.*

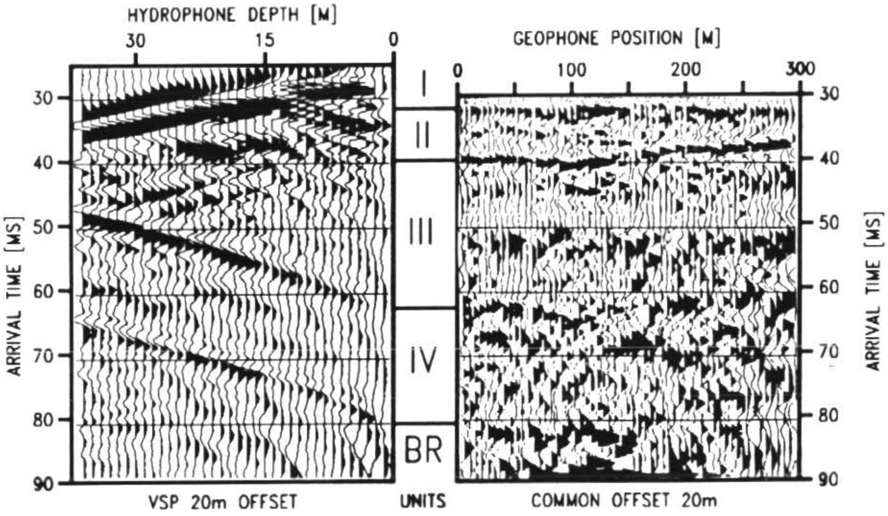


Figure 9 *VSP correlation to surface common offset records. The VSP record of Figure 7 is compared to a CO record. Both were shot with a 20 metre shot to geophone/borehole offset. The right-most trace on the (rotated) VSP record has the same shot/detector geometry as the left-most trace on the surface recording. Seismic reflection events are also correlated to the boundaries between electrofacies sequences seen on the geophysical log data.*

such good quality. The problem of separating up-going and down-going events on VSP records was investigated by Bloomer (1989) using singular valued decomposition, who found that the technique was poorly suited to this application. This separation is currently performed by frequency-wave number (F-K) filtering, since the up-going and down-going events occupy different spaces in the F-K domain. Down-going events are identified and suppressed in F-K space and then data are inverse transformed back to time-distance space. An example is shown in Figure 8, in which the raw data on the left have been processed to enhance the upward moving events at higher frequencies. The result is superior to band-pass filtered records and reveals more upward moving events (probably tube waves) on the right of the record. Multiples of the first arrivals are a problem on records obtained at particular boreholes. We are currently examining predictive deconvolution as a technique for removing multiples on records that are dominated by these multiples.

Correlation of VSP to Common Offset

Clearly the wealth of subsurface information in these borehole records is extremely valuable when it comes to interpreting the surface seismic data. In particular, note that the near surface geophone in a VSP survey will mimic the record of a common offset surface survey having the same shot-to-geophone offset (20 m in the case of Fig. 7). The uppermost trace of the VSP record can, therefore, be compared directly with the surface data recorded adjacent to the borehole. It is particularly instructive to observe the deterioration of the reflected signals as they approach the surface in Figures 7 and 8, and therefore how useful the VSP records can be in identifying them on surface records.

In Figure 9, the VSP record of Figure 7 has been turned on its side so that it can be compared directly with a 20 m common offset record shot whose first geophone lies immediately beside the borehole. The common offset record quality is not good, but we can begin to define the origins of the various events on the basis of their continuation with depth on the VSP record. Four events are identifed and can be correlated to the boundaries between electrofacies units. The arrival times for the events I–II and II–III on the VSP and CO records do not correspond exactly, presumably because seasonal variations in the water table change the near-surface P-wave velocity. At depth, the arrival times for III–IV and IV–BR correspond quite well. There is also evidence of an event separating the top and bottom of III; it is particularly noticeable on the common offset record.

CONCLUSIONS

By integrating the geophysical methods of well logging, vertical seismic profiling, and seismic reflection, overburden stratigraphy is being resolved in detail that could not have otherwise been achieved.

Well logs have provided much important information about overburden stratigraphy in the RMW. They are indicators of lithology, stratigraphy and physical properties. The concept of Quaternary electrofacies can serve as a correlational tool across the RMW.

Seismic reflection can help to resolve the vertical structure and lateral discontinuities in the aquifer/aquitard system, but the method needs further adaptation to the ground conditions in this glaciated region. Vertical seismic profiling of boreholes is the key to correlating seismic reflections observed in surface surveys with well-log electrofacies observed in boreholes.

The adaptation of these methods to this particular environment poses challenges. Much higher lateral and vertical resolution is required of geophysics today, compared to a decade ago. Several other geophysical research groups, in Europe and North America, are also working on these problems. When fully developed, we believe that these geophysical techniques can effectively serve communities in their efforts to secure and manage their overburden groundwater supplies.

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Facies Models

RESPONSE TO SEA LEVEL CHANGE

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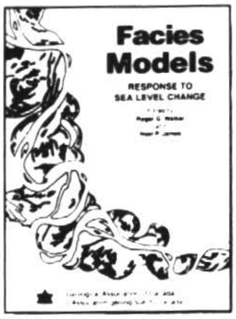

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