INTRODUCTION

There is an increasing need for three-dimensional (3D) geological information on shallow deposits in order to assess or protect critical water resources, and to address other environmental questions such as hazard or waste disposal issues. This presents the geological community with a particularly challenging task, as data on the third dimension (depth) are generally sparse. Information on the subsurface can come only from (1) borehole logs, (2) geophysical surveys, or (3) projection of surface mapping. All these methods have important roles to play in advancing our understanding of the third dimension; however the aim of this paper is to consider specifically the role of geophysics. Geophysics can be an extremely powerful tool in 3D mapping, and its effectiveness can be increased when some simple questions are first considered, about why, what, where, when and how geophysics should be used. These questions will be addressed in a general sense in this paper, using examples taken from near-surface or “shallow” geophysical surveys carried out primarily in glacial environments. However, the concepts apply in general for all geophysical surveys, including borehole and airborne methods, other geological settings, and different scales.

The reader is referred to papers from previous workshops which provide an overview of the different geophysical techniques that are available for mapping the shallow subsurface (Pugin and Larson, 2002), and a discussion of the utility of geophysical borehole logs (Hunter, 2004).

WHY USE GEOPHYSICS?

Ideally, a geologist would like to “identify” and “map” subsurface sediments in the same way they can “identify” units and “map” structure within an outcrop. However, subsurface deposits can usually only be physically examined in core samples retrieved by drilling. These provide extremely valuable information on the nature of the material, but the samples are small and understanding their depositional context, stratigraphic relationships, lateral extent and variability can be difficult. In contrast, geophysical surveys in themselves cannot directly “identify” the subsurface materials; instead the power of geophysical data is the context it can provide on the subsurface architecture, stratigraphic relationships, and variation in materials. Thus, in a simplistic sense, drill core can be used to “identify” subsurface materials, whereas geophysics can provide some of the information required to “map” those materials in subsurface space. This role can be hugely important in developing or testing conceptual 3D geological models.

Geophysical surveys provide information about the magnitudes and variation of the physical properties of the subsurface. Some specific applications include: (1) mapping target horizons or units (e.g. bedrock depth/topography, water table, etc), (2) providing information on subsurface architecture and its complexity (e.g. deltaic structures, buried valleys, existence of clay units within sands), and (3) identifying subsurface anomalies (e.g. contaminant plumes, salt water intrusion).

An example is shown in Figure 1, which is a short (<1 km) shallow seismic reflection profile that demonstrates the value of geophysics in “mapping” complex subsurface stratigraphy and architecture. In this case, the borehole (drilled prior to the geophysical survey) only sampled two of at least six stratigraphic units identifiable on the seismic section. Two units likely to be of considerable interest from a groundwater perspective (a thick discontinuous “sand” unit at 40-80 m depth, and the “buried esker?” within the bedrock valley) were not identified by the drilling. The section also shows that the upper clay unit is highly variable in thickness and is locally considerably thinner than indicated by the borehole. If the clay was considered important in source water protection, such information on the local variability of its thickness would be extremely important. This survey, which could be carried out for less than the cost of a single cored drillhole, provides critical insight into the complex subsurface architecture in this glacial environment, and into the depositional context and stratigraphic relationships of buried units.
Figure 1. Shallow seismic reflection profile from the Waterloo Moraine area in southern Ontario, Canada, showing the complex subsurface architecture of glacial deposits and the underlying bedrock surface to depths of ~100 m. If the information from the geophysics had been available prior to drilling, the borehole could have been sited so as to intercept and identify more stratigraphic units.

WHAT CAN GEOPHYSICS DO, AND WHAT GEOPHYSICS?

Different types of geophysical surveys measure different physical properties of the subsurface: e.g. seismic methods respond to variations in the seismic velocities of subsurface materials, electrical methods depend on the resistivity or conductivity of subsurface materials (including pore waters), gravity methods respond to variations in density, etc. Thus, geophysics requires subsurface targets to be characterized by a physical property that contrasts significantly with its surroundings. The geophysical method(s) used must be chosen based on an understanding or estimate of this physical property for the target and its environment, as well as a clear understanding of the capabilities of the geophysical method(s). The contrast in properties must also produce a signal that is measurable at the ground surface (or other measurement location). In general, deeper targets must be larger or contrast more significantly with their surroundings to be observed.

Figure 2 presents an example of a ground penetrating radar (GPR) survey that was used to map the depth to water table in a surface sand unit. In this case the shallow water table is readily measured by GPR as it is in a resistive material and provides a strong dielectric contrast with the overlying dry sand.

Figure 2. Ground penetrating radar section from the Oak Ridges Moraine area in southern Ontario, Canada, showing details of foreset bedding (F1) in a surface sand unit, and clearly delineating the water table (WT) as a large-amplitude, flat-lying reflection at a depth of ~9 m. Signal penetration is limited to ~15 m.
WHAT CAN GEOPHYSICS NOT DO?

Just as it is important to understand the potential of geophysics, it is equally important to fully understand its limitations. Geophysical surveys all have an inherent limitation on resolution, which depends on the method, instrumentation and survey parameters being used, and on the particular geological setting of the survey area. For example, GPR surveys (e.g. Fig.2) can provide resolution on the order of cm to 10s of cm in shallow sands and gravels, but the depth of signal penetration is limited to a few metres, and in conductive materials (e.g. clays) may be essentially zero. Using lower frequency antennas will usually increase the depth of signal penetration to a few tens of metres, but with a corresponding decrease in vertical resolution. Data from electrical resistivity surveys can be used to map electrical properties to greater depths even in conductive sediments (e.g. Fig. 3), but as these methods measure average electrical properties of the subsurface the resolution is quite different from that achieved with GPR. It is important to realize that no single survey can map all depths and/or targets!

WHERE SHOULD GEOPHYSICS BE USED?

The effectiveness of geophysical surveys can be maximized if thought is given to where the surveys are carried out. Clearly, geophysical information can be critical where subsurface architecture and stratigraphy is complex (e.g. in many glacial terrains – see Fig.1), or where the target is the boundaries or limits of a subsurface unit (e.g. saline groundwater – see Fig. 3). However, in order to be most effective, geophysical surveys should be conducted in areas where good signal-to-noise data can be acquired or there is a risk of wasting much effort in collecting data that are of marginal use. These areas should be determined by a testing phase carried out early in the investigation to identify and refine the optimum geophysical method(s) to use, the data acquisition parameters and the survey locations. Figure 4 displays an example of two seismic reflection records acquired within a few hundred metres of each other. Different surface conditions at the two sites result in a very significant difference in data quality. A testing program can be used to 1) ensure that the geophysical technique chosen is capable of detecting the target, 2) identify variations in data quality within the survey area due to geological or cultural conditions, and therefore allow optimum sites for follow-up surveys to be determined, and 3) possibly identify anomalies that warrant further investigation in the follow-up surveys.

Figure 3. Electrical resistivity section across a slope in eastern Ontario delineating the contrast between very low resistivity saline clays in the channel floor, and more resistive surficial sands and leached (fresh porewater) clays beneath the adjacent terrace. This method can measure the apparent resistivity to depths of tens of metres below ground surface, but clearly does not provide the high resolution of the shallow subsurface that is shown in Fig. 2.
Figure 4: Two seismic reflection field records obtained only a few hundred m apart. Dry surface materials and a low water table at the first site (left) result in low frequency reflection signals and strong ground roll interference. Damp surface sediments at the second site (right) improve the ground coupling of the source signal and result in much higher resolution reflection data. A testing program helps identify optimum sites or conditions for a follow-up surveys.

A testing program (i.e. a series of site surveys) can also be a means of mapping vertical and lateral variations in a target horizon over a regional area. An example is shown in Figure 5 where ~50 seismic reflection test sites were used to map the depth to bedrock over a 180 sq. km area underlain by a deep bedrock basin. In this case, the Paleozoic bedrock surface beneath a thick sequence of marine sediments and glacial deposits produced an recognizable seismic reflection. The depth to bedrock in the centre of the basin (~180 m) was confirmed by drilling.

Figure 5. Depth to bedrock determined in a region east of Ottawa, ON, from a series of ~50 seismic reflection test sites. The red line is the outline on the ground surface of slightly hummocky topography, which is the only visible expression of this subsurface feature. Information on the vertical and lateral variation of a target horizon can often be effectively and efficiently produced using geophysics.

WHEN SHOULD GEOPHYSICS BE USED?

Geophysics should be used when it has been ascertained that the target horizons and/or structure are characterized by a significant contrast in physical properties that is measurable at the surface using the geophysical method(s) chosen. This requires 1) a discussion with the geophysicist about the goals of the survey and his/her judgment of the potential success of various geophysical techniques, and 2) a testing phase, prior to a commitment to a complete survey, to ensure that the data quality obtained at the site is adequate to meet the survey targets. In
general, the most effective use of geophysics is early in a project, so that it can be used to 1) check or develop hypotheses, 2) verify or refine geological models, and 3) identify drilling targets. Using the results of geophysical surveys to identify borehole sites can be extremely important, as it allows drillholes to be judiciously located to identify anomalies and intercept as many stratigraphic units as possible (e.g. Fig. 1).

HOW SHOULD GEOPHYSICS BE USED?

Geophysics should be used to provide subsurface architecture (lateral and vertical context) in conjunction with boreholes or other information that can be used to verify the results. This ensures that the geophysical results can be interpreted in a way that is clear and meaningful to the geologist or other project participants. Once an understanding of the physical response of units within the survey area has been acquired through some verified geophysical results, additional geophysical surveys may be confidently interpreted without the same level of verification. Additionally, the effectiveness of geophysics can be enhanced when there is strong collaboration between geologist/hydrogeologist and geophysicist from the planning through the interpretation phase. The different perspectives of these various experts can together provide an improved insight into the third dimension.

SUMMARY

When used well, geophysics can play an extremely important role in 3D mapping. It has the potential to provide a structural context on the subsurface architecture, stratigraphic relationships or variation of materials.

In order for geophysics to be effective, three basic conditions must be met:

1. The measured physical property of the target horizons or units must contrast significantly from the surrounding material.
2. Data from the target depth must be sufficient in amplitude and signal-to-noise ratio to be interpretable.
3. The resolution of the methodology used and of the recorded signal must allow appropriate definition of the target (depends on signal characteristics and on depth and size of target).

The following are simple recommendations that will help ensure geophysics can be effectively integrated into a 3D mapping project:

1. Involve geophysicist(s), geologist(s) and hydrogeologist(s) in identifying the targets of geophysical surveys and planning the geophysical program. Be sure all participants understand the potential and limitations (including resolution) of the geophysical survey(s) chosen.
2. Conduct tests to ensure that the planned geophysical survey is capable of mapping/identifying the target horizons/structure. Use these tests to identify the optimum areas/times/parameters for surveying so that data with as high a resolution as possible can be obtained.
3. Plan to acquire borehole or other information that can be used to verify the geophysical results.
4. Involve the geophysicist(s), geologist(s) and hydrogeologist(s) in the final assessment and interpretation of results.

One final consideration: The subsurface is generally complex, and geophysics will undoubtedly bring up new questions/insights that will challenge or require refinements/revisions to any preconceived 3D model. Be prepared for this!

REFERENCES
