Review of Satellite, Airborne and Surface Based Geophysical Tools and Techniques for Screening Potential Nuclear Repository Candidate Sites

NWMO TR-2008-15 December 2008

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ABSTRACT

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Report No.: **NWMO TR-2008-15**
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Abstract

This report presents a discussion of the available geophysical techniques that could be used in a site screening programme for a deep underground repository. The techniques considered in this report include satellite, airborne and surface based techniques, with the surface based techniques being subdivided into shallow and deep geophysical methods. The report provides guidance on the benefits that specific techniques may provide along with some constraints. Details on the accuracy and resolution of geophysical methods are provided. These are guidelines as they are dependent on many investigation specific factors, including depth of the target, geology and topography, to name a few.

The report has also reviewed some of the geophysical investigations undertaken in other countries around the world as part of their site characterisation programmes for a deep geological repository, essentially looking from the perspective of the two geological environments most closely related to the Canadian programme: sedimentary and crystalline host rocks. This review complements the sections on geophysical techniques, as it illustrates the application of these methods in a relevant context.

Canada is well advanced in geophysical exploration for hydrocarbons (sedimentary rock environments) and at the forefront in geophysical exploration for mineral deposits (crystalline rock environments). As such, the equipment and the contractors required to perform the geophysical surveys and techniques discussed in this report are commercially available in the Canadian market. Canada is also well advanced in satellite imagery and remote sensing techniques, making these methods also readily available.

Geophysical methods and remote sensing have been an integral part of the geosphere characterisation in all repository studies in both crystalline and sedimentary rock. Many satellite, surface and airborne techniques have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development, and the available technology at the time.

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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 waste 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. One of the strategic objectives of the NWMO is to develop in collaboration with Canadians a siting process to seek an informed and willing community to host the deep geological repository.

The initial stages of any site evaluation are preliminary in nature and designed to assess the geoscientific characteristics of the sites and determine their potential suitability to host a deep geological repository based on a suite of geoscientific criteria. Initial site evaluation stages are based on readily available geoscientific information and on the use of no-intrusive remote sensing techniques which would include satellite, airborne and ground based geophysical methods. In order to develop readiness for the initial stages of site evaluation, the NWMO commissioned a review of available satellite, airborne and surface based geophysical methods that could be included in a preliminary site investigation program to assess the suitability of potential candidate sites. This report discusses these methods focussing on applicability, accuracy, limitations and constraints, commercial availability and timescales. The report also discusses some of the geophysical investigations undertaken in other countries for their site characterization programmes for a deep geological repository in both sedimentary and crystalline rock.

1.1 Geophysical Investigations

Geophysical methods can provide information that contributes across a range of other disciplines (including the geological, hydrogeological, hydrochemistry, geotechnical, transport and biosphere properties models) which together form a geosphere characterisation programme. Geophysical investigations can provide important information forming input to numerous aspects of the project:

- Geophysical data can be used in the construction of the geological model.
- Information derived from seismic data can be used to provide rock stress and rock strength for the geotechnical model.
- Geological and geophysical data can be combined to develop an understanding of the hydrogeology of the site.
- The orientation of fracture systems can be inferred from geophysical data and used to model groundwater flow. This information, together with other data sets, can also be used to understand how the fracture systems are interconnected.
- Geophysical data can be inverted to provide information on the distribution of physical properties such as porosity, density and electrical resistivity.
- Deep electromagnetic surveys can assist in understanding salinity distribution and the geochemical model and environment.
- On a smaller scale, shallow high-resolution geophysical surveys can provide an understanding of the near surface geology and even the biosphere.

A siting programme, although comprised of a number of specialised disciplines, is an interrelated connected system, which means that a holistic approach should be adopted in the design and implementation of surface based and eventually the underground investigations. This holistic approach must consider the use of data during all phases of the project and into the post operational phases (post closure).

It is also important to understand what the monitoring requirements may be post closure. For example, it may be important even at the screening stage to know whether the use of time-lapse geophysical surveys will be required for post closure monitoring. If such surveys are necessary, the surveys that are carried out during the initial 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 presented in this document, which was commissioned by the NWMO, was to develop a state-of-the-science review on available satellite, airborne and surface based geophysical site characterisation tools and methods that could be used during the initial stages of a site evaluation process. These methods are considered non-intrusive. The information gathered through this study identifies the methods that are available and also highlights recent developments in processing and acquisition technologies, although the latter changes slowly while the former shows more rapid change. The report also presents some of the current research areas undertaken in some fields. Borehole geophysical techniques and methods were excluded from the scope of this study, as they are intrusive methods applicable to characterisation rather than screening.

The study also includes a review of geophysical methods and techniques that have been used in similar site characterisation programmes in other countries, based on publicly available information, to determine what can be learned from other cases that may be transferred to the Canadian programme.

The following techniques are presented and discussed in this report:

SATELLITE SURVEYS

- High Resolution Satellite Imagery
- InSAR
- ASTER

AIRBORNE SURVEYS

- Aerial Photography
- Digital Terrain Mapping (LiDAR / Radar)
- Hyperspectral Imaging
- Magnetic Surveys
- Radiometric Surveys
- Electromagnetic Surveys
- Gravity Surveys

GROUND BASED SURVEYS (DEEP)

- Seismic Reflection Surveys
- Gravity Surveys
- Electromagnetic Surveys
- Magnetic Surveys

GROUND BASED SURVEYS (SHALLOW)

- Seismic Refraction Surveys
- Electrical Resistivity Imaging Surveys
- Ground Penetrating Radar Surveys
- Electromagnetic Surveys
- Spontaneous Potential
- Induced Polarisation

Information on the following aspects of each method are discussed:

- A brief description of each of the techniques including the application of the methodology to a screening or characterisation programme;
- A description of the processing that is typically applied to the data including QA/QC;
- An assessment of the precision and typical accuracy of such data;
- The limitations associated with the various technologies and the constraints placed on them by site and/or other conditions and the consequences implied for the site characterisation programme, and strengths and weaknesses of the method;
- The potential to combine two or more technologies to allow for simultaneous acquisition;
- A discussion on the commercial availability of the surveys in the Canadian market; and
- The time scale typically required to complete the survey.

Where appropriate, the discussion on processing has included information on other processing methods that may be required to address the objectives of a site screening programme. Additionally, to develop a state-of-the-science review, some of the current research into new processing techniques is also included.

It is noted that in the sections on commercial availability, some commercial companies are identified. These lists are not exhaustive and have only been provided for example purposes.

This report has been assembled from a number of sources and has drawn heavily on the experience of the authors. Additional information has been derived from ad hoc conversations with geophysical contractors and information from the following sources:

- http://www.fugroairborne.com/
- http://www.geoexplo.com/
- http://www.sgl.com/
- http://www.microimages.com
- http://jpl.nasa.gov/
- http://gsc.nrcan.gc.ca/
- http://earth.esa.int/

- http://www.lr.tudelft.nl/
- Geophysical Technology – Present and Future Capabilities, Geophysical Seminar presented by Petroleum Exploration Society of Great Britain (PESGB) and the International Association of Geophysical Contractors (IAGC), December 10-11, 2003.
- Application of Geophysical Technology in Exploration, Development and Production, Geophysical Seminar, Petroleum Exploration Society of Great Britain, January 30-31, 2008.

Other references are cited throughout the text.

The report initially discusses approaches to geophysical characterisation (Section 2.0) and includes data uses and design approach. Sections 3.0 to 7.0 then consider details of various geophysical characterisation techniques with separate sections for satellite surveys (Section 3.0), airborne surveys (Section 4.0), deep surface based surveys (Section 5.0) and shallow surface based surveys (Section 6.0). Repository case studies are presented and discussed (Section 7.0). Final concluding comments (Section 8.0) and references (Section 9.0) are also provided.

2. SURVEY DESIGN

Site screening using satellite, airborne and surface based geophysical tools and techniques is considered to be one of the preliminary steps in the screening of candidate sites. The geophysical data sets acquired during this process are an important first step in understanding the geosphere, providing guidance for next step decisions.

The screening process, the survey selection process and also the design process, should consider how the data may be used in any future phases of a programme for developing an understanding of the site and for Performance Assessment. Additionally, the design needs to consider the uses of the data through operation of any facility 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. The acquisition of data in a screening process even at a reconnaissance scale also forms part of the baseline, which can be referenced in future during operation and post closure stages.

The design of any screening survey should first consider what data are readily available either in the public domain or can be procured. As such, Section 2.1 considers the role of undertaking desktop studies of public domain and non-exclusive data sets and the impact this may have on geophysical data acquisition relative to the geological setting under investigation.

Section 2.2 considers the geological setting and how this may influence the selection and design of the surveys to be used in site screening. Section 2.3 considers the nature of the site itself (i.e. accessibility, infrastructure, and cultural features) and the influence it may have on survey design from a practical perspective. Section 2.4 considers how the selection of geophysical data acquisition methods may be influenced by data needs. Section 2.5 describes approaches to investigation design and draws parallels to geophysical exploration and prospecting which are, after all, processes of screening an area to decide on a favourable location to drill for hydrocarbon or mineral resources.

Quality assurance and data management requirements, as they pertain to the acquisition of geophysical data, are discussed in Sections 2.6 and 2.7.

2.1 Desktop Studies - Public and Non-Exclusive Data

Desktop studies of available geophysical data sets are an important component of any programme. Studying available data can not only help prepare for a field programme, in some cases it can be a replacement. Large scale available data can help pinpoint regions of interest, thus focusing the survey area; while small scale surveys can replace or complement other geophysical techniques, whether they are ground based or airborne. The use of available data can provide valuable geophysical data for a fraction of the cost of a dedicated survey.

Canada is at the forefront of hydrocarbon and mineral exploration and as a result there is a wealth of available geophysical data across Canada. Geophysical data that is publicly available has been collected by various government agencies or by mineral and oil and gas exploration companies. There are two classifications of available data sets: public and non-exclusive.

Public data are typically acquired by government geologic surveys or by other government institutions and universities. Public data typically have very few restrictions on its use and are often available free of charge. Public data are becoming increasingly available in real time via the internet. Depending on the agency providing the data, the data are often available at different spatial resolutions. Public surveys are typically very broad as the goal is regional mapping, rather than targeted mapping. Smaller infill studies, as seen fit by the agency collecting the data, can offer higher resolution data. A wealth of both ground based and airborne geophysical data are available.

The Geoscience Data Repository (GDR), is a collection of Earth Sciences Sector geoscience databases that is managed and accessed by a series of Information Services (GDRIS) through Natural Resources Canada (NRCAN) (http://gdr.nrcan.gc.ca). The data has been collected by national and provincial agencies and amalgamated into one large, real-time accessible database. Geophysical data sets available include:

- magnetic,
- electromagnetic,
- gravity,
- radiometric,
- seismic, and
- magnetotelluric

The aeromagnetic database maintained by the GDR is extensive and contains over 11 million line kilometres which represents coverage of 80% of Canada's land mass and 20% of the offshore territory at a transverse line spacing of 800 metres. Detailed aeromagnetic data are also available in some areas and offer higher resolution with a line spacing of 300 metres.

Gravity data are available Canada-wide, but are of relatively low spatial resolution as it is measured at large station intervals (i.e. at a regional scale). Radiometric coverage is not Canada-wide but covers a very large area throughout Central Canada. Electromagnetic survey coverage is more limited, owing to the high cost of acquisition. The GDR provides any electromagnetic data that has been acquired, although there are very limited regional maps that may reflect large geological trends in comparison with other methods.

There is a large and extensive database of seismic transects data and magnetotelluric site readings maintained by the GDR. Most seismic transects available were collected offshore, however land-based data from the Lithoprobe programme are available. The Lithoprobe programme funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Geological Survey of Canada (GSC) performed seismic transects consisting of thousands of line kilometres. It should be noted that the design objective of such surveys is to provide very deep information and, as such, the near surface (the top 1,000 metres) is not imaged at a high resolution. However, the transects cross major, distinct, yet geologically representative, regions of Canada. In conjunction with the Lithoprobe programme, magnetotelluric data was collected across the same transects and that data is also available through the GDR.

Each province's own geologic survey contributes their data to the GDR, although provincial geologic surveys should not be overlooked as a source of public data. The Ontario Geologic Survey (OGS) for example, routinely conducts geophysical surveys each year and has its own geospatially searchable on-line data repository. Provincial geologic surveys may also have data that has been processed further and offer more useful information.

A novel method of obtaining geophysical information from public sources is using Geosoft's Dapple software (http://dapple.geosoft.com). Dapple is open-source software that is designed to graphically display various publicly available geophysical datasets. The data is stored on Dapple compatible servers by Geosoft and the agencies providing the data. Graphical representations of geophysical datasets are retrieved by the users spatially and in real-time through the software. In addition, details about the dataset selected will be reported including data parameters and the agency providing the data.

Non-exclusive data is privately owned data that has been acquired speculatively by survey companies for exploratory or other purposes, but certain rights for use have been waived and it is available for purchase. These data, while commercially available, may cover areas where mineral or other land use rights are not available. Typically the purchase of non-exclusive data does not include any legal rights to the areas surveyed. There is a limited amount of non-exclusive data available solely because surveys are expensive and once data is acquired it is retained. Non-exclusive data ranges in its size and scope. The survey companies collecting the data have typically designed the survey for a specific target. The target specific methods used in the survey may or may not be useful when applied to repository site screening. Both ground and airborne survey data are available from a number of different companies.

Both airborne and ground based geophysical data are available through non-exclusive data sales. There is a limited supply of non-exclusive data however companies such as Fugro Airborne Surveys and GEDCO do offer some data. Hydrocarbon exploration companies offer seismic data for resale typically at 30 to 40 percent of the original acquisition cost if recently collected. The data are usually available for areas that the company is longer interested in.

The quality of the available data can be expected to be high, although it can vary between data sources. Surveys conducted by, or in conjunction with, government agencies are typically of very high quality. Geological surveys require testing and data quality to standards not necessarily held to by private companies. Public data provided by these agencies is also commonly corrected to a national standard so differences between regions and surveys are minimised. Public data as provided by the GDR has been collected over a large time window and older technology could potentially impact the quality, although where data is held digitally the data may be reprocessed using up to date processing techniques. Public data collected or obtained with non-governmental oversight, could be more prone to quality issues.

Available data resolution and accuracies can vary widely between sources and techniques. Public data varies between large low resolution surveys, to smaller high resolution surveys. Airborne gravity data which typically has larger resolutions, for example, can have resolutions on the order of kilometres, whereas high resolution magnetic surveys can have a resolution on the scale of a few metres. There is no standard resolution for all the available techniques, but for the most part it can be assumed that public data has less resolution than non-exclusive data. Non-exclusive data typically offers higher resolution; the resolution of these surveys depends on the technique and the intended target.

Using existing data is an excellent strategy, as the data is relatively inexpensive and easy to obtain. Solely, the availability of public and non-exclusive data can be as important as the data itself. A targeted survey could indicate that mineralisation or oil and gas reserves are expected, reflecting geology, and this area may not be appropriate for a repository site as it may be targeted for exploration at some time in the future. Public data at low spatial resolution could indicate that only a regional programme was planned or that nothing worth surveying at higher resolution was found. High resolution public data could suggest something in the regional programme was detected that warranted further investigation.

An additional source of relevant geophysical information can be found on the Earthquakes Canada web site (http://earthquakescanada.nrcan.gc.ca/) operated by NRCAN. This web site includes information on recent earthquakes, historic earthquakes and data from seismic stations across Canada.

2.2 Geological Setting

An understanding of the repository programmes from around the world indicates that most agencies are considering developing a repository in one of two geological settings. These are a sedimentary rock environment and a crystalline rock environment (the crystalline rock may or may not be under a sedimentary cover). In fact, one of the screening criteria may be to find a site where a thick unit of shale or clay overlies the basement rock, forming a seal, much in the same way that oil reservoirs often have a seal over them, trapping hydrocarbons. One other geological environment that is also considered by some agencies is an evaporite sequence such as salt; these may be favoured based on the near zero water content of the salt (although pockets of remnant water are known to exist in some situations) and the “self-healing” properties of salt formations.

The sedimentary sequences currently under consideration as potential repository sites around the world are clay (i.e. shale) and mudrocks. These have generally been selected for their homogeneity, continuity and low permeability, although they can contain layers and lenses of other materials, and they may also be fractured. Sedimentary rocks are typically horizontally stratified; the boundaries between these strata act as marker horizons, which are readily mapped by surface geophysical imaging techniques, such as seismic reflection. Seismic reflection surveys from surface can map these marker horizons in detail over large spatial areas and demonstrate continuity of the subsurface geology with a high degree of confidence. Some agencies have placed considerable emphasis on geophysical survey methods in characterizing a sedimentary environment; take for example the NAGRA investigation of the Opalinus Clay (NAGRA, 2001). The quality of the 3D seismic data is such that the geological sequence can be mapped over large areas and corroborated with a very small number of deep boreholes.

A number of repository sites currently under study are in crystalline rock environments, in many cases, Precambrian-aged rocks. The crystalline rock environment can cover a range of rock types including volcanics and massive intrusive rock types 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. This leads to a number of potential issues that have to be considered even at the time of site screening. These include the potential for fluid flow through the fault/fracture systems, and increased complexity of the geology that needs to be imaged. Given that the faults/fracture systems are often small and can have limited throws, and that generally the same rock type exists on either side, these features can be difficult to image geophysically.

The thickness and type of overburden at a particular site may also influence the applicability and effectiveness of some geophysical surveys to image the underlying rock. However, given that it is likely a repository will be sited at a depth of hundreds of metres below surface, most geophysical methods suitable for imaging the subsurface to these depths will be able to penetrate the overburden in a "typical" Canadian geological environment.

In a given geological environment, greater emphasis may be placed on one methodology over another or even other disciplines (i.e. it may be possible to rely more on geophysical methods in one setting as opposed to another, where greater emphasis on borehole drilling may be required).

2.3 Site Setting

The applicability and practicality of some geophysical methods can be strongly influenced by site specific factors. These include factors such as tree cover, terrain, wetlands, environmentally sensitive features, watercourses, road access, buildings and other infrastructure, and power transmission lines, to name a few. These factors will need to be taken into consideration in the design of any geophysical survey and, in most cases, the limitations posed by these factors can be addressed. Limitations specific to particular geophysical techniques are discussed further in Sections 3.0 to 6.0.

2.4 Data Uses

The selection of a geophysical survey method also must consider the planned and potential future use(s) of the data. It is clear that only information that is required should be obtained from the characterisation 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 and at the site screening 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 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 rigorous manner. As these features are also likely to have an effect on the transport properties, the challenge will be to incorporate the extra level of detail into the modelling process.

2.5 Design Approach

Logic suggests that the best approach in the design of geophysical investigations for site screening would be to adopt an exploration approach. In hydrocarbon exploration within a sedimentary rock environment, that approach can be generalised as 2D seismic surveying, followed by 3D seismic surveying of smaller but targeted areas. These two phases of seismic survey activity may be punctuated by a phase of drilling targeted boreholes that are used both to gather initial information and to test the geologic model (a traditional approach of formulating a hypothesis and testing). Examination of structural maps developed during hydrocarbon exploration over time show how the detail of the target structure improves as more work, including interpretation and the acquisition of 3D data sets, is undertaken in the site areas.

In mining exploration within a crystalline rock environment, that approach can be generalised as airborne geophysics (i.e. magnetics, electromagnetics, radiometrics, and/or gravity) followed by ground based geophysics. Again, the two phases of geophysical survey activity may be punctuated by a phase of targeted drilling.

In summary, the geophysical survey design approach for site screening should follow an exploration approach of: conducting desk studies, followed by regional surveys covering the larger search/screening area, followed by detailed studies of target (site) areas (at a later stage).

2.6 Quality Assurance

An effective quality assurance programme for geophysical data is essential for the completion of a successful site screening and subsequent characterisation programme. All geophysical 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 any site screening or characterisation activities that may gather geophysical data that could ultimately be used in a compliance demonstration.

In the context of geophysical surveying, 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 means that these procedures have been followed throughout the process, and that this has been documented.

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.

2.7 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 all involved on the site characterisation programme will have access to the most current data and can clearly identify the pedigree of that data.

3. SATELLITE SURVEYS

This section describes a range of satellite based remote sensing surveys that may be applied during a site screening and characterisation programme. Methodologies discussed include high resolution satellite imagery, Synthetic Aperture Radar interferometry (InSAR) and the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER).

3.1 High Resolution Satellite Imagery

Brief Description

In the last decade, a number of commercially available high resolution remote sensing satellites have been launched. The majority of these platforms are owned and operated by companies in the United States. As a result of these successful launches there is now a variety of sensors and resolutions and, most importantly, pricing options that can now be considered as a viable alternative to air photo or helicopter based surveys for any given application. Data acquisition in both Panchromatic (Pan) and Multispectral (MSS) formats is available from one satellite. Although the MSS data is generally of lower resolutions, software algorithms and tools exist to process and manipulate this type of imagery and integrate or "fuse" it with higher resolution data.

Currently there are five high resolution satellites available to the public. These are:

- EROS-1A (1.2 m)
- IKONOS-2 (1 m)
- GeoEYE-1 (50 cm)
- Quickbird (62 cm)
- WorldView-1 (50 cm)

Commercial satellites, such as IKONOS-2 (launched in 1999) and GeoEye-1 (launched in September, 2008), are capable of both panchromatic (PAN) and multispectral (MSS) images. GeoEye-1 has 0.5 m resolution images available to (non-government) customers which now effectively achieves air photo resolution from space.

Figure 3-1 presents a 50 cm resolution image of Moffett Federal Airfield (also known as Moffett Field) that was collected on October 12, 2008 by the GeoEye-1 satellite, which was launched September 6, 2008.

Satellite imagery is the highest quality when the image is taken at nadir; that is, looking directly towards Earth. Satellites orbit the Earth relatively quickly and on-nadir pictures can be taken within days of each other. Some satellites can acquire images off-nadir (up to 60^o) with very little reduction in quality, allowing images to be acquired at shorter time intervals. Satellite imagery provides high spatial resolution as well as the ability to acquire large geographic areas in a single pass. Image swaths in a single pass are on the order of 10 km wide or greater depending on the satellite.

Figure 3-1: Example GeoEye-1 high resolution satellite image. (GeoEye Inc.)

Similar to aerial photography, some satellite imaging systems can acquire stereo imagery. Stereo imagery can be recorded on consecutive passes or in one pass by changing the camera angle during the pass (most ideal). Using advanced image processing software, a Digital Elevation Model (DEM) can be extracted from stereo imagery at very high resolutions. For remote locations, the use of high resolution stereo imagery may be an ideal alternative to traditional airborne surveys. The resulting DEMs can then be used in support of site visualisation and 3D perspectives, watershed delineation, viewshed analysis, as well as to complement other types of surveys and modelling applications. Figure 3-2 below illustrates the acquisition of single and stereo satellite images in the same pass.

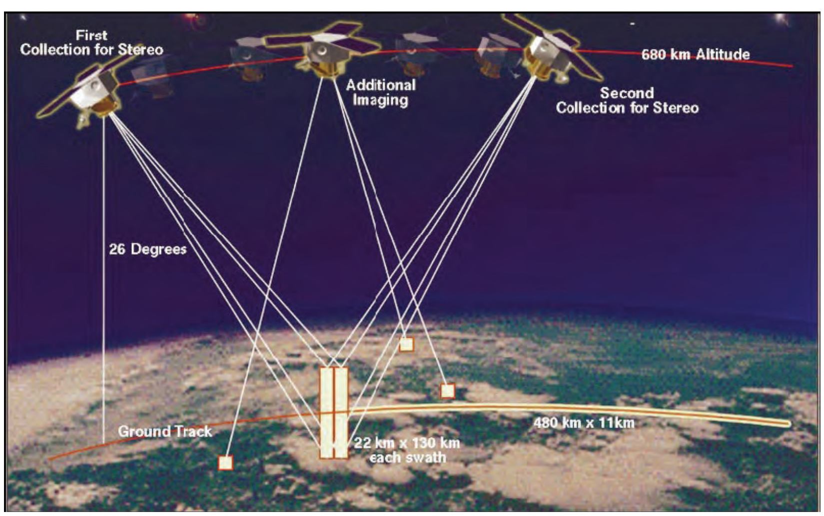

Figure 3-2: Satellite imagery acquisition. (GeoEye Inc.)

The distinct advantage of high resolution image acquisition from satellite based sensors is the ability to obtain imagery without the mobilisation of expensive aircraft based systems. If weather is a problem there are no fees for crew and equipment stand-by, as the satellite will attempt to acquire the image on its next available pass. Typical repeat coverage for a project area is every 2 to 3 days.

Analogous to aerial photography, the satellite's location and orientation must be known at the time of imaging to allow for more advanced processing. The position is determined by GPS, much like locations on the ground. The attitude of the satellite is determined by advanced star tracking algorithms and gyroscopes.

Applicability to Programme

The main purpose of satellite imagery in a site screening and/or site characterisation investigation will be to provide important information about cultural features, the biosphere, land use, surface water systems, geomorphology and surficial geology. It is also possible to interpret the location of faults and other structural features in some cases. A DEM can also be derived from these data if collected in stereo mode. This type of detailed mapping is also very useful in the logistical design of other land based geophysical surveys, such as large scale 2D or 3D seismic reflection surveys. As with most remotely sensed data ground truthing is required to confirm the analysis of the multispectral data.

Processing and QA/QC

As an initial step, the satellite image data need to be corrected using their satellite's geometry to ensure position accuracy. Each image is recorded with its location/orientation parameters and corrected using an orbit model that closely approximates its parameters to real world parameters. Both panchromatic and multispectral images can be extracted. A popular technique is to merge both panchromatic and multispectral images to create a pansharpened or "fused" image. Pansharpened images boast better resolution than their parts. Images can be processed to different degrees depending on the desired end product.

Another basic processing technique is to georectify images. Georectification is the digital alignment of a satellite or aerial image with a map of the same area. A number of corresponding control points, such as street intersections, are marked on both the image and the map. These locations become reference points in subsequent processing of the image. Georectified images do not take into account topographic effects.

A further step in processing is to orthorectify the image. Orthorectification removes topography effects from images allowing for accurate mapping and overlaying of the image on digital terrain models. Spatial accuracies of less than a pixel can routinely be achieved.

The other advantage to satellite based systems is that the data are acquired digitally with specific radiometric characteristics which can then be utilised in other image analysis programmes. Various processing such as image classification and manipulation are thus possible for the project area. Products such as detailed landcover mapping and vegetation stress mapping, as well as some basic channel ratios (iron index) are possible. Typical colour aerial photography (colour IR) is little more than a static picture.

Images can be obtained in raw or processed forms. Images are almost exclusively processed by proven software which helps ensure the final product is of a known quality.

Typical Accuracies and Resolution of the Acquired Data.

Remotely sensed data offers a wealth of information and is a perfect complement to most projects. In some cases it will be the most up to date map you will ever get of an area. A variety of data is available ranging in both spatial resolution as well as radiometric (spectral) resolution. Some of the more well known satellites (Landsat Thematic Mapper (TM)) have been around since the 1970’s and thus provide an excellent multi-temporal data source at regional scales. The type of imagery used would depend on the intended application, aerial extent and budget. Satellite image resolution varies between systems. Older systems such as Landsat have resolutions as coarse as 25 m for typical images, whereas the newest high resolution satellites can obtain images with resolutions as fine as 0.50 m.

Although atmospheric effects have the greatest impact on quality, the repeatability of satellite images can almost eliminate any issues with cloud cover. Satellite image accuracy is a complex function of many factors including, mainly, satellite geometry (nadir, measurement of orientation and geolocation, etc.). These factors can affect quality considerably by limiting the control on spatially positioning the images.

Limitations and Constraints

The methodology is generally limited by climatic conditions including cloud cover and temperature variations during the orbits and also changes in sun angle. Thermal infrared imagery is less affected by cloud cover. Some of the wavelengths used (visible wave lengths) are affected by atmospheric scattering and absorption. Additionally, it is often necessary to acquire satellite images at different times during the year to look at vegetation changes with the seasons.

Strengths and Weaknesses

Satellite images can provide excellent resolution with high spatial accuracies. Image acquisition times can vary depending on satellite availability and environmental conditions in the project area.

Potential to Combine Technologies

The ability to combine this technique with others is dependent on the agencies providing a number of different instruments and sensors on the same platform.

Commercial Availability

Satellite imagery is available from a number of vendors and government agencies. A well known vendor in Canada is MacDonald, Dettwiler and Associates Ltd. (MDA), which provides commercial products from a number of systems, including IKONOS-2, GeoEYE-1, and QuickBird satellites. A number of Canadian Consulting firms such as Golder Associates Ltd. are also resellers of many commercial high resolution satellite imagery products.

Time Scales

There is a wealth of archival images available, at various processing stages, through satellite image providers and government organizations such as the United States Geological Survey (USGS) and the Canada Centre for Remote Sensing (CCRS). Since the images are already taken and archived, retrieval is relatively quick. New satellite images can be captured upon request within a few days to months, depending on availability and environmental conditions being conducive to obtaining quality images. Processing time can be on the order of days to weeks, depending on the required final product.

3.2 InSAR

Brief Description

Differential or SAR interferometry using space borne sensors has become an established tool for the detection of very small surface deformations. The premise is to analyse the phase changes in Synthetic Aperture Radar (SAR) caused by surface displacements between two data sets.

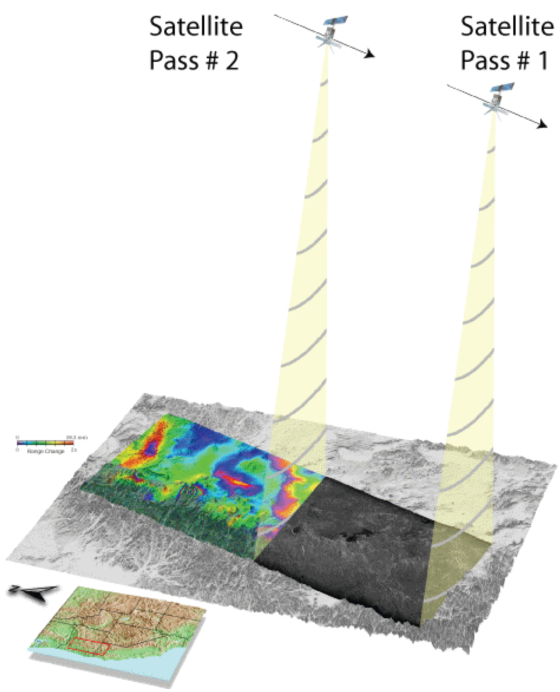

Figure 3-3: InSAR image acquisition and resulting interferogram. (USGS)

Synthetic Aperture Radar (SAR) is a method of accurately measuring distance. The concept is that as the ground elevation varies, the returned radar signal will arrive slightly later (or earlier) in time as it has had a slightly greater (or lesser) distance to travel depending on the elevation of the ground. SAR interferometry (InSAR) makes use of the phase data of the SAR data from two images of the same area by subtracting the phase value in one image from that of the other, for the same point on the ground. This is, in effect, generating the interference between the two phase signals.

Differential interferometry uses SAR images of the same area acquired at different times. By subtracting one interferogram from the other (see Figure 3-3 above), areas that relate to common topography cancel each other out and any remaining areas represent a difference in topography; this difference represents a change in topography during the time interval when the SAR images were acquired.

Currently, there are two ways of performing differential interferometry:

- Three-pass (or double difference method) – Three SAR images of the same scene are used in this method (two scenes must be taken within a short amount of time, assuming no deformation). One interferogram is made from the phase differences in the first and the second image, a second interferogram is made from the phase differences in the second and the third image. Then the first interferogram is then subtracted from the second to produce a third, double difference interferogram.

- Two-pass + Digital Elevation Model (DEM) – This method only requires two SAR images, thus producing just one interferogram. To perform the differencing, another interferogram has to be created from an existing DEM of the area (and from precise knowledge as to the satellite position at the time of image acquisitions). The synthesised interferogram is then subtracted from the original interferogram, thereby removing all fringes that relate to ground elevation, leaving only fringes that represent surface displacement.

Due to the short wavelength of SAR sensors, surface movements on the sub-centimetre scale can be detected with a number of orbiting satellites. This makes the technique unique for applications like large-scale detection and monitoring of geological stress change processes, including sudden co-seismic displacements and long-term tectonic movements. Additional applications include volcanic bulging before eruptions, land subsidence in mining areas and underground construction, the occurrence of landslides in mountainous areas, and ice deformations and glacier dynamic studies.

Figure 3-4 below illustrates the use of InSAR to monitor the deformation pattern of the lower part of the Frank Slide in Alberta. The white hatch indicates the locations of underground coal mines, the red line outlines the Frank Slide boundary, and the black rectangle is the reference area.

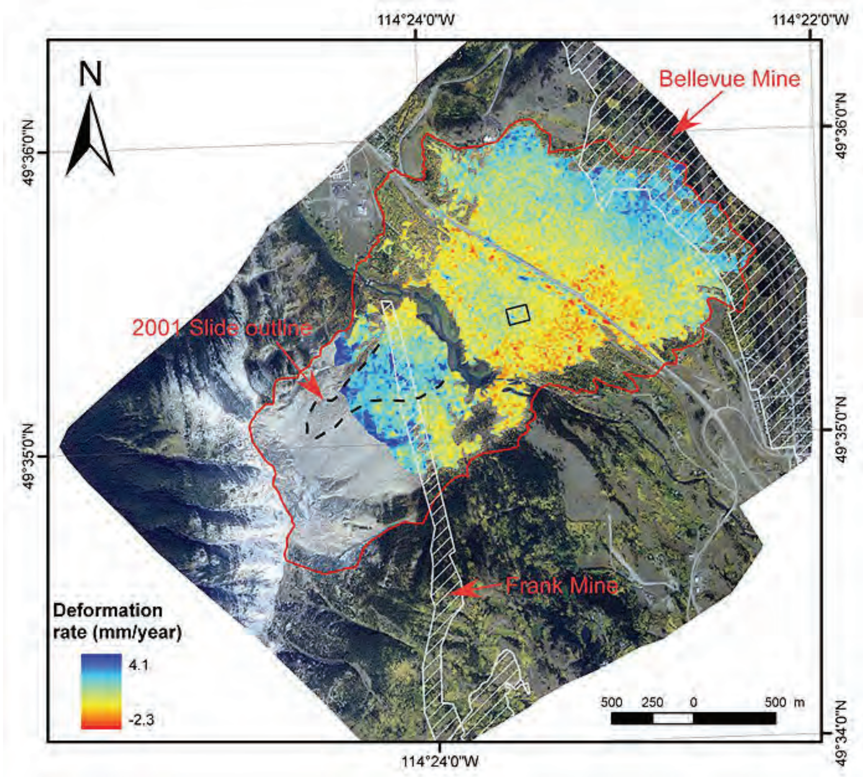

Figure 3-4: InSAR image of the Frank Slide, Alberta, Canada. (Alberta Geological Survey, August 11, 2008)

Applicability to Programme

The application of this method could include the assessment of geologic stress change processes or, at later stages, the detection and ongoing monitoring of land subsidence resulting from the excavation process. Documented examples exist of the subsidence caused by the excavation of underground structures, including the Paris Metro (BRGM, 2003). SAR images, such as those acquired by the Shuttle Radar Topography Mission, can also be used for the generation of a DEM.

Processing and QA/QC

Depending on the method applied (Two- or Three-Pass), the overlapping SAR images are resampled and corrected for geometric differences and referenced (co-registered) such that a single pixel in one image relates, spatially, to a single pixel in the other image. Subtraction of SAR images to form interferograms is followed by the subtraction of these, or a synthetic interferogram derived from a digital elevation model, to produce a differential interferogram. The final interferogram can then be georeferenced for presentation.

Much like optical satellite imagery, the quality assurance for collected data is methodically documented by vendors and expected to be accurate. External QA/QC is not likely to be applicable for this method.

Typical Accuracies and Resolution of the Acquired Data

Typical accuracies of the acquired data are on the sub-centimetre scale.

Limitations and Constraints

Limitations of differential SAR interferometry result from strong decorrelation effects, particularly over vegetated areas. Vegetated areas would require the installation of corner reflectors at additional cost to the project. Additionally, the repeat cycles of satellites, after which the same region is imaged again, can in some cases be longer than the changes requiring detection.

Another important source of error is improper co-registration. Atmospheric effects can cause differential phase contributions which cannot easily be distinguished from surface displacements. These sources of error usually cause a loss in coherence and precision and can even prevent the generation of proper differential SAR interferograms.

Strengths and Weaknesses

Differential interferometry is very useful for monitoring changes and for creating accurate, although coarse, Digital Elevation Models. The requirement of special missions to acquire data can be costly and time consuming, should ground conditions be limiting. Approximations used in processing and geolocation can introduce small amounts of error, although this is expected to be very minor.

Potential to Combine Technologies

The ability to combine this technique with others is dependent on the agencies providing a number of different instruments and sensors on the same platform.

Commercial Availability

The commercial availability is increasing as the technology gains acceptance. Satellites capable of collecting InSAR data remain owned and operated by the larger government institutions and research organizations. However, the amount of data available for purchase is ever increasing as new satellites are launched. Currently there are six (6) operational satellites designed to collect InSAR data and one which is now decommissioned, but archived data can still be accessed.

- RADARSAT-1/2
- ENVISAT
- ERS-1/2
- JERS (decommissioned)
- ALOS
- TerraSAR X
- Cosmo SkyMed

Time Scales

Differential interferometry is used to detect change and as such images from two different times are required. Selected pre-project data may be readily available from commercial sources, however it is likely that post-data will require a special project. The time to acquire the data is very short as SAR satellites can image night or day and are not affected by cloud cover. However it may take time before the satellite is in the correct orbit for the particular project and data required. Turnaround time, once all the data is collected, is expected to be relatively short.

3.3 ASTER

Brief Description

The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) is an imaging instrument that is flying on NASA's Terra satellite which was launched in December 1999, as part of the space agency's Earth Observing System (http://asterweb.jpl.nasa.gov/).

It is designed to obtain high resolution global, regional, and local images of the Earth in 14 colour bands, from the visible to the thermal infrared wavelengths, and provide stereo viewing capability for DEM creation (Figure 3-5).

It is used with other instruments on the satellite which monitor the Earth at moderate to coarse spatial resolutions. ASTER consists of three separate subsystems, each of which has its own sensor, which view the Earth in a different part of the energy spectrum. Energy spectrums utilised include visible and near-infrared, shortwave infrared and thermal infrared.

Instrumentation was provided by Japan's Ministry of Economy Trade and Industry and each of the three subsystems was built by a different company in Japan. ASTER imagery is primarily used to study the following.

- Land surface climatology – investigation of land surface parameters along with surface temperature, to understand land surface interaction and energy and moisture fluxes.

- Vegetation and ecosystem dynamics – investigations of vegetation and soil distribution and their changes to estimate biological productivity, understand land atmosphere interactions and detect ecosystem change.

- Volcanic monitoring – monitoring of eruptions and precursor events, such as gas emissions, eruption plumes, development of lava lakes, eruptive history and eruptive potential.

- Hazard monitoring – observation of the extent and effects of wildfires, flooding, coastal erosion, earthquake damage and tsunami damage.

- Hydrology – understanding global energy and hydrologic processes and their relationship to global change; included is evapotranspiration from plants.

- Geology and soils – the detailed composition and geomorphologic mapping of surface soils and bedrocks to study land surface processes and Earth's history.

- Land surface and land cover change – monitoring desertification, deforestation, and urbanisation; providing data for conservation managers to monitor protected areas, national parks and wilderness areas.

Applicability to Programme

The main purpose of ASTER data in a site screening and/or site characterisation investigation will be to provide important regional information about the biosphere, surface water systems, geomorphology and surficial geology. It may also be possible to interpret the location of faults and other structural features.

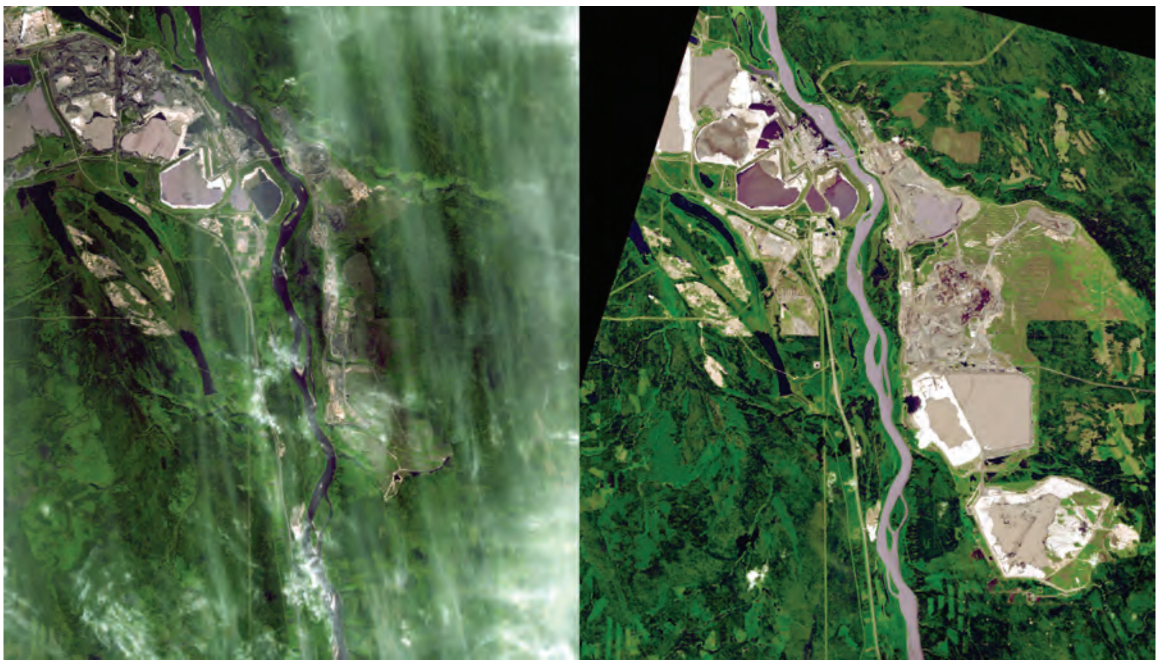

Figure 3-5: ASTER images of the Millennium Open Pit Mine, Alberta, Canada. (NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team)

Processing and QA/QC

Routine processing includes a number of steps and can also include on demand processing requests. The processing steps include:

- Recovery of the instrument source data. The spectral band information is multiplexed with the image.

- Demultiplexing of the instrument source data. The instrument source data are demultiplexed to separate image data for every spectral band.

- Image Data Realignment - Image data are realigned to compensate for the staggered configuration of the sensors in the satellite. The pixel addresses are changed such that all the pixels for each band lie on one line.

- Following the front end processing, radiometric and geometric system corrections are calculated and the coefficients added to the data set.

- Scene cutting is carried out according to the World Reference System (WRS) and a set of geolocation data is generated for each scene.

- Resultant data contains the image data, appended radiometric coefficients, geolocation data and auxiliary data.

- Data sets are also produced by applying radiometric calibration and geometric resampling data and these form the input data for all the derivative image processing.

Typical Accuracies and Resolution of the Acquired Data

As the ASTER instrument has three separate subsystems or sensors it therefore has three resolutions which are 15 metres, 30 metres and 90 metres, respectively, for each of the visible and near-infrared, shortwave infrared and thermal infrared spectra.

Limitations and Constraints

The data and images available may not cover the areas of interest.

Strengths and Weaknesses

ASTER images can provide a wealth of information. Ground conditions could restrict the ability of ASTER to collect quality images in a short amount of time. ASTER data resolution is considered coarse and may not provide enough detail for site specific characterisation but would be an excellent data source for regional investigations.

Potential to Combine Technologies

There is no potential to combine ASTER with any other technology.

Commercial Availability

ASTER data is acquired by NASA and Japan's Ministry of Economy Trade and Industry. Archived data, at different levels (processing stage) are available from NASA. There are a number of ASTER products available. Certain archived data is available free of charge while some data requiring a planned mission are available for purchase. As complexity of processing increases, so does price.

Time Scales

ASTER data that is archived can be requested on demand via internet based utilities. If data does not exist, it can be tasked and processed, and purchased, upon request.

4. AIRBORNE SURVEYS

This section describes a range of airborne remote sensing and geophysical surveys that may be applied during a site screening and characterisation programme. Methodologies discussed include aerial photography, digital terrain mapping (Radar, LiDAR), hyperspectral imaging, magnetics, radiometrics, electromagnetics and gravity.

Airborne surveys are commercially available from a wide range of companies, headquartered around the world. Some operate purely geophysical services, while others provide aerial photography and scanning services. Only a few of these service providers are listed in this report. A longer list can be found at www.iagsa.ca, the web site of the International Airborne Geophysics Safety Association.

4.1 Aerial Photography

Brief Description

Aerial photography is, as the name suggests, the capture of photographic images of the ground surface from a view point above the ground surface (see Figure 4-1 below). Air photos are most useful when fine spatial detail is more critical than spectral information, as their spectral resolution is generally coarse when compared to data captured with multi-spectral sensors.

Figure 4-1: Sample high resolution aerial photographs. (USGS)

Most aerial photographs are classified as either oblique or vertical, depending on the orientation of the camera relative to the ground during acquisition. Oblique aerial photographs are taken with the camera mounted in the aircraft and angled at a low or high angle. High oblique photographs usually include the horizon while low oblique photographs typically do not include the horizon. Oblique photographs can be useful for covering very large areas in a single image and for depicting terrain relief and scale. However, they are not widely used for mapping as distortions in scale from the foreground to the background preclude easy measurements of distance, area, and elevation.

Vertical photographs taken with a single lens camera are the most common use of aerial photography for mapping purposes. The cameras used are specifically built for capturing a rapid sequence of photographs while limiting geometric distortion. They are often linked with navigation systems on board the aircraft platform, to allow for accurate geographic coordinates to be instantly assigned to each photograph. Most camera systems also include mechanisms which compensate for the effect of the aircraft motion relative to the ground, in order to limit distortion as much as possible.

When acquiring a series of vertical aerial photographs, the aircraft normally flies in a series of parallel lines (flight lines). Photographs are taken in rapid succession looking straight down at the ground, often with a 50% to 60% overlap between successive photographs. The overlap ensures total coverage along a flight line, facilitates stereoscopic viewing, and allows edge effect and distortions to be removed when photographs are stitched together. Successive photo pairs display the overlap region from different perspectives and can produce a three-dimensional view of the area. The use of stereoscopic pairs enables the interpretation of subtle structural features in 3D.

Aerial photography can cover the entire optical spectrum including UV, the visible spectrum, near and mid infrared and can also be extended into the far infrared (thermal). Additionally, with the use of scanning technology rather than photographic film, this can be extended to multispectral scanning images as well.

Photographic (panchromatic) films are sensitive to light from 0.3 μm to 0.9 μm in wavelength covering the ultraviolet (UV), visible and near-infrared (NIR). Where film rather than digital cameras are used, black and white film is the most common type of film used for aerial photography. UV photography also uses panchromatic film, but a filter is used to absorb and block the visible energy from reaching the film. UV photography is not widely used, due to the atmospheric scattering and absorption that occurs in this region of the spectrum. Black and white infrared photography uses film sensitive to the entire 0.3 to 0.9 μm wavelength range and is useful for detecting differences in vegetation cover due to sensitivity to IR reflectance.

Colour and false colour (or colour infrared, CIR) photography involves the use of a three-layer film with each layer sensitive to different ranges of light. For a normal colour photograph, the layers are sensitive to blue, green, and red light. In colour infrared (CIR) photography, the three emulsion layers are sensitive to green, red, and the photographic portion of near-infrared radiation, which are processed to appear as blue, green, and red, respectively. In a false colour photograph, targets with high near-infrared reflectance appear red, those with a high red reflectance appear green, and those with a high green reflectance appear blue, providing a "false" presentation of the targets relative to their normal colours.

Multi-Spectral Scanners (MSS) can be used to collect data over a variety of different wavelengths and have several advantages over photographic systems. The spectral range of photographic systems is restricted to the visible and near-infrared regions while MSS systems can extend this range into the thermal infrared. They are also capable of much higher spectral resolution than photographic systems. Multi-band or multispectral photographic systems use separate lens systems to acquire each spectral band. This may cause problems in ensuring that the different bands are comparable both spatially and radiometrically and with registration of the multiple images. MSS systems acquire all spectral bands simultaneously through the same optical system to alleviate these problems. As MSS data are recorded electronically, it is easier to determine the specific amount of energy measured and they can record over a greater range of values in a digital format.

Applicability to Programme

The main purpose of aerial photography in a site screening or characterisation investigation will be to provide important information about cultural features, the biosphere, surface water systems, geomorphology and surficial geology. It may also be possible to interpret the location of faults and other structural features in some cases. A DEM for the site can also be derived from these data. This type of detailed mapping is also very useful in the planning of other land based geophysical surveys, such as large scale 2D or 3D seismic reflection surveys.

Multispectral imaging and thematic mapping allows for the various reflection and absorption properties of soils, rock, and vegetation to be catalogued and can also be used for the interpretation of surface lithologies. Ground truthing of the interpreted geology would be required to confirm the analysis of the MSS data.

Processing and QA/QC

The majority of aerial photography utilises photographic papers and/or digital cameras. As such standard photographic processing is generally carried out. However, products are available that are entirely digital and can combine data acquired using multiple sensors to potentially produce Digital Surface Models (DSM), Digital Elevation Models (DEM), and ortho-rectified images. Depending on the product, images can be checked for accuracy and calibrated using known benchmarks.

Typical Accuracies and Resolution of the Acquired Data

Typical accuracies and resolutions are a complex function of many factors including the amount of ground covered in a photograph, the focal length of the lens, the platform altitude, and the format and size of the film. Aerial photographs can commonly provide detail down to a spatial resolution of 10 centimetres.

Limitations and Constraints

Air photo quality is generally limited by climatic conditions including cloud cover and temperature variations during the flights and also changes in sun angle. Thermal infrared images are less affected by cloud cover. Some of the wavelengths used are affected by atmospheric scattering and absorption. Additionally it is often necessary to acquire aerial photographic data at different times during the year to look at vegetation changes with the seasons.

Strengths and Weaknesses

Aerial photography is a useful tool for obtaining a very detailed and accurate picture of an area. Stereo photographs can help enhance the identification of geologic structure. Aerial photography surveys are not as cost effective as satellite imagery, if a resolution of 0.5 m (that of satellite imagery) is acceptable.

Potential to Combine Technologies

The aerial photography can be acquired in combination with other airborne methods, depending on the vendor. It can be commonly collected in conjunction with other mapping data, such as LiDAR.

Commercial Availability

Archival air photographs are generally available for many areas of Canada, including an extensive collection housed at the National Air Photo Library in Ottawa, some dating back to the late 1920's.

Multi-spectral scanning data is available through the various Federal and Provincial natural resource agencies.

Commercial providers of aerial photography tend to be regionally based. Two well known providers in Ontario are First Base Solutions and Northway Photomap. They have archival data available for purchase and will fly surveys on demand. Some providers have on-line GIS databases showing their inventory of archival coverage, which is very convenient.

Time Scales

Custom projects can typically be completed within 1 to 2 months, depending on the vendor's project backlog, weather conditions and aircraft availability.

4.2 Digital Terrain Mapping (LiDAR / Radar)

Brief Description

LiDAR and Radar are two technologies aircraft can utilise to determine altitude. LiDAR (**Li**ght **D**etection **A**nd **R**anging) is an airborne scanning technology whereby a laser beam is directed at the ground along a swath below the aircraft flight path (see Figure 4-2 below). The sensor records the time difference between the emission of the laser beam and the return of the reflected laser signal to the aircraft. The time difference is used to calculate the distance to the ground and is an effective way of acquiring data to form a DEM. An airborne LiDAR system is composed of a laser source, scanning assembly and timing electronics, a positioning and orientation system consisting of the differential GPS and inertial measuring units (IMU), a data storage unit, and processing software.

LiDAR systems also have the ability to record the intensity of the reflectance data in addition to the coordinates and height of the surveyed point. Reflectance values differ depending on the type of surface they scan and are called "LiDAR intensity". These data can be processed to produce a georeferenced file, which looks like a conventional image. The laser wavelength of some systems is in the near infrared which in addition to providing the laser measured distance can also record the 24-bit RGB colour of the target's surface. The digital colour image of the ground surface and the reflectance images can be useful for the identification of broad land use and serve as ancillary data for post-processing.

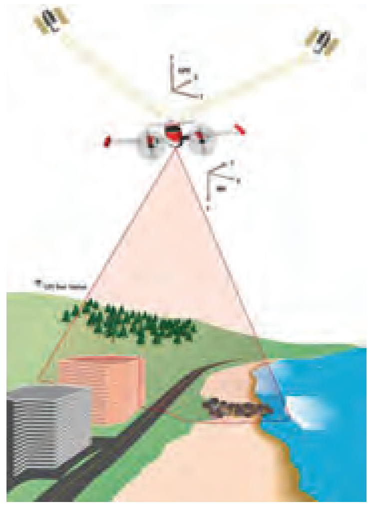

Figure 4-2: Airborne LiDAR mapping illustrating LiDAR swath, orientation deviations, and aircraft receiving GPS signals. (Optech Inc.)

Radar (**Ra**dio **D**etection **A**nd **R**anging) applies basically a similar methodology as LiDAR. Typical aircraft radar used for navigation can provide a good Digital Elevation Model (DEM) in some instances. Radar, unlike LiDAR, is not focused enough to record point reflections. To obtain a high quality DEM with Radar, a very large antenna is required. The practical solution to a very large antenna is Synthetic Aperture Radar (SAR). **S**ynthetic **A**perture **R**adar is a technique to record multiple broad radar reflections at different times and locations. Combination of the reflections can then be modelled as if the total received signal was generated and received from a large antenna.

Both instruments basically collect elevation data. To make these data spatially relevant, the positions of the data points must also be known. A high precision global positioning system (GPS) antenna is mounted on the upper aircraft fuselage. As the sensors collects data points, the location of the data are simultaneously recorded by the GPS sensor.

Applicability to Programme

Both technologies can be used to produce a very accurate site DEM, which will be an essential component of a site screening or characterisation investigation. These methods may also provide information on surface materials, through the analysis of reflectance data.

Processing and QA/QC

After the flight, data are downloaded and processed, the first step in the routine processing being the assignment of GPS coordinates. High quality GPS positions are determined, the scanner position and sensor orientation are used to compute the position on the ground. The data are also corrected for pitch, roll, and yaw of the aircraft. Once the geometrically corrected data are obtained, appropriate transformation can then be applied to derive the DEM in a relevant geographic coordinate system.

Radar data can be “sharpened” using Doppler measurements to increase accuracy.

A “bare-earth” DEM (see Figure 4-3 below), in which the effects of vegetation are removed, can be generated through the application of an iterative process during the post processing phase. DEMs can also be combined with aerial photography and spectral imaging to generate a more complete end product.

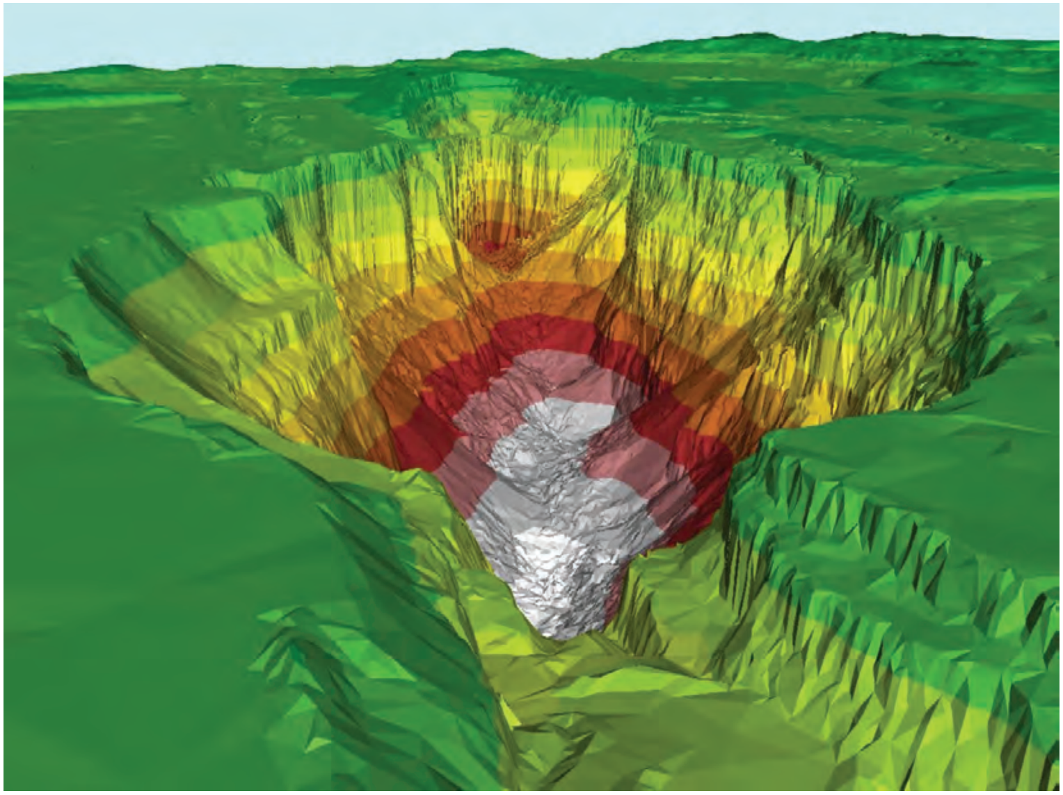

Figure 4-3: An example of a DEM generated from airborne LiDAR data. (Terrapoint Canada Inc.)

Quality control of Radar is very important as small sources of error can propagate forward. High quality GPS and sensor orientation needs to be recorded and corrected. Known ground control points can be used to determine the accuracy of data.

Typical Accuracies and Resolution of the Acquired Data

For both LiDAR and Radar, the accuracy of the range measurements or the distance to the “ground” is typically sub-centimetre accuracy.

Sampling of the ground surface or measurement interval depends on a range of factors including the altitude of the aircraft and the flying speed but may typically be in the range 0.19 to 0.72 m across the track (field of view) and 1.53 m along the track (flight path). However, the accuracy of the derived DEM is largely dictated by the accuracy of the GPS position, sensor orientation measurements, and type and density of vegetation. For LiDAR systems especially, high quality inertial measurement units (IMU) are required to accurately determine the sensor orientation. The horizontal position accuracy is generally reported to be better than 0.2 metres with vertical position accuracy of twice the horizontal.

Limitations and Constraints

The general limitations and constraints on the method are the weather conditions and vegetation. Surveys cannot be flown during times of rain or fog as the water vapour in the air could cause the LiDAR or Radar to scatter and give a false reading. New LIDAR systems minimise the effects of vegetation that used to produce false results by causing pulses to be returned too early (i.e. the ground appears more elevated).

Strengths and Weaknesses

Both methods in their advanced forms can produce very accurate DEMs. LiDAR and Radar systems in more basic configurations can acquire limited accuracy and resolution terrain information from any airborne platform. More complex systems may require significant sources of power which may prove difficult for all aircraft. Error can be introduced by vegetative canopy cover and by inclement weather.

Potential to Combine Technologies

Both methods can be flown in combination with the other geophysical surveys. The data would be recorded from an airborne platform with simultaneous collection of magnetic, electromagnetic, radiometric, and gravity surveys.

Scanning LiDAR system allow for the production of high resolution DEMs which can also be used for gravity terrain corrections. More and more frequently, LiDAR surveys are flown with digital camera systems and are used to quickly generate orthophotographs for a complete representation of the Earth’s surface.

Radar systems, in their basic forms (i.e., not SAR) are almost always integrated into geophysical data sets as the aircraft use them for elevation control. More complex LiDAR and SAR systems could be deployed with other airborne methods but this could require more power resources than some aircraft could provide.

Commercial Availability

LiDAR is available from a number of survey companies. The following are some of the companies that provide LiDAR surveys in the Canadian market:

- LiDAR Services International
- Terrapoint
- Fugro Airborne Surveys
- Sander Geophysics
- Airborne1
- Terra Remote Sensing

Time Scales

Surveys can be flown from both fixed wing and helicopter platforms and as such are limited by the capability of the aircraft. Surveys can typically be flown in a periods of days and processing time can be extensive, depending on quality of the data and final product required. Typically results are produced within 1 to 2 months of acquisition.

4.3 Hyperspectral Imaging

Brief Description

Hyperspectral imaging is the simultaneous acquisition of images in many narrow, contiguous spectral bands. Data sets are generally composed of about 100 to 200 spectral bands, of relatively narrow bandwidths (5 to 10 nm), although some sensors record 288 bands.

Hyperspectral data provides a more detailed view of the spectral properties of a scene (a view of the Earth), than the more conventional broad (spectral) band data, which is collected in wide and sometimes non-contiguous bands. The detailed spectrum resulting from hyperspectral imaging allows the comparison of the remotely-acquired spectrum to the spectra of known materials (Spectral Libraries). Also, the detailed spectra of targets permits a better discrimination among near similar targets, while subtle spectral differences may be hidden in spectra acquired with more conventional broad band sensors. Hyperspectral imagery data are typically collected (and represented) as a data cube with spatial information collected in the X – Y plane and spectral information represented in the Z-direction. Hyperspectral data (or spectra) can be thought of as points in an n-dimensional scatter plot. The data for a given pixel corresponds to a spectral reflectance for that pixel. The distribution of the hyperspectral data in n-dimensional space can be used to estimate the number of spectral end members and their pure spectral signatures and to help understand the spectral characteristics of the materials which make up that signature.

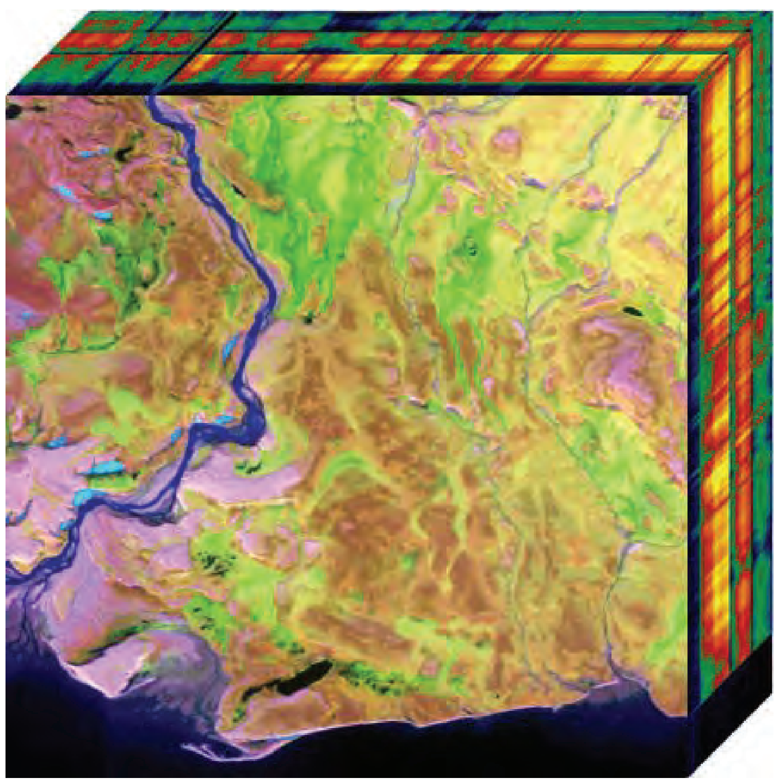

Figure 4-4: A hyperspectral data cube example (Nicholas M. Short, Sr., June 18, 2007. The Remote Sensing Tutorial)

Figure 4-4 above provides a hyperspectral data cube example, which has 126 bands in the original data set. This view shows an RGB image of band 75, 35 and 16 with the intensity of the 126 bands shown on a scale from blue over green and red to yellow.

There are many applications for hyperspectral remote sensing, including:

- Atmosphere: water vapour, cloud properties, aerosols;
- Ecology: chlorophyll, leaf water, cellulose, pigments, lignin;
- Geology: mineral and soil types;
- Coastal Waters: chlorophyll, phytoplankton, dissolved organic materials, suspended sediments;
- Snow/Ice: snow cover fraction, grain size, melting;
- Biomass Burning: sub-pixel temperatures, smoke; and
- Commercial: mineral exploration, agriculture and forest production.

As a consequence of the unique spectral characteristics of many alteration and rock-forming minerals, hyperspectral remote sensing has made a significant contribution to the field of geology. The data can also be used to indicate vegetation stress caused by processes such as gas/fluid escape at the ground surface.

Applicability to Programme

The main purpose of hyperspectral imaging in a site screening and/or site characterisation investigation will be its potential to help characterise the biosphere, surface water systems, geomorphology and surficial geology.

Processing and QA/QC

Hyperspectral imaging sensors collect radiance data primarily from airborne platforms which must be converted to apparent surface reflectance before analysis techniques can take place. Atmospheric correction techniques have been developed that use the data themselves to remove spectral atmospheric transmission and scattered path radiance. There are seven gases in the Earth’s atmosphere that produce observable absorption. These are:

- Water vapour;
- Carbon dioxide;
- Ozone;
- Nitrous oxide;
- Carbon monoxide;
- Methane; and
- Oxygen.

Removing the atmospheric effects through atmospheric correction algorithms results in the production of the scaled surface reflectance. If the topography is known, the scaled surface reflectance can be converted into real surface reflectance.

A minimum noise fraction (MNF) transformation is used to reduce the dimensionality of the hyperspectral data by segregating the noise in the data.

The Pixel Purity Index (PPI) is a processing technique designed to determine which pixels are the most spectrally unique or pure. PPI is usually performed on data transformed by the minimum noise fraction transformation which has reduced the data to coherent images. The PPI is computed by continually projecting n-dimensional scatter plots onto a random vector. The extreme pixels for each projection are recorded and these are excellent candidates for selecting end members which can be used in subsequent processing.

The pixels can then be classified using algorithms such as a Spectral Angle Mapper Classification (SAM) which is an automated method for directly comparing image spectra to a known spectra often maintained in a large spectral library e.g., USGS Spectroscopy Lab. The result of the classification is an image showing the best match at each pixel and works well for determining the mineralogy in homogeneous areas.

However, most surfaces on the earth, whether geologic or vegetated, are not homogeneous, which results in a mixture of signatures characterised by the single pixel. How the materials are mixing on the surface dictates the type of mathematical models used to estimate the abundances of these materials. The first step to determining the abundances of materials is to select end members, which typically is the most difficult step in the unmixing process. N-Dimensional visualisation techniques can be used to select end members within a scene. Alternatively, matched filtering can be used to detect specific minerals based on matches to specific library or end member spectra. The results of the matched filtering are usually represented as a greyscale image with values ranging from 0 to 1 which corresponds to the relative degree of the match.

Other classification and feature extraction methods, applied to multispectral data sets have been used for many years for the mapping of minerals and vegetative cover. However, conventional classification methods cannot be applied to hyperspectral data, due to the high dimensionality of the data. A nonparametric classifier, such as a neural network, and other feature extraction methods, can be used to accurately classify a hyperspectral image. Feature extraction methods, such as the decision boundary feature extraction (DBFE), can extract the features necessary to achieve classification accuracy, thus reducing the amount of data that needs to be analysed.

Typical Accuracies and Resolution of the Acquired Data

The resolution of the data is, in part, a function of the altitude at which the imaging device is flown. For example, NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) has a spatial resolution of 20 metres when flown at an altitude of 20km on NASA research aircraft. Other more commercially available hyperspectral scanners (i.e., PROBE-1, HyMAP, AisaDUAL) when flown at more moderate altitudes collect data ranging from 6 to 8 m resolutions.

Limitations and Constraints

Weather conditions affect data quality, as all spectrometers rely upon solar energy to record reflectance. Higher amounts of incoming radiation yield greater ranges of energy reflection or absorption. Hence, data should ideally be acquired when the sun is high in the sky. Shadows can be a major difficulty in mountainous terrain. For this reason, acquiring data at a time of year when the sun is high (i.e., summer) and around the middle of the day is normal practice.

Cloud cover and wet ground conditions also degrade the data because water absorbs energy in most of the important wavelengths being recorded. Thus, the need for clear skies and dry ground can override sun angle when determining the ideal time to acquire data.

Heavy vegetation coverage will obscure surface rocks but surveys of vegetated terrains can still be useful in inferring geological conditions. However, cover density and ground resolution need to be considered in order to compare its cost effectiveness to alternative methods.

The limitations of the method also include the ability to process the data and in particular unravel the signatures of different materials observed in the same pixel. While there are several mathematical schemes to achieve this they are limited in their abilities due to the complexities of the system.

Strengths and Weaknesses

The main strength of hyperspectral imaging is that it can obtain a wide range of information about the atmosphere, biosphere and ground surface across and entire study site in reasonable detail. It is, however, somewhat expensive to acquire.

Potential to Combine Technologies

The ability to combine this technique with others is dependent on the agencies providing a number of different instruments and sensors on the same platform.

Commercial Availability

The commercial availability is extensive, and the instruments are generally owned and operated by both private industry and larger government institutions and research organizations. Data is available commercially for purchase and it is possible to request particular mission flight paths to survey areas of interest.

Time Scales

It would typically require on the order of weeks to schedule the survey and obtain hyperspectral survey data, depending on vendor commitments. Depending on the intended use of the data, it could require on the order of a month to several months to analyze the data.

4.4 Magnetic Surveys

Brief Description

Airborne magnetic surveys are similar to magnetic surveys carried out on the ground, but allow much larger areas of the Earth's surface to be covered more quickly at the cost of resolution. Data are typically sampled at 4 to 10 m intervals along flight lines, depending on the survey type. The basic principals of magnetics are described in Telford et al. (1990).

Figure 4-5: A fixed wing aircraft mounted tri-axial gradient magnetic survey. (Fugro Airborne Surveys)

The magnetometers can be installed in a number of different configurations. For fixed wing aircraft (see Figure 4-5), magnetometers can be fixed directly to the aircraft, separated, and supported away from the aircraft on rigid booms, or housed in a towed “bird”.

For helicopters (see Figure 4-6), configurations can also be in booms or a single, forward facing, boom called a stinger. Helicopters can also tow birds containing magnetometers. Another platform for airborne magnetic surveys is through the use unmanned airborne vehicles (UAVs). UAVs typically only carry a single magnetometer.

Figure 4-6: A helicopter mounted horizontal gradient magnetic survey. (Fugro Airborne Surveys)

An airborne magnetometer's purpose is to measure the total magnetic field. Arrays of two or more magnetometers can be used in gradient surveys to make vertical, transverse, and/or longitudinal gradient measurements (see Figure 4-7). Magnetic surveys are used for detailed geological mapping of lithology and structure, including faults and fracture systems, in addition to the traditional activity of defining basement structure.

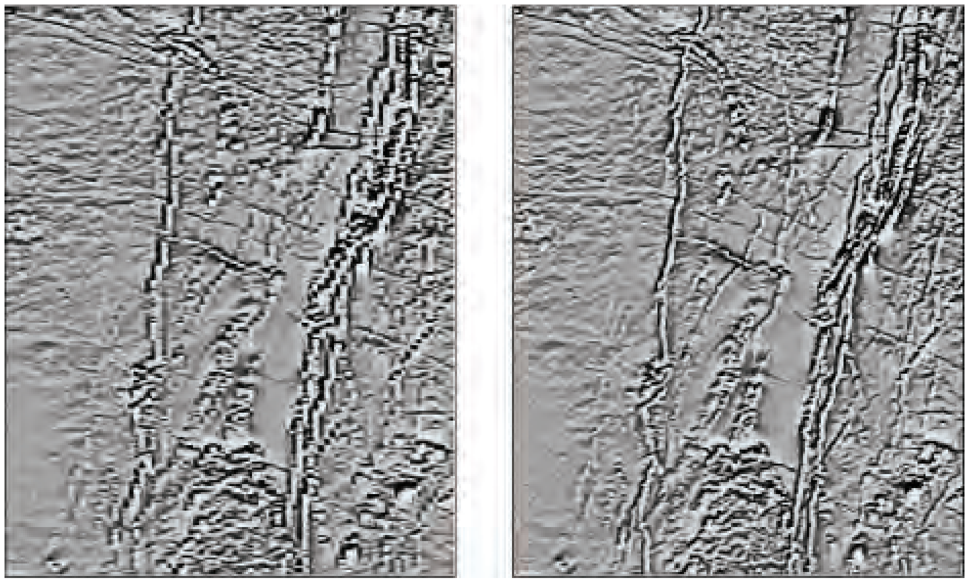

Figure 4-7: Airborne magnetic data - total field (left) and gradient (right). (Fugro Airborne Surveys)

Fixed wing magnetic surveys are often flown at constant elevation above sea level, but sometimes surveys are flown at a constant elevation above a somewhat smoothed surface; these are known as drape surveys. Helicopter magnetic surveys are often flown as contoured surveys where a constant height above ground surface is maintained. The line spacing and flight altitude used in the survey controls the resolution of the data.

Surveys are usually performed using optically pumped caesium magnetometers that can operate at a resolution of up to 0.001 nT (nanoTeslas). There are a few companies that manufacture optically pumped caesium magnetometers, all of which have comparable specifications. In most cases, airborne magnetic surveys utilise magnetometers situated both in the aircraft and at a ground station in proximity to the survey area (i.e., a base station). They are often identical, which helps ensure that all magnetometer data are equivalent in terms of sensitivity and noise. The base stations are used to record diurnal fluctuations of the Earth's magnetic field, which is later used in processing to correct the data.

As the aircraft flies, the magnetometer records variations in the magnetic field resulting from the spatial variations of the Earth's magnetic field, which are due to both the regional magnetic field and the local effects of magnetic minerals in the Earth's crust. The magnetic field is also affected temporally due to factors such as varying solar "winds", which are later removed during processing. Upon removing regional magnetic effects, the resulting map shows the spatial distribution and relative abundance of magnetic minerals in the subsurface.

Applicability to Programme

A magnetic survey is useful in a site screening and characterisation programme, particularly in a crystalline rock environment, as it provides important information regarding the underlying geology, both in the near surface, and at depth. Magnetic field mapping can be used to differentiate rock types, and to identify structural features within the rock mass, including the presence of faults, zones of alteration, and folding. Magnetic data can be very complimentary when interpreted in conjunction with other geophysical data sets, such as electromagnetic (EM), very low frequency (VLF), radiometric or gravity surveys, for example.

Magnetic gradient surveys provide better resolution of magnetic structures than single magnetometer surveys; most surveys acquired are multi-sensor gradient surveys. Airborne magnetic surveys are commonly followed by a ground based survey, which provides data of a much higher spatial resolution, which can be important in resolving structural features in further detail.

Processing and QA/QC

Processing requires good navigation data and accurate flight path recovery, which are very important aspects for high resolution airborne magnetometer surveying. Pre-flight there are a number of tests performed to determine what systematic corrections should be applied and can include:

- Lag - The lag test data would be analysed to see if the magnetometer data should be time shifted to ensure proper synchronisation with the flight path.

- Air minus ground - The airborne magnetic data should be corrected for diurnal drift; however, tests should be made to determine whether subtraction of the data recorded on the ground from airborne magnetometer data would improve the overall quality.

- Heading Test - This heading test is used to determine any anisotropy in the magnetometer measurements based solely on flight path direction caused by the magnetic effect of the aircraft.

- Manoeuvre/Turbulence Noise Test - This test is performed to ensure there is minimal effect of the magnetometer from aircraft “noise” due to the magnetometer moving with respect to the aircraft due to turbulence or manoeuvres.

The manoeuvre/turbulence test is performed when a magnetometer is located near the aircraft. The attitude and motion of the aircraft in flight, with respect to the Earth’s magnetic field vector, is monitored by a three-component fluxgate magnetometer which is very sensitive to attitude changes. The outputs of this magnetometer are used to deconvolve the artificial anomalies created by the aircraft itself, from anomalies created by geologic variations. The test will produce a Figure of Merit (FOM) values which represents how well variations can be corrected. Where magnetometers are towed in a bird, roll and yaw detectors in the bird are used to correct for geometric errors created as the bird departs from its assumed ideal flight orientation.

Magnetic values are checked by calculating the fourth difference of the data, which effectively is a five point difference filter applied to every data point that accentuates small spikes in the data that may be missed by visual inspection. The operator is applied to the data four times to determine the fourth difference with the generation of an error list. Single incorrect magnetometer values are corrected automatically. Any noise spikes in the data are removed and its value replaced based on neighbouring values with a physically appropriate interpolation technique. More complex errors are corrected manually, on the basis of the calculated fourth differences.

Subtracting base station measurements from airborne magnetometer measurements is the most common method of removing the effect of temporal fluctuations from the airborne data.An alternative method where practical, is the tie-line intercept method. Intersections of each line and control line would be calculated from the flight path data. The differences in total magnetic intensity from the two measurements, on-line and tie-line, would be calculated and automatically analyzed to produce a pattern of smooth adjustments to level the data together. Differences at all intersections are analysed and distributed proportionally along the control lines and the traverse lines to yield an identical final total field value for both lines at the given intersection. Final values would then be assigned to the traverse profiles at the appropriate intersections and used as corrections to the digitally recorded values along the traverse lines. In areas of steep magnetic gradient and/or of rugged topographic relief, the intersection adjustments may be deleted or an appropriate adjustment assigned to the traverse line.

Magnetic data is typically contoured using a bi-directional gridding algorithm with a minimum curvature or Akima (polynomial) interpolation technique. Gridding methods that take into account gradient calculations and data trends can also enhance data. If the survey has been flown as a horizontal gradient survey, the average value of the total magnetic field can be taken as the true total magnetic field with the gradient measurement used to enhance gridding.

Once magnetic data has been contoured, the next step in processing is to micro-level the data. Micro-levelling applies filters of different types and wavelengths, and in different directions. Properly chosen filter parameters help smooth minor imperfections in the final data.
As a final step, magnetic data can be corrected to IGRF (International Geomagnetic Reference Field) or other known reference data to ensure survey to survey consistency.

Once final data has been produced, a number of operations can be performed for presentation and interpretation. Standard methods could include producing a vertical gradient map to enhance features, upward/downward continuing data to enhance broad/sharp features, or to reduce data to the pole. Reduction to pole involves transforming the data though a phase shift which effectively gives the field which would be produced by a vertical magnetisation (effectively would be produced at the magnetic north or south pole). Anomalies then become symmetrical rather than skewed which aids interpretation especially the location of causative bodies.

Typical Accuracies and Resolution of the Acquired Data

Operational sensitivities and overall system resolutions are quoted as 0.005 nT and 0.01 nT respectively. Typical accuracies are on the order of 1 to 3 m in terms of positioning the recorded data.

Limitations and Constraints

Limitations and constraints are generally those produced by topographic relief, which is often accompanied by high magnetic gradients. High FOM (Figure of Merit) values can reflect noise in the system (i.e., unstable booms where the magnetometers are mounted). If an FOM is intrinsically high, then high winds and turbulence can be a major cause of noise and flights may be suspended.

The other main constraint on the acquisition of airborne magnetic data is the occurrence of magnetic storms which cause unpredictable changes in the solar magnetic variation and, as such, these cannot be corrected for and surveys have to be suspended during such times.

Strengths and Weaknesses

Airborne magnetic surveys are one of the most cost effective airborne survey methods. Magnetic surveys can be flown from both fixed wing and helicopter platforms with a minimum of equipment and crew. They are typically only limited by weather, aircraft (or flight rules), and magnetic storm interference.

Bird type surveys require little testing and compensation while fixed magnetometer surveys require more complicated testing and compensation, but allow for flexible survey conditions and navigation. Both fixed wing and helicopter can provide the full suite of magnetic surveys. Both types of aircraft can offer all the different combinations of gradient surveys, including all three gradients (longitudinal, transverse, and vertical). While fixed wing aircraft can cover significantly more area with lower costs, helicopters can offer significantly greater resolution as they can fly at lower speeds and altitudes.

The use of UAV's is not widely applicable for most surveys.

Potential to Combine Technologies

Airborne magnetic surveys form a very valuable data set, particularly when acquired in combination with electromagnetic, gravity, and/or radiometric surveys. It is essential to be acquired in conjunction with any airborne EM geophysical survey.

Commercial Availability

Airborne magnetic surveys are available from a number of vendors in the Canadian market, including:

- Fugro Airborne Surveys;
- McPhar Geosurveys Limited;
- Aeroquest International Limited; and
- Sander Geophysics Limited.

Time Scales

Time scales for performing and delivering magnetic survey data are typically short. Providing survey conditions are ideal, survey time can be very quick with upwards of a thousand to several thousands of line kilometres acquired over the course of two to three days, for helicopter and fixed wing surveys respectively.

Limited pre-project testing and calibration is required. The limited processing and corrections applied to magnetic data allow for short turnaround times for reporting. Times increase with gradient surveys and additional products requested. If magnetic data is collected along with other methods, it can be assumed that final magnetic products would not be available until the final report.

4.5 Radiometric Surveys

Radiometric surveys measure natural gamma ray radiation either as total gamma ray intensity or, more commonly, the gamma ray energy spectrum (gamma ray spectrometry). Airborne gamma ray spectrometry is an effective geological mapping tool in many different environments and has been applied to mineral, environmental, geothermal, hydrocarbon, and even groundwater investigations.

Brief Description

Radiometric surveys involve the measurement of concentrations of the naturally occurring radioactive elements; potassium, uranium (series) and thorium (series) by airborne gamma ray spectrometry (or radiometrics) and is a well established technique. The basic principles of the radiometric method are described in Telford et al. (1990).

These surveys are carried out using either a fixed wing or helicopter platform. Surveys using a fixed wing aircraft offer both speed and lower operating costs; however, helicopter borne surveys flying at lower altitudes are capable of defining smaller anomalies more accurately and result in data of higher resolution.

Gamma ray spectrometers use a thallium-doped sodium iodide [NaI(Tl)] detector crystal that measures the energy and number of gamma ray interactions in a time period. In the early stages of the development of airborne gamma ray spectrometry, only four energy windows were recorded. The typical, modern system enables automatic gain control for individual crystals, multi-channel analysis, and full spectrum recording; this significantly enhances the resolution of radiometric data and allows for more complex processing

A system's efficiency is dependant in part on the size of the detector crystal. The larger the system's detector size, the more efficient the system. Modern systems are available that allow spectral data to be acquired for up to 4 detectors, thus effectively increasing the detector size. While most systems record 256 channels, others record up to 1024 channels, increasing the quality of the data for a similar sized detector. Airborne gamma ray spectrometers also include an upward looking detector which is used to collect gamma rays from airborne radon and cosmic sources. There are a number of airborne gamma ray spectrometer manufacturers on the market, each having systems that perform well, typically only separated by advancement in electronics and stabilisation method.

Data are acquired in conjunction with real-time differential global positioning system (dGPS) navigation to allow for accurate positioning of the data. Additional data including radar altimeter, barometric pressure, and temperature are also collected during the acquisition of airborne gamma ray spectrometer surveys, and used to apply corrections to the raw data.

Applicability to Programme

Airborne radiometric surveys compliment other airborne geophysical methods in characterizing the geologic environment. They are particularly useful in a crystalline rock environment. They also provide a general background radiation data set that can be used as a baseline to compare with other radiometric surveys that may be acquired through the operation of the facility and into post closure monitoring.

Processing and QA/QC

Processing uses a number of approaches, one of which is spectral component analysis, to reduce statistical noise in airborne gamma ray spectrometer survey data and is based on the method of Hovgaard and Grasty (1997).

These techniques utilise the complete spectrum and represent considerable advances in radiometric data processing. The processing is used to enhance the resolution of radiometric data. The reduction in statistical noise is equivalent to increasing the detector volume by a factor of between 3 and 4. The results are a more accurate measure of radioelement ground concentration, which improves considerably the discrimination between different geologic units with similar radioelement concentrations. This processing also results in improved discrimination of man-made radioactive sources from background sources. A combination of spectrum fitting and noise reduction techniques allows for the production of maps of caesium and other man-made nuclides.

Processing may be conducted in a number of software packages that follow the processing procedure outlined in the International Atomic Energy Agency (1991) Technical Report No. 323.

Broadly, processing follows the general sequence of:

- Check for spectral drift.
- Dead time correction (if applicable).
- Filtering to prepare for background corrections. A narrow non-linear filter is applied to the radiometric data to remove spikes. A low pass filter can be applied to smooth the data prior to further processing.
- Cosmic and aircraft background correction.
- Background radiation levels can be estimated by flying background calibration lines over water and by analysing flight lines passing over lakes.
- Radon corrections.
- Altitude corrections.
- Topographic corrections.

After these corrections, the data are next corrected for spectral overlap using experimentally derived stripping ratios in the following steps.

- Spectral stripping.
- Altitude and temperature related (density) attenuation corrections.
- Calibration and conversion to apparent radioelement concentrations.
- Calculation of radioelement ratios.

Gridding airborne gamma ray data presents certain challenges because of the inherent statistical fluctuations in the data. Data is typically smoothed and interpolated across flight lines or by generating an average surface based on statistical or by smooth, mathematically varying gridding methods.

Products normally delivered for airborne gamma ray spectrometer surveys include colour or contoured parameter maps reflecting the radioelements of interest or total gamma ray counts, ratio maps, ternary maps (see Figure 4-8 below), and/or full spectrum and windowed digital data on a variety of media and formats.

Care needs to be taken when acquiring airborne radiometric data and ensuring it is accurate. Factors during the acquisition phase such as recent precipitation and snow cover can cause significant attenuation. Other factors that need to be performed accurately include pre-survey tests and calibrations and daily stabilisations. As well, auxiliary systems, altimeters and barometers need to be accurate to ensure quality processing of radiometric data.

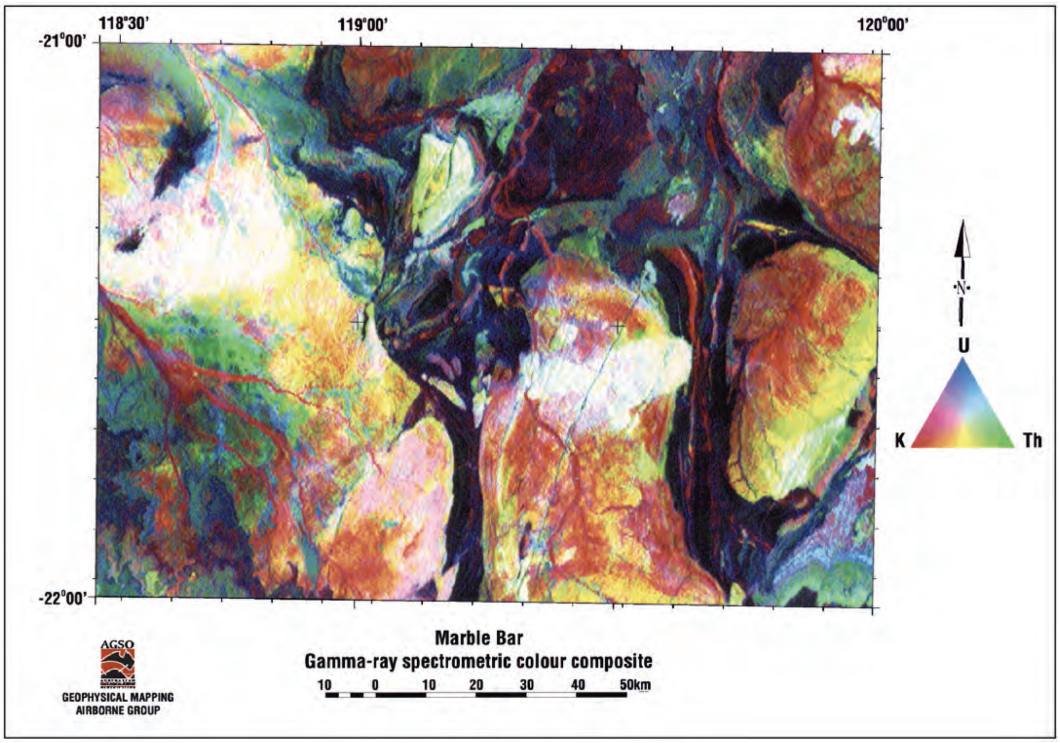

Figure 4-8: A three-color composite of airborne gamma ray spectrometry for Marble Bar, Western Australia. (Australian Geological Survey Organization)

Typical Accuracies and Resolution of the Acquired Data

The accuracies of the data are dependent on the ability to recover the flight line and navigation data but with the use of dGPS positioning, the accuracy of the data in terms of position is typically on the metre scale. The instruments generally are capable of recording data at rates of 100,000 cps (counts per second) and have an accuracy of better than 2%.

Limitations and Constraints

Topography and weather conditions (rain in particular) can limit the survey method. Thick overburden can also attenuate gamma rays, such that the radiometric signature is not representative of the underlying geology. Another real constraint on the methodology is the level of cosmic radiation and radon, and the ability to measure and compensate for these levels.

Strengths and Weaknesses

Radiometric surveys are a valuable tool and provide supplemental data that enhance any airborne programme. Results reflect surface geology and mineral distribution, as well as the distribution of natural gamma radiation at surface. Airborne radiometric surveys record very small responses that are statistically variable. As such, great care needs to be taken in performing tests and processing data appropriately.

Potential to Combine Technologies

Radiometric surveys are generally flown in conjunction with any other airborne instruments such as EM and/or magnetometer systems.

Commercial Availability

Airborne radiometric surveys are available from a number of vendors supplying the Canadian market, including:

- Fugro Airborne Surveys;
- McPhar Geosurveys Limited;
- Aeroquest International Limited; and
- Sander Geophysics Limited.

Time Scales

Time scales for performing and delivering radiometric survey data are typically short. Providing survey conditions are ideal, survey time can be very quick with upwards of a thousand to several thousands of line kilometres recorded over a two to three day period, for helicopter and fixed wing surveys respectively.

4.6 Electromagnetic Surveys

Airborne electromagnetic (EM) surveys traditionally include:

- Time domain EM systems;
- Frequency domain EM systems; and
- Very Low Frequency (VLF) systems.

Brief Description

Frequency domain EM systems allow for very high resolution surveys to be flown quickly, with moderate depth of penetration. Time domain EM systems (see Figure 4-9) provide depth of penetration on the order of hundreds of metres, at the sacrifice of resolution and near surface information. Depending on the survey objectives, it may be appropriate to acquire both time and frequency domain data sets. Modern frequency and time domain systems have capabilities that offer a good compromise on their inherent shortcomings. The basic principles behind EM methods are described in Telford et al. (1990). Further background on time domain and frequency domain EM can be found in McNeil (1980a, 1980b and 1994)

Time Domain EM Methods

Time domain EM surveys involve the application of a low frequency, time-varying waveform to a transmitter coil. Airborne time domain EM systems can be borne by both fixed wing aircraft and helicopter. The coil geometry is heavily dependent on the aircraft. Fixed wing configurations are dependent on the size and type of the aircraft, whereas helicopter coil designs are more variable; limited more by aerodynamics and helicopter lift.

The current waveform applied to the transmitter is typically a current pulse that is switched on, then off, at a predetermined frequency. The frequency components of the pulse are thus time varying. Depending upon the system, the transmitted waveform may be a half sine wave, triangular, or square waveform. Time domain frequencies are typically very low, anywhere from 25 Hz to 150 Hz and can be of variable/selectable frequency, although through a small range.

In the absence of conductors, a sharp transient pulse proportional to the time derivative of the induced magnetic field is detected at the receiver. 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 4-9: A fixed wing time domain airborne EM system. (Fugro Airborne Surveys)

Time domain EM fields can be decomposed into "in-phase" and "quadrature" components. The components in time domain EM fields are not directly analogous to that of frequency domain EM systems, but labelled as such because of the similarity in their properties. It is the quadrature component that is traditionally measured in time domain EM surveys corresponds to the secondary field, while the in-phase component can be used to remove the primary field and potentially for detecting good conductors (i.e., no quadrature component).

The secondary field is measured by a receiver coil. Receiver coils can be situated in a bird towed below or behind the aircraft, or can be fixed to the same platform as the coil in the case of some helicopter systems. Historically, receiver coils were orientated such that the flight direction component of the secondary field is measured. Modern systems are capable of measuring all three components, including the vertical component and the flight line orthogonal component.

Vertical component measurements are very important, as the signal-to-noise ratio is higher and the geometry allows for better resolution of layered structure. The receiver in early time domain EM systems "listened" only while the transmitter was "quiet" or "off". These off-time measurements reflect solely secondary fields (quadrature) and were used for generating conductivity models for deeper conductors. On-time measurements are becoming more important to time domain EM as they allow for better imaging of shallow structure by allowing any secondary field during the on time to be measured. The inherent design of induction coils only permits the rate of change of the resulting magnetic field to be measured.

One important advancement is that modern time domain EM systems not only measure the rate of change of the magnetic field, dB/dt, but the magnetic field, B, itself. The B-field data will help resolve and thus enhance the identification of good conductors.

The large scale and high transmitter power of fixed wing time domain EM systems can provide a large effective depth of exploration/mapping as well as a large search footprint. The broad bandwidths available with some systems allow for both shallow and deep mapping capabilities. The depth of investigation is in part determined by the transmitter power or dipole moment, which is a function of the coil size, the number of turns of the coil and the current. The large coil size, however, can limit the spatial resolution for target interpretation. The depth of investigation is however generally limited to the upper 600 m and is dependent on a number of factors.

In recent years, helicopter borne time domain EM systems have become considerably more advanced. Helicopter systems typically have smaller coil sizes but their ever increasing dipole moments can achieve great penetration. The height, speed, and line spacing capabilities of a helicopter based system allow for great spatial resolution while still providing good depth penetration.

Time domain EM systems are used to map changes in the conductivity of the earth that result from changes in geology, geologic alteration zones, or conductive sediment layers; changes in groundwater or salinity; or changes in overburden type or thickness. The method can be used in site screening or characterisation for determining/providing geologic and structural information.

Frequency Domain EM Methods

Frequency domain EM surveys are traditionally acquired using a helicopter platform (see Figure 4-10) and use multiple fixed-frequency EM fields to measure and map the electrical conductivity of the earth in three dimensions. In typical helicopter frequency domain EM systems, both the transmitter and receiver coil are housed in a rigid shell or bird that is towed beneath the helicopter. Helicopter frequency domain EM birds are typically 3 to 8 m long. The length of the bird is representative of the distance between transmitter and receiver coils.

Coil spacing is an important factor in depth penetration. The transmitter coil generates an electromagnetic field at a fixed frequency or set of frequencies. Receivers measures both the amplitude, in parts per million (ppm), and the phase of the secondary field with respect to the primary field. The in-phase and out-of-phase (or quadrature), components represent the phase shift of the secondary field. In-phase measurements are 180^o out of phase with the primary field and reflect responses from good conductors. Quadrature measurements reflect responses from poor conductors.

System operating frequencies are selected to maximise the overall depth of penetration while still coupling well with conductivity differences in geology, and not interfering with other frequencies. Higher frequencies more effectively measure the conductivity of the near surface, while low frequencies have a greater “skin depth”, which allows them to resolve deeper targets. Frequency domain EM birds typically contain from three to six coil pairs, although systems with larger numbers are available.

Figure 4-10: A helicopter borne frequency domain EM system. (Fugro Airborne Surveys)

Between coil pairs in a particular system, there can be different coil spacings and orientations for different frequencies. Most systems use one of two different coil orientations: coplanar or coaxial. Coplanar coils share the same plane which is oriented such that the axes of the coils are both normal to the plane and point directly toward the ground. Coaxial coils are oriented parallel to one another and share a common axis.

Coplanar coils couple better with, and, as a result, better represent the conductivity of horizontal layered structure, while coaxial coils couple better with inclined structure. Coplanar and coaxial coil pair frequencies can be complementary to help better image structure at depth, although should not be identical to avoid interference.

Changes in the conductivity of the earth are caused by changes in geology, geologic alteration zones, or conductive sediment layers; changes in groundwater location or salinity; or changes in overburden type or thickness.

Magnetometer survey data are generally acquired simultaneously with the frequency domain EM surveys to measure the earth’s magnetic field, which can be interpreted to identify changes in bedrock geology to a great depth.

While exploration for metallic mineral deposits is the most common application of frequency domain EM systems, they have also been successfully applied to geologic mapping, engineering applications such as overburden and permafrost depth mapping, sand and gravel location, and soil characterisation.

Other applications have included mapping shallow salt water intrusion, detection of buried metal objects and mapping brine leaks from abandoned oil wells. The systems are designed for the calculation of 3D earth resistivity models, overburden thickness, layered inversions, and EM derived susceptibility.

VLF

VLF surveys are sometimes acquired in conjunction with frequency domain EM surveys. The primary field is supplied by powerful radio transmitters operated by governments for use in military communications and navigation. The available frequencies are in the range of 15 kHz to 22 kHz, relatively high for geophysical surveying, but relatively low for communications (hence, the term VLF).

The receiver usually consists of a coil, or a set of orthogonal coils, and supporting electronics towed in a bird. The VLF method can be used to map the subsurface conductivity distribution, however, the systems are particularly susceptible to “geologic” (i.e., telluric) noise.

A major shortcoming is that the primary field direction generated by VLF transmitters is determined by the location of the transmitter, which may not be well coupled with the dominant geologic strike of the target of interest (although a project specific ground based transmitter can be set up for the survey). Another concern is that existing VLF transmitters are not under the control of the survey team, so it is possible that they may not transmit continuously throughout the period of the survey.

Applicability to Programme

Airborne EM surveying will be an important part of screening and characterizing a potential repository site in crystalline rock. It is part of the initial assessment of the geology and structures (i.e., faults, folds and alteration zones that will have a controlling effect on groundwater movement), and will help focus ground based geophysical surveys and drilling. The required depth of the investigation and resolution will determine the best selection of technique and instrumentation.

Processing and QA/QC

As with all airborne methods, processing requires good navigation data and accurate flight path recovery, which are very important aspects for high resolution airborne EM surveying.

All airborne EM systems require calibration prior to use and experience instrument drift, which must be accounted for. These calibration checks are performed by taking the EM system to high altitudes (greater than 300 m for the lowest frequency domain EM systems). It is assumed at these heights that the system is beyond the range of ground effect and therefore the secondary field induced will not reach the receiver. The checks and subsequent corrections are performed at the very least before and after surveying, and often frequently during the survey. Basic calibration errors are corrected in real time in the field, while drift corrections are performed post-survey.

Time Domain EM Processing and QA/QC

Time domain EM data are routinely checked for quality during the processing steps. Time domain EM channels, gates, are checked to determine they are decaying with depth and that there is no unexpected noise on one channel that is not on others. While some designs are better than others, time domain EM data can have low signal-to-noise ratios. Noise envelopes are measured to ensure data is not lost within the noise. The data is filtered to remove as much high and low frequency noise as possible while preserving data. Spheric noise (due to natural atmospheric lightning discharges), power line noise, VLF noise, and coil-motion noise are also filtered out.

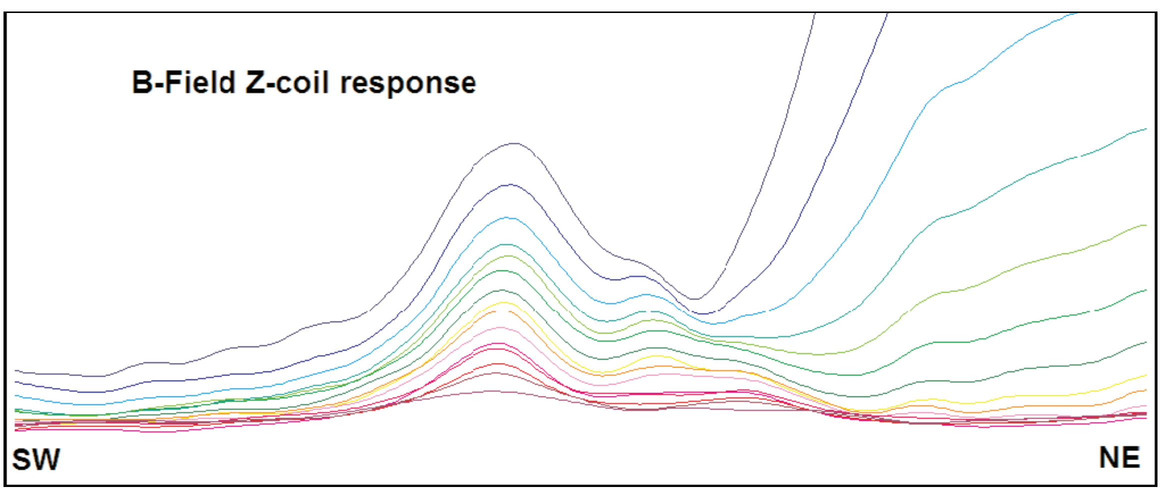

Figure 4-11: TDEM response over an inclined conductive target. (Fugro Airborne Surveys)

Figure 4-11 above illustrates the TDEM response over an inclined conductive target. Coloured lines indicate response from different time channels and shows signal decay in late time.

Time domain EM processing utilises the three components of the B-field and time derivatives of the B-field components, using inversion or forward modelling codes to yield resistivity depth section models. While the processing steps vary between platforms and companies, the processing stream typically involves three key steps:

- Deconvolution of the system response - The deconvolution stage removes the system self-response. The system transfer function between transmitter loop current and received dB/dt response is measured at high altitude in the absence of any ground response and this is removed by deconvolution.

- Primary field removal - Sources of primary field effects in the measured response include variation of currents in the transmitter loop and the secondary (eddy) currents induced in the conductive metal frame of the aircraft. The primary field must first be simplified by removing the system response characteristics through deconvolution, and then subtracted to produce an approximate impulse response of the ground.

- Conversion to square-wave magnetic (B) field response - Discrete conductor analysis and resistivity mapping are performed on the data sets. Subsurface conductivity is derived from square-wave B-field window amplitudes for every observation using inverse modelling. Limitations of 2D and 3D inversion techniques for the large data volumes involved in EM surveys has historically restricted transformations of the observed data to 1D models of the conductivity structure of the ground, although recent modelling advancements are changing this. Traditionally, each observation is treated in isolation with the assumption that the ground is composed of horizontal conductive layers of infinite horizontal extent.

The processing produces outputs including energy envelope, conductivity depth sections and realisable resistive limit maps and stationary current images to aid interpretation.

<u>Frequency Domain EM Processing and QA/QC</u>

At the start of a survey, a frequency domain EM system's phase and gain must be calibrated. The phase is a measure of how well in-phase and quadrature channels measure their respective components. Gain measures the amplitude of the received signal. Phase and gain compensations, are performed pre-flight at a high altitude (removed from any ground response), and are corrected for automatically or manually, depending on the system. Post flight, these values are checked and adjusted as needed. Typically, a situation where major corrections need to be performed are indicative of other system problems.

In-phase and quadrature measurements drift during flight and between flights. On a flight-by-flight basis, the drift is measured and checked at high altitude to ensure drift is not excessive and is linear. These measurements, which should be zero at altitude, are corrected post flight. The component data is then selectively filtered to remove system noise associated with spherics, wind, and harmonics (interactions between coils causing oscillations). Noise on the channels is reported in the same units as measured, parts per million (ppm) of the primary field.

Typical noise limits vary between frequencies and coil orientations, but are low or can be filtered out in most cases with no reduction in data quality. The in-phase and quadrature components are then used to calculate a conductivity value at each sample, for each frequency (coil pair). Manual and automatic levelling of the data must be performed at this stage. All of the channels, their conductivity values, and tie-line crossover information, are used to level the data such that there are smooth gradients across the grids and no line-to-line effects.

Inversion of in-phase and quadrature components with conductivity calculations generate resistivity models for selected earth models, and depth sections can be extracted. Typical products of the processing are listed below.

- Airborne resistivity mapping;
- Three dimensional resistivity mapping;
- Mathematical inversion of data to geological layering; and
- Calculation of combined resistivity, magnetic permeability, and dielectric permittivity.

Figure 4-12 below illustrates an example of frequency domain EM inversion results (a) Model Geometry, (b) Sengpiel, (c) Differential (d) Multi-layer Inversion, (e) Occam Inversion.

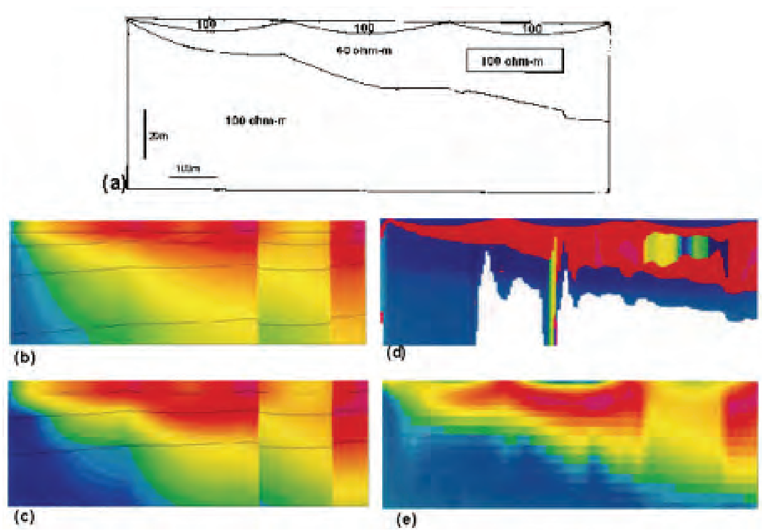

Figure 4-12: An example of frequency domain EM inversion results. (Fugro Airborne Surveys)

Typical Accuracies and Resolution of the Acquired Data

The accuracy and resolution of airborne EM is dependent on the quality of the data and the ability to invert or model the data appropriately. Resolution with airborne systems should be thought of in terms of spatial (horizontal) and vertical resolution.

Systems factors affecting quality of the data with respect to resolution and accuracy include system footprint, sampling rate, and depth of penetration. Time domain EM systems are typically flown at a greater height above the ground, resulting in a larger ground area being sampled.

Frequency domain EM systems have a much smaller footprint. Fixed wing systems, by design, have a footprint that is considerably larger than that of a helicopter system. Sampling rate, and equally, the speed at which a system can survey, also determine resolution. Helicopter frequency domain EM surveys will often sample ten times per second, equating to a sample every 2 to 4 m on the ground. Helicopter time domain surveys will often fly slightly slower with samples being taken every 3 m or less. By contrast, fixed wing surveys cannot fly nearly as slow and samples must be taken further apart. Time domain EM systems therefore maximise depth of penetration, while frequency domain EM systems are designed for high resolution, near surface surveys.

Depth penetration and resolution are also dependent on conductivity of the subsurface. Geologic units and overburden with high conductivity will limit depth penetration and vertical resolution of EM systems. Furthermore, there has to be a contrast in conductivity between soil or rock types for EM methods to be useful in detecting them.

Where additional information exists to assist in the interpretation, the models produced can have accuracies that are on the order of metres to a few tens of metres. However, altitude errors and geometric simplifications made during modelling can lead to the generation of artefacts and an overestimation of the depth to the source and an underestimation of the conductivity.

Limitations and Constraints

All EM methods have decreasing resolution with depth, which is a fundamental limiting factor in their ability to detect fine features that may be of significance in screening and characterizing a potential repository site. The depth of investigation of EM methods is also limited by the electrical conductivity of the subsurface; a conductive subsurface will yield a lesser depth of penetration than an electrically resistive one.

EM methods are also affected by power sources and other cultural features that are metallic, such as power transmission lines, or railway lines, for example.

For time domain EM systems, the depth of investigation is governed by the size of the transmitter coil and the dipole moment, which in general are both required to be large to obtain a good depth of investigation. The large transmitter sizes, however, can limit the spatial resolution. Helicopter based systems can be used to improve spatial resolution, due to the smaller size of the transmitter coil, slower flying speed, and operating height of helicopter, but with a lower depth of investigation.

For frequency domain EM systems, the depth of investigation is controlled by the coil spacing and frequencies used, and the conductivity of the subsurface.

Modelling the data in 1D, which necessarily treats the subsurface as being composed of horizontal conductive layers of infinite horizontal extent, can lead to the generation of artefacts in the model when sharp lateral conductivity changes occur laterally in the subsurface. In general, the 1D treatment of the response measured over a 3D conductive source is likely to result in an overestimation of the depth to the source and an underestimation of the conductivity. These effects are compounded in situations where the transmitter and receiver geometry is not perfectly constant, such as in “towed bird” systems. Slight altitude errors during acquisition can also result in errors in modelling.

A major limitation in all airborne survey methods is weather conditions. Airborne EM systems typically require a high (in airborne survey terms) ceiling in order to perform calibrations prior to flights. The required ceiling can be as high as 1,300 m above ground level for fixed surveys and 500 m for helicopter surveys. Low clouds can delay surveys considerably. Heavy precipitation can cause electronics to malfunction. Clouds associated with rain can increase the spherics until they are not isolated incidents any longer and cannot be filtered without degrading the data. High winds can cause “bird swing”, resulting in loss of coupling with the ground and flexing, which can distort transmitter/receiver alignment.

Strengths and Weaknesses

Airborne EM systems can be borne by either fixed wing or helicopter aircraft. Fixed wing aircraft fly higher and faster, thus have a larger footprint. Also, fixed wing aircraft are only capable of carrying time domain systems, but because of their size and ability to transmit more power, the depth of investigation is much greater than a helicopter based survey. Their larger size also allows them to carry many more instruments and as such several airborne surveys can be flown at once. Fixed wing systems must fly at a constant altitude or a drape-type survey.

Helicopter aircraft can be used to conduct both time and frequency domain EM surveys. The “low and slow” method of helicopter surveys allows for better spatial and depth resolution. The size and power of helicopter based systems are restricted by the limited lift capacity of helicopters. The main advantage of helicopters is their ability to contour terrain, as a near constant height can be maintained.

Airborne EM technologies, whether frequency or time domain, vary in size and complexity. The often harsh operating conditions can cause systems to malfunction leading to increased survey costs. In comparison to other airborne geophysical surveys, the processing of airborne EM data can be very time consuming.

Potential to Combine Technologies

Other geophysical systems are routinely flown in conjunction with airborne EM, including magnetics and gamma spectrometry. VLF systems can also be flown in tandem, although the use of VLF is limited. Additionally, airborne gravity and hyperspectral imaging can be acquired at the same time.

Commercial Availability

Airborne EM surveys are available from a number of vendors supplying the Canadian market, including:

- Fugro Airborne Surveys;
- McPhar Geosurveys Limited;
- Aeroquest International Limited; and
- Sander Geophysics Limited.

Time Scales

Airborne EM systems are generally a very fast and reliable method of conducting large geophysical surveys. Aircraft whether fixed wing or helicopter, can be mobilised to most areas, remote or otherwise, usually within a week. System availability, local weather and remoteness impact how quickly a system can be mobilised.

Helicopter electromagnetic surveys are realistically capable of acquiring, on average, a few hundred line kilometres per flight. Flights can last up to 3 hours before refuelling. Fixed wing surveys are capable of acquiring much more data per day, as fixed wing aircraft can survey many more hours without refuelling and travel at much greater speed.

Processing of electromagnetic data can be a very time consuming. Both time and frequency domain data can require extensive, line by line, levelling. Inversion and modelling on levelled data is generally a straightforward and automated process. A typical-sized airborne EM data set may require several months to process.

4.7 Gravity Surveys

Brief Description

An airborne gravity survey involves the use of a stabilised gravity meter installed in a fixed wing aircraft or helicopter to acquire data over a given area. The data acquired by a gravity survey may be used to:

- Locate and detail map sedimentary basins (salt diapir identification, assisting seismic survey planning, processing and model constraint);
- Infer the location of the thickest sedimentary section;
- Delineate basin outlines and boundaries;
- Define plate tectonic structures; and
- Map structures within the basin.

Localised variations in the Earth's gravimetric field are caused by a number of factors, most importantly, the geometry and density of geologic formations in the Earth's crust. Gravity information can be used for geological mapping/investigations and provide important input to geophere models. The basic principles of gravity methods are described in Telford et al. (1990).

There are a number of airborne gravimeters available commercially of significantly different designs. Examples of airborne gravity meters include the Canadian Micro Gravity GT-1A airborne gravity meter which may be flown installed on a fixed wing aircraft or installed in a small to medium-sized helicopter, and Sander Geophysics Limited's **A**irborne **I**nertially **R**eferenced **Grav**imeter – AIRGrav.

Gravity sensors are typically accelerometer-type or spring-type and are highly, highly sensitive. Changes in the local gravitational field apply a changing force to the sensors, reflecting a local change in mass (i.e., rock density). The sensors are mounted on platforms that can compensate for and accurately measure aircraft movements. Inputs from fibre optic gyroscopes, inclinometers, angle sensors and dual frequency high resolution differential GPS are used to drive servo motors which maintain the gravity sensor in a vertical position and help stabilise or correct for sensor motion. The entire assembly is mounted on a rotation table to maintain the sensor orientation with respect to aircraft heading.

Gravity measurement devices are also categorised by what they measure: scalar or full tensor. Scalar-type gravimeters measure the gravitational field at each point during flight, up to ten samples per second or every few meters. Scalar instruments can use one or more sensors to measure the different components of the gravitational field and help correct for motion. Accelerometers are typically used but there are spring-type scalar gravimeters available.

Full tensor gradiometry is the second type of gravity system. Full tensor measurements use pairs of accelerometers, mounted in all three orthogonal directions. The pairs of accelerometers not only measure the individual components of the gravity field, but also measure the gradient in each direction, resulting in a nine-component tensor per sample. The nine components (5 independent) are related to one another and as such they can be used to help remove aircraft noise as well as obtain gravity measurements in both horizontal directions and the vertical direction. Directional measurements allow for better imaging of the subsurface.

Gravity surveys have been flown under a variety of conditions by both fixed wing aircraft and helicopters. Fixed wing aircraft, in most cases, are not required to fly at constant altitudes, as the systems are relatively tolerant during turbulence and will operate well in drape surveys and in moderate turbulence, and altitude corrections to the raw data are subsequently made. Helicopter systems provide much more of a challenge in comparison to fixed wing platforms because helicopter motion is less stable and require more complex systems. Sander Geophysics Ltd. has flown production surveys with the AIRGrav system under a variety of conditions including offshore, at a constant altitude over rolling terrain and with a loose drape over high mountains (>3,000 m). As the systems are relatively tolerant during turbulence, they work well in drape surveys and in turbulent conditions (http://www.sgl.com/gravity.htm).

Applicability to Programme

Airborne gravity surveys can help define large, deep, underlying structure regardless of the degree of exposure in the survey area. Gravity changes reflect a change in density of particular geological units. Gravity data provides useful insight into spatial distribution and geometry of bodies of rock and also the presence of faults and folds. Information from an airborne gravity survey is important as the data can be used in conjunction with other airborne methods, especially airborne magnetic data, to model geologic structure.

Processing and QA/QC

Processing of airborne gravity data is complex and varies between scalar and full tensor designs and from system to system, even within manufacturers. As such, all processing techniques are not readily available.

The most important aspect of airborne gravity surveying is to remove noise and the effects of aircraft motion. This can be done inherently in systems by their design, i.e., quality of the stabilised platform and gyros, or by post processing. Processing gravity data to remove noise can be performed in a variety of simple ways including filtering and gridding, and subsequent adjustments at crossover points.

New approaches that combine several pre-processing steps, including filtering, gridding and adjustment of crossover misfits, with parameter estimation, are currently being developed at the Technical University of Delft (Alberts et al., 2007). The approach is based on a spectral representation of the gravity field. The gravitational potential is parameterised as a linear combination of harmonic functions, which are fundamental solutions of Laplace's equation in Cartesian coordinates. The parameters of this representation are estimated using least-squares techniques. Rather than apply low pass filtering to suppress the noise, new processing methods use frequency dependent weighting to handle observation noise. Therefore, the concept of filtering is replaced by frequency dependent data weighting; frequencies at which the noise is high get a lower weight than those at which the noise is small, but the signal is preserved. Other methods include, in the full tensor system case, using tensor components to remove noise.

Once the measured gravity values, scalar or tensor, have been obtained, the general processing includes a number of corrections that are applied to the data including:

- Drift correction;
- Theoretical normal gravity correction;
- Airborne Eötvös correction;
- Latitude correction;
- Free-air anomaly correction;
- Bouguer correction; and
- Terrain correction.

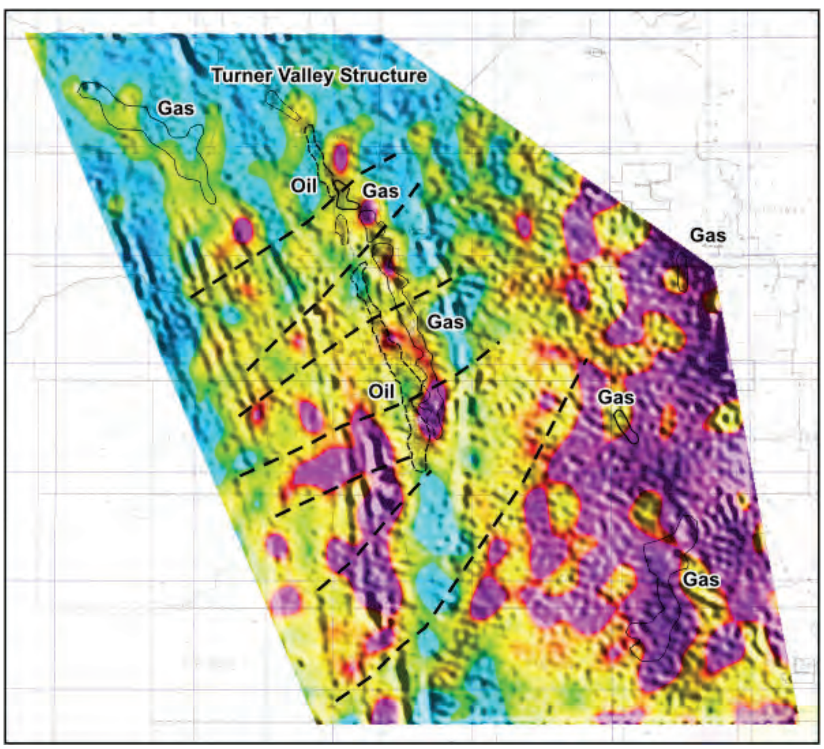

Figure 4-13: Airborne gravity survey example from Turner Valley, Alberta, Canada. (Sander Geophysics Ltd.)

Figure 4-13 illustrates the use of airborne gravity in oil and gas exploration in Western Canada. The first vertical derivative of the terrain corrected Bouguer gravity is shown with the shadow of the first vertical derivative of the total magnetic intensity.

After these processes have been carried out, the data are levelled and gridded. Gravity data can be manipulated to produce a number of different products. Further processing can be conducted and this may include downward continuation, which is a popular technique that can help enhance smaller geologic features. Conversely, upward continuation can better show broad geologic features. Gravity data when used in conjunction with magnetic data can help better model geologic features.

The quality of gravity data depends heavily on measurements of and accurate corrections for noise. While some systems are inherently better than others, care needs to be exercised when assessing the amount of turbulence a survey flight could have. Processing techniques can be complex so while direct processing of raw data is straightforward, quality control of contractor's methodology and their adherence is important.

Typical Accuracies and Resolution of the Acquired Data.

Resolution depends on aircraft type and ground speed, type of system and to a point, the processing steps performed and is quoted as varying from 700 to 4,000 m. With a fixed wing aircraft, flown at 175 km/hr, anomaly resolution using a GT-1A survey is quoted as being of the order of 2,000 m. Although sampling rates can be quite high, they do not match resolution. Airborne gravity is considered a more broad geophysical technique and resolutions in the range of a kilometre should be expected. Tests with realistic noise models have shown that the geoid[1] may be determined from airborne measurements at centimetre accuracy. RMS accuracy of the acquired data is generally quoted as 0.2 mGal and anomalies as small as 2 mGal can be observed in the data.

Limitations and Constraints

The limitations and constraints are generally those of topography and poor resolution of the data.

Strengths and Weaknesses

Gravity data can be used in interpreting other geophysical data sets and in modelling. The dependence of gravity measurements on accurate stabilisation and the ability to monitor relative motion can hinder surveys during times of turbulence. Processing techniques are complex and often cannot be processed independently. Complicated systems can be unreliable and could delay field operations.

Potential to Combine Technologies

Airborne gravity surveys are often conducted in association with EM surveys. As mentioned previously, any of the other geophysical systems may be flown in conjunction with airborne gravity surveys, depending on the lift capacity of the aircraft.

[1] The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level

Commercial Availability

The survey methodology is available from a small range of survey companies in the Canadian market including:

- Fugro Airborne Surveys;
- McPhar Geosurveys Ltd.; and
- Sander Geophysics Ltd.

Time Scales

Gravity surveys, like many other airborne methods under ideal conditions, can cover considerable areas and can be conducted in a short amount of time. Processing gravity data, especially in full tensor systems, is quite involved and may require more time than other methods, certainly on the order of months. Further processing such as downward continuation requires minimal time and would not add greatly to the basic processing time. Modelling using gravity data can be very time consuming and magnetic or other data sources are required to develop meaningful models.

5. GROUND BASED SURVEYS (DEEP)

This section describes a range of deep ground based geophysical surveys that may be applied during a site screening and characterisation programme. Methodologies discussed include seismic reflection (2D and 3D), gravity, electromagnetic (EM) and magnetic surveys.

5.1 Seismic Reflection Surveys

Seismic reflection surveys can generally be subdivided into two categories which are:

- 2D seismic reflection; and
- 3D seismic reflection.

The differences in these two categories are essentially the acquisition geometries, the amount of equipment used to acquire the data, data volume and the processing and interpretation methodologies. However, the principles used are essentially the same.

In general, the discussion that follows looks at the acquisition of data to provide information on the geological structure of the subsurface to depths of several thousand metres (Figure 5-1). However, the techniques can be used to provide information to much shallower depths and are used to provide high resolution data in the top 100 m where detailed information is required.

Brief Description

A seismic reflection survey is used to map geologic structure and/or stratigraphic features. Measurements are made of the arrival time of events attributed to seismic waves that have been reflected from interfaces where changes in acoustic impedance occur. The objectives of the survey methods in a site screening programme include mapping/imaging the depth, dip and strike of the bedding and lateral changes in the reflectors that may indicate structural changes (e.g. faults). In 3D and 4D surveys, the objective may be to monitor changes in fluid content and levels over time; this is done, for example, in producing hydrocarbon reservoirs.

The seismic reflection method involves placing a series of motion (velocity) detectors (geophones) or groups of geophones along a line and connecting these to a geophone cable and/or relay unit which in turn connects to recording instrumentation. The geophones convert the ground motion to a voltage and this is recorded as a function of time. A detailed description of all of the basic principles of the seismic reflection method is beyond the scope of this report, but can be found in Telford et al. (1990) and Yilmaz (1987).

For a 3D survey, many geophones and groups of geophones are laid out on the ground surface generally over a regular 2D grid. The source used to generate the seismic waves on land can be one of a number of different types that include:

- Explosives;
- Vibrators or Vibroseis vehicles; and
- Land air guns (less likely to be used for a survey).

The acquisition of 2D data typically utilises Vibroseis vehicles or shot holes (for the explosives) that are located in line with a geophone array, and are used as the vibrational energy source.

For each "shot record", vibrational energy is transmitted into the ground and the received energy is recorded simultaneously at a group of the geophones for a period of up to several seconds. Only geophones at particular locations around the shot point are "live" and record data for a particular shot record. This is done for practical reasons, as not all geophones are required for a particular recording, and the number of receiver channels that can be recorded at once is limited. As the survey progresses, the shot point is moved and a new group of geophones (in the required geometric position) are selected for recording; this is called "rolling" through the spread.

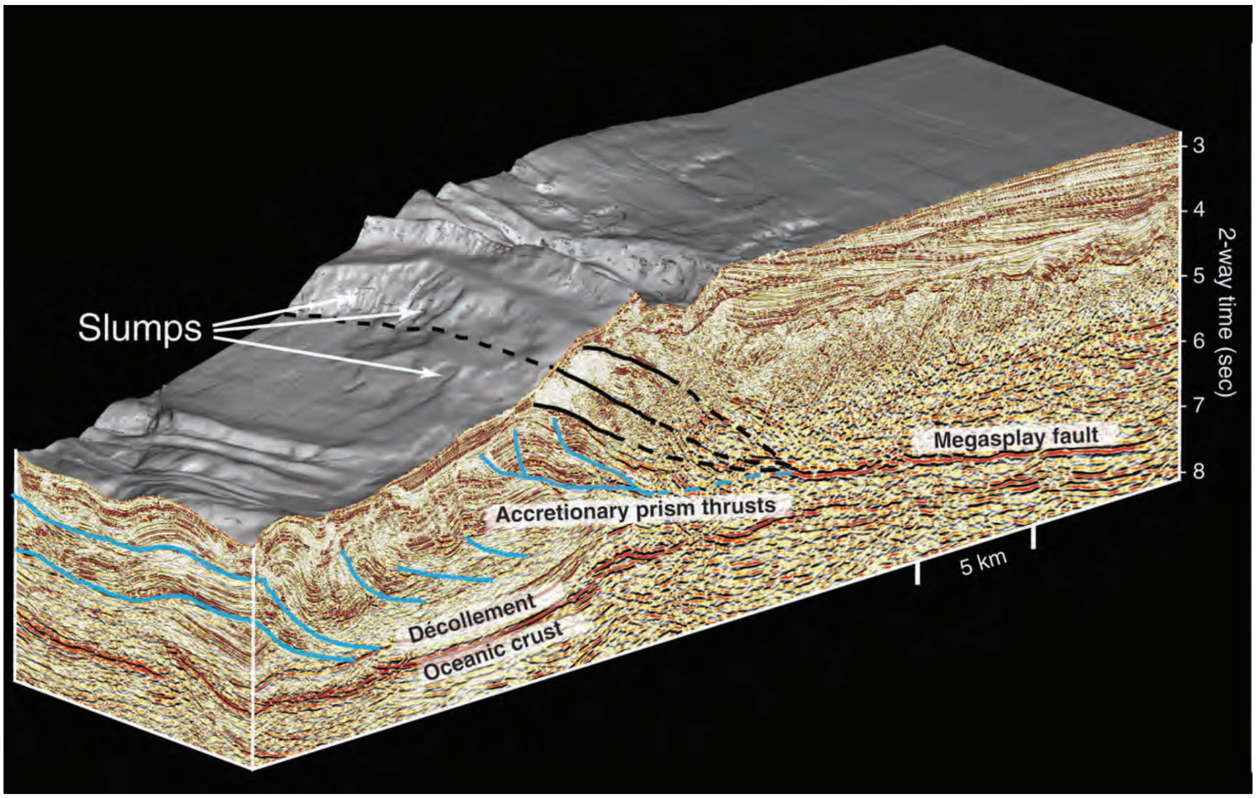

Figure 5-1: A 3D seismic data example from the Nankai Trough. (G. F. Moore et al. 2007, Science 318 (5853), 1128)

The survey is designed so that a sufficient number of seismic traces are recorded in "bins" that have a common mid-point or CMP, at the target horizons. The traces are later corrected during processing to a zero source-receiver offset; this is called a normal moveout or NMO correction. These NMO corrected traces are the summed together or "stacked" into a single trace for that CMP.

Stacking increases the signal-to-noise of the traces, by reinforcing the reflected signal and cancelling unwanted signals and noise. The number of traces that are stacked for a particular bin is called the CMP "fold". The technique of stacking multi-fold seismic reflection data is arguably the single most important advancement made in seismic reflection since the inception of the method.

3D seismic reflection surveys follow the same principles as a 2D survey, except that the collinear geophone array and shot points are replaced with a 2D grid of geophones and a 2D grid of shot points, resulting in 3D subsurface coverage.

Recent developments in seismic acquisition include the use of a wider range of source-receiver offsets for each CMP. These are referred to as Wide Azimuth and Rich Azimuth surveys; additionally there are Full Azimuth surveys, but these are often difficult to acquire on land due to access restrictions and associated costs. The acquisition of data sets with a range of offsets and azimuths (3D) allows for a range of additional processing methodologies and studies that, while not routine, may be useful in a site screening or characterisation programme. These include amplitude variation with offset (AVO) and amplitude variation with azimuth (AVA).

Applicability to Programme

2D and 3D seismic reflection surveys are likely to be one of the most important site screening and characterisation tools in a repository investigation, given the method's potential to obtain detailed subsurface information at depths ranging from 100 to 1,000 m or more. Due to seismic reflection's long history of development and application in a sedimentary rock environment, existing techniques can be applied to the sedimentary rock environment with little modification and great success.

Applying seismic reflection to a crystalline rock environment has been historically less common, but has the potential to be equally applicable with some adaptations. The key challenges in a crystalline rock environment are that the features of interest (typically fractures and different rock types) generate much weaker reflections than sedimentary rock layers, and these features are commonly not horizontally oriented, whereas sedimentary strata typically are.

Processing and QA/QC

The processing steps described below are typical examples of the processing performed on seismic data sets acquired on land. The principles of seismic reflection processing and interpretation can be found in Yilmaz (1987) and Yilmaz (2001). The processing of seismic reflection data sometimes utilises the results of seismic refraction surveys conducted along the same lines. Seismic refraction surveys are discussed in Section 6.1.

<u>2D Seismic Processing (Including Refraction Statics)</u>

The following is an example of a typical processing flow. Although references are made to specific software tools, the processing flow is a general one that could be followed using most seismic processing software platforms.

- Transcription from SEG-Y[2] to ProMAX[3] internal format.
- 2D CMP[4] crooked line where necessary binning geometry and trace data quality control (QC).

[2] SEG-Y is a standard format for recording geophysical data defined by the Society of Exploration Geophysicists.

[3] Interactive seismic processing software produced by Haliburton.

- Recording system response filter application and delay correction. Response filter designed from the geophone pulse test of each line.
- Polarity or phase correction for different source types.
- Spherical divergence correction.
- Time and offset varying gain correction or surface consistent gain and testing.
- First break suppression mute.
- Pre-filter testing (source cone noise filtering if necessary).
- First break picking.
- Trace edit.
- An initial elevation static correction would be applied and if available including Low Velocity Layer (LVL) for V0 (initial velocity).
- Pseudo 3D global refraction static analysis and application to final datum using Green Mountain Millennium Suite refraction statics software. This process includes LVL and deep uphole data (assumes explosive source rather than a vibrator source) in the near surface refraction model and, if available, one and two layer models derived from the first break picks.
- Pre-stack shot and receiver domain F/K[5] filtering and application if necessary.
- Pre-stack deconvolution and testing.
- 2D NMO[6].
- Initial 2D interactive velocity analysis.
- Moveout stretch muting interactively picked from corrected shots.
- Automatic residual statics surface consistent corrections and algorithm testing.
- Second 2D interactive velocity analysis.
- Automatic residual statics surface consistent corrections and algorithm testing.
- First miss-tie check using Kingdom interpretation software.
- 2D DMO[7] and testing of DMO parameters.
- Further 2D interactive velocity analyses to include re-pick at first velocity function locations with further intermediate locations where required to improve reflection continuity adjacent to target geological structure.
- 2D CDP[8] DMO stack.
- Time variant bandpass filter and testing.
- Post stack linear noise testing and attenuation if necessary.
- Post stack random noise testing and attenuation if necessary.
- Second miss-tie check using Kingdom interpretation software.
- 2D post stack time migration using time interval velocities derived from the RMS[9] stacking velocity functions.
- Station post stack interpolation if necessary.
- Time variant equalisation.
- Archiving of 2D stacks to CD ROM in standard SEG-Y format.

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[4] CMP – Common Mid Point

[5] F = frequency K = wavenumber.

[6] NMO – normal moveout

[7] DMO – dip moveout

[8] CDP – common depth point

[9] RMS – root mean square

Additional Processing that could be considered at additional cost may include:
- Pre-stack 2D time migration.

3D Seismic Processing (Including Refraction Statics)

The following is an example of a routine processing route:

- Transcription from SEG-D[10] to ProMAX internal format.
- 3D CMP binning geometry and trace data QC.
- Spherical divergence correction.
- Time and offset varying gain correction or surface consistent gain and testing.
- First break suppression mute.
- Pre-filter testing (source cone noise filtering if necessary).
- First break picking.
- Trace edit.
- An initial elevation static correction would be applied and if available including LVL (Low Velocity Layer) for V0. After completion of post stack time migration of the elevation static volume, 3D refraction statics analysis would be carried out.
- 3D refraction statics analysis and application to final datum using Green Mountain Refraction statics software. This process includes LVL and deep uphole data in the near surface refraction model and a two layer model derived from the first break picked. The LVL and deep uphole data (assumes an explosive rather than a vibrator source) would be examined for quality and effectiveness.
- Pre-stack shot and receiver domain F/K filtering testing and application if necessary.
- Pre-stack deconvolution and testing.
- 3D NMO.
- Initial 3D interactive velocity analysis on a 500 metre by 500 metre grid.
- Moveout stretch muting interactively picked from correct shots.
- Automatic residual statics surface consistent corrections and algorithm testing.
- Initial 3D interactive velocity analysis on a 500 metre by 500 metre grid.
- Automatic residual statics surface consistent corrections and algorithm testing.
- 3D DMO and testing of DMO parameters.
- Further 3D interactive velocity analyses to include re-pick at first velocity function locations with further intermediate locations where required to improve reflection continuity adjacent to target geological structure.
- 3D CDP DMO stack.
- Time variant bandpass filter and testing.
- Post stack linear noise testing and attenuation if necessary.
- Post stack random noise testing and attenuation if necessary.
- 3D post stack time migration using time interval velocities derived from the RMS stacking velocity functions.
- Time variant equalisation.
- Archiving of 3D volume to CD ROM in standard SEG-Y format.

[10] SEG-D is a standard format for recording geophysical data defined by the Society of Exploration Geophysicists.

Additional processing that could be considered, at additional cost, may include:

- Pre-stack 3D time migration.

The processing of either 2D or 3D data are documented in a processing report to include detailed account of processes and their testing and evaluation of seismic data target quality.

Processing reports typically include:

- All QC processing plots;
- QC interim stacks (2D data);and
- Seismic attribute plots and maps.

Interpretative Processing

There is a large range of additional processing work that can be carried out on 3D data sets that is often interpretative in nature, as an example, the CGG (CGG have now merged with Veritas forming CGGVeritas) code FracVista is briefly reviewed. This processing can be used to look at layer based velocity anisotropy. This inversion process can provide information on the direction and intensity of the anisotropy (anisotropy being an indicator of rock fabric/layering and/or fracture direction) and can be used to develop anisotropy parameter maps. Having developed layer based maps the results can be used to develop Discrete Fracture Network (DFN) models, assuming that the anisotropy is fracture related. Having generated a DFN model, a finite element flow grid can be utilised for the simulation of pressure transients (information provided by the hydrogeological testing programme – hence linking two of the strands of any future investigation programme). This modelling leads to the generation of grid scale permeability values for the subsurface, which can be used in reservoir modelling codes which can, in turn, be used to understand fluid flow through the system under investigation.

A similar, but structurally based approach can be developed using codes such as Ikon Sciences' FaultX, but instead of developing models based on geophysical or mathematical parameters, this can be considered to derive models based on geologic interpretations derived from the geophysical data. FaultX started development in the mid to late 1990s and is used to consistently pick faults in 3D data sets. It is often considered that if the same data set was provided to different seismic interpreters they would generate different interpretations, although it would be anticipated that the major features would be the same; this code attempts to remove the interpreter bias from the process. Once a 3D volume has been analysed and fault trace maps have been generated, these can be used to generate DFN models and then to allow pressure transients to be modelled in a geologically realistic system. The eventual aim is the generation of data sets that can be used in reservoir modelling codes.

What has not been tried to date is a combination of the two techniques, which may be a powerful modelling approach. DFN models could be constructed using deterministic or quasi-deterministic features derived from the FaultX analysis, while the FracVista inversion providing the more stochastically derived information, although this being more deterministic in nature.

Seismic Interpretation Validation

Having produced a seismic interpretation using either automated programmes or the expert judgement of the seismic interpreter, these are likely to be challenged. Therefore, a further consideration in the 3D seismic process is validation. Structural validation, restoration and analysis should be carried out to demonstrate the robustness of the earth model. The leading industry code for this type of work is considered to be the code 3DMove produced by Midland Valley. The code can be used for in depth structural analysis and for all tectonic regimes. One of the other benefits of using this code is the provision of strain analysis information that could form an input to the geotechnical model for the site.

Seismic Inversion

There are a number of inversion codes that can be used to extract further information from seismic data. This is a large subject area and a detailed analysis of all the available codes is beyond the scope of this document and is perhaps not relevant in site screening. However, significant quantities of data can be derived from the inversion of seismic data, for example porosity volumes and dynamic rock mass property information. These volumes can be used to predict the results from other investigations. They can also be used to test the conceptual models and understanding of the site under consideration.

As an example of available technology providers Hampson Russell (which is a CGG Veritas company) produces a number of different codes. For example:

- AVO used for the analysis of Amplitude Variation with Offset which is used to look at fluid content.
- EMERGE can be used to predict petrophysical logs from other logs and can be used to predict petrophysical logs from seismic attributes. The code uses both the seismic attributes and the well log properties to derive reservoir properties. Using the seismic data 23 instantaneous attributes may be derived.
- ISMAP, a geostatistical mapping tool designed for the comparison and statistical analysis of mapped data sets.
- STRATA, a seismic inversion code designed to transform post stack seismic volumes to impedance traces for lithology and fluid determination.

From this list of codes available from just one provider, it can be seen that in general these are focused on the determination of reservoir properties. But in site screening and eventual site characterisation it will be necessary to determine and understand the lithologies present and be able to extrapolate these between the wells where hard data are acquired. It will also be necessary to understand the fluids present, in the investigation phase it is likely that this is going to be water but at later stages, following closure, a gas phase may be generated and it will be necessary to discriminate between the two fluid types.

A further consideration is the stage at which the seismic attribute analysis work is carried out. Traditionally, codes are applied post stack however, there are codes that use pre-stack data volumes. For example LithSeis combines advanced well log analysis with pre-stack seismic data to accurately determine volume based lithology, porosity and pore fluids. The developers of the software state, that by extracting lithological measurements from the seismic data before stacking, results in a more accurate rock based description of the subsurface.

An example of how data sets can be integrated is the application of the Ikon Science code now called RokDoc-Chronoseis which provides a method of integrating seismic interpretation, geology, rock physics and 3D seismic inversion and provides a method for predicting borehole derived data sets and logs.

Research

The main acquisition methodologies do not change radically, however, processing and interpretative processing are ever evolving. An example of one of the topics being investigated is seismic interferometry (nomenclature borrowed from astronomy) which is briefly outlined below.

Without going into detail, seismic interferometry refers to the principle of generating new seismic responses by cross-correlating seismic observations from different receiver locations to reconstruct the Earth's reflection response. The use of these methodologies also appears to provide a method for imaging in the presence of clutter (noise). This may be important, depending on the geological setting where the survey is being conducted. In some areas the reflected energy field may be both scattered and noisy to a greater extent than in other sequences or areas. This method therefore suggests that reliable imaging may be possible in the presence of the noise, although with some loss of resolution. Additionally, where the velocity structure of the "near surface" is not well known, the accompanying defocusing and distortions in the data can be reduced or removed without the need for a complete knowledge of the velocity structure.

Other ongoing research includes work being conducted at the Centre for Modelling Petroleum Reservoirs at the Technical University of Lisbon where new seismic inversion codes have been developed that use an inverse modelling approach, which aims to generate final seismic images that reflect the quality of seismic data through the uncertainty associated with the Final Seismic Impedance Cube.

The research highlighted illustrates the main fundamental that processing technology is consistently progressing forwards, driven primarily by the hydrocarbon industry. Consequently, through the life of any project, which may take a number of decades, particularly if the data are to be used for time lapse studies, it must be recognised that it may be necessary to reprocess and re-interpret the data sets on a (semi)regular basis.

Typical Accuracies and Resolution of the Acquired Data

The resolution of the seismic reflection method is frequency dependent and is also dependent on the velocity of propagation of the seismic wave through the rock mass. This is because the resolution of the method is dependent on the wavelength of the seismic wave and wavelength = velocity/frequency. The resolution of the method is further complicated by the fact that the seismic wave travels from the source (on the surface or at shallow depth) to a reflecting horizon at depth and then returns to the surface where it is recorded. The distance travelled by the wave (the ray path) affects the frequency content of the recorded signal; the longer the ray path the greater the attenuation of the high frequencies and thus the resolution will decrease with depth. (This is termed the convolution of the source signature with the earth response and one of the objectives of processing is to deconvolve the signal to obtain the earth response.)

For most deep seismic reflection surveys, the resolution of near surface features is typically poor, owing to the fact that the stack fold is low. Hence, there is an optimal depth interval below the surface where the stack fold is sufficient to yield good data, and it is not so deep that significant frequency attenuation has taken place. For typical deep seismic reflection surveys, this optimal depth interval is in the range of 300 m to several kilometres, noting that surveys can be tailored to focus more on the near surface, or deeper features, as required.

Seismic reflection data acquired on land (Vibroseis or explosives sources) are unlikely to achieve frequency contents at probable target depths in excess of 200 Hz. The general expectation would be in the region of 30 to 150 Hz. However, it is known and has been demonstrated that where crystalline rocks are exposed at the surface or are very close to the surface the frequency content of the data may be considerably higher, this has been observed in the investigations in Scandinavia (e.g., Finland), logic therefore suggests a similar situation may occur in Canada. Therefore, the limits on vertical resolution should be in the following ranges, assuming the lower frequency contents:

- 120 to 160Hz **2D** 3 metres, **3D** 2 metres; and
- 30 to 50Hz **2D** 15 to 20 metres, **3D** 5 to 15 metres.

However, it must be considered that the lower frequency content (thus the lower resolution) is to be expected in general.

It should also be considered that the accuracy of the methods is dependent upon the ability to accurately estimate the velocity model of the subsurface, as this will affect the migration of the data conducted during processing. Where the velocity model has lower confidence levels, the migration of the data may be less accurate resulting in the misplacement of the energy and data, the smearing of the reflection and the inaccurate positioning of the reflection event. In 3D space, therefore the accuracy of the method is diminished. This is perhaps more apparent in 2D seismic reflection surveys where out of plane effects caused by lateral velocity changes cannot be quantified. While it is easier to model the lateral velocity changes in 3D data, the velocity model is based on a “grid” basis and this depends on the extent or amount of the velocity analysis conducted.

There are processing methods for improving the imaging and thus the accuracy and resolution but these require additional processing steps that do not usually form part of the routine processing flow. Examples of such processing include the Multifocusing™ technology provided by Geomage and the common reflection surface stack methods provided by TEEC.

Limitations and Constraints

The limitations and constraints for land based seismic surveys are generally those determined by factors such as land access, the presence of buildings and topography of the survey area. In areas of rugged topography the quality of the seismic data can be adversely affected. Where buildings, villages or towns exist these also have detrimental affects on the acquisition and hence the data quality. Even in volunteer host communities, there are likely to be objections and complaints resulting from the vibration levels and vehicle movements. Depending upon the type of source used for the survey there are likely to be areas that are inaccessible, such as woodlands where alternative source types may have to be used to fill the gaps.

Vibrations from vehicle traffic and machinery can also result in significant seismic noise. While this can in part be addressed by survey design and processing, it is still a significant issue. Further constraints in terms of archaeological sites and protected habitats and species are also likely to put constraints on a survey of this nature, perhaps more so for a 3D survey than a 2D survey. Additional constraints may be areas of permafrost which have been known to adversely affect the quality of the seismic data.

Strengths and Weaknesses

The main strength of seismic reflection imaging is its potential to resolve relatively small features at greater depths below ground surface than virtually any other geophysical technique. Its main weaknesses are the limited ability to detect features that have a small acoustic impedance and the limited ability to image features that are steeply dipping or near vertical (at least, from surface).

Potential to Combine Technologies

Seismic reflection surveys are sometimes, although not always, acquired in conjunction with gravity surveys, this is particularly useful and represents good practice in areas of complex geology where the gravity data can assist in the interpretation of the data. Some seismic reflection surveys use seismic refraction survey data to determine the velocity of the near surface materials, velocities that are not well resolved in reflection surveys (as this information is often muted in processing). The ability to combine the two seismic methods is likely to be dependent on the specific objectives for the seismic refraction survey.

Commercial Availability

The vendors listed below are members of the CAGC (Canadian Association of Geophysical Contractors) and typically conduct medium sized 2D and 3D seismic reflection surveys in Western Canada. They are listed in alphabetical order.

- CGG Veritas Land
- Conquest Seismic Services Ltd.
- Eagle Geophysical Canada Inc.
- Geokinetics Exploration Ltd.
- Geostrata Resources Inc.
- PGS Onshore (Canada) Inc.
- Polaris Explorer Ltd.
- Tesla Exploration

Time Scales

A reconnaissance 2D seismic reflection survey is expected to take on the order of 6 months to complete. A 3D seismic reflection survey can take on the order of a year or more to plan the survey, acquire the field data and process these data.

5.2 Gravity Surveys

A gravity survey is a series of measurements of variations in the Earth's gravitational field over an area of interest; this can be along profiles or on a grid basis depending upon the objectives of the survey. In site screening and characterisation programmes, the objective is to associate gravity variations with differences in the distribution of densities and hence of rock types, which can be used in geological modelling and as an aid to seismic interpretation. Gravity data are usually displayed as Bouguer anomaly maps.

Brief Description

The gravity technique is a natural source method, in which local variations in the density of subsurface strata cause minute changes in the main gravity field of the Earth. The basic principles of the gravity method are described in Telford et al. (1990). The method is fundamentally simple, but the minute changes that are measured require the use of highly sophisticated instruments and techniques.

A gravity survey is conducted using one or more gravimeters (Figure 5-2). Measurements are made of variations in the vertical gravitational field of the Earth, which involves measuring very small differences in the force field. Force is related to mass by an acceleration. The symbol ‘g’ denotes gravitational acceleration and is known simply as ‘gravity’. Gravity measurements are undertaken at pre-determined, sometimes closely spaced positions. The measurements reflect the Earth’s true gravitational attraction and the relative variations from one point to another are used to define the gravity anomalies.

The measured values of gravity depend upon latitude, elevation, topography of the surrounding terrain, tidal movements of the earth (earth tides) and lateral changes in the density distribution in the sub-surface. The last factor is the only one of significance in gravity surveying and its effect is generally very much smaller than that of the first four. It is necessary to remove these large systematic variations to obtain the net effect due to lateral density variations in the underlying strata.

Figure 5-2: The Scintrex CG-5 “Autograv” Gravimeter. (Scintrex Ltd.)

The accuracy and usefulness of the results obtained depend upon the quality and spatial frequency of the readings and on the interpretation of the data to isolate the effects of density variations.

All gravimeters change in null reading with time; that is, repeated readings at one station (termed a base station) over a period of hours will give a series of different gravity values. This change is the result mainly of creep in the meter, which under ideal static conditions is unidirectional, but is also a result of earth tides. Gravimeters respond to the gravitational attraction of the Sun and Moon and registers the periodic variations in the attraction caused by movement of the Earth with respect to these bodies. The Earth is acted upon by these tidal forces and is deformed in a similar way to a free water body. This displacement causes small but measurable changes in gravity. These are long wavelength effects that are easily removed using a drift curve. Earth tides can also be calculated theoretically if the elastic response of the earth is known or can be estimated. It is imperative, therefore, to re-occupy the base station periodically during the day, in order to produce a drift curve for the instrument, which takes into account the effects of these variables. After the value of gravity has been obtained at the base station, the points on the survey profile or grid can then be occupied and the value of gravity obtained at these positions. The base station must be re-occupied at approximately 60 minute intervals and also at the beginning and end of all periods of data acquisition. To maintain precision each point must be surveyed in and levelled to an appropriate accuracy (1-2 millimetres) relative to the base station. For large scale regional surveys of the deep geological environment, the use of base stations alone to correct for drift is not adequate, so reference measurements are also made at points where the value of gravity is known.

Applicability to the Programme

Gravity data can be very useful in providing insight into deeper geological structures in a site screening or characterisation programme. In particular, gravity data are very complimentary to other data sets in developing a geosphere model, and are often acquired to support the interpretation of seismic or magnetic surveys, for example.

Processing and QA/QC

Gravity data processing requires a number of steps to be carried out and needs strict quality control throughout the process. The first step in the processing sequence is to average the measured readings obtained from the gravimeter; any inconsistent data being rejected at that stage. Corrections are made to account for drift, by applying the drift curve acquired during each day which takes account of instrumental changes and the effects due to Earth tides.

It is necessary to apply a latitude correction where there is an appreciable north-south excursion of the stations. This correction is linear over distances of one to two kilometres. As gravity varies inversely with the square of distance, it is necessary to correct for the relative changes in elevation between stations so that all field readings are reduced to a datum surface. This is accomplished by applying an elevation correction to each data point, which consists of two parts:

- The Free Air correction; and
- The Bouguer correction.

The Free Air correction is based on the fact that the external gravitational attraction of the earth as a whole can be considered to be the same as if it's mass were concentrated at its centre. If the distance between the point of observation and the centre of mass changes from station to station, this effect must be removed. This is independent of whether or not there is any rock or soil material between the datum and the station's elevation. The Free Air correction is added to the field readings when the station is above the datum and subtracted when below.

To take account of the attraction of the material between the station and the datum, which is ignored when applying the Free Air correction, a Bouguer correction is applied to the data. An assumed density difference (in gcm^{-3}) is used for the calculation of the Bouguer correction in data processing. An example of a Bouguer anomaly contour map is shown on Figure 5-3 below.

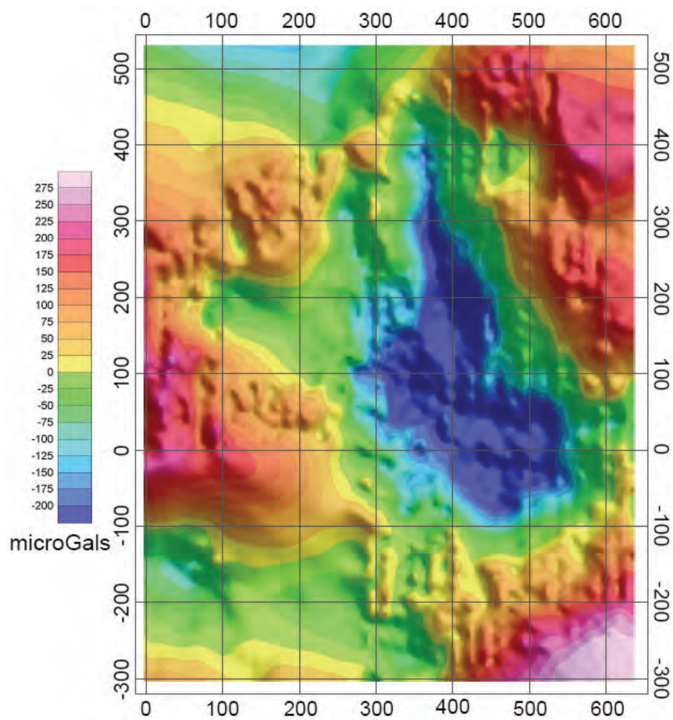

Figure 5-3: A microgravity survey example in karst terrain. (Golder Associates Ltd.)

Terrain corrections are of critical importance to the processing of gravity data where abrupt changes in topography or terrain are encountered within or around the survey area as this will have a significant affect on the measured data. The terrain correction is calculated using a digital elevation model (DEM). The gravitational effect of the DEM is calculated and removed from the data.

This routine processing flow can be summarised as:

- Averaging of the measured readings obtained from the gravity meter;
- Drift corrections;
- Latitude correction (where applicable);
- Elevation correction (which consists of parts);
- Free Air correction;
- Bouguer correction; and
- Terrain correction.

Strict quality controls are used at all stages during processing. Having completed the above sequence of processing steps, the Bouguer gravity values for the stations are presented as maps and may be further processed as required. Additional processing may include downward continuation, Euler deconvolution, inversion and modelling.

Typical Accuracies and Resolution of the Acquired Data

The results of a gravity survey are generally presented as Bouguer anomaly maps. In theory any given anomaly can result from a small feature at a shallow depth or alternatively a larger feature at greater depths, as there can be a multiplicity of solutions in terms of size and depth of a causative feature for a given relative density. However, through modelling and inspection of the shape of the anomaly and the gradients seen in the data, it is possible to model size, depth and shape of the causative feature.

The accuracy and resolution of gravity data is generally a function of a number of factors including the instrumentation used, the accuracy of the topographic survey, the methods used to acquire the data and also the method used to determine the drift and earth tides. With respect to the equipment, the gravimeter selected for the survey will also have an affect on the accuracy and resolution of the acquired data. The meters with the highest precision are microgravity meters such as a Scintrex CG-5 that are quoted, by the manufacturer, as having a reading resolution of 0.001 milligals; this is determining absolute value of ‘g’ to a precision of 1 in 10^{10} of the Earth’s gravitational field. Many readings are taken in rapid succession over a period of minutes and averaged, with the measurement error reported in terms of the standard deviation of the reading. Such instruments are generally used to locate “small” cavities in the top 100 m below surface.

Other instruments are available that have reading resolutions of 0.01 milligals and are perhaps more appropriate for regional geological studies. Instruments that are in general use include those made by Scintrex and also LaCoste and Romberg; other instruments are also available.

Limitations and Constraints

Land-based gravimeters are very sensitive to spurious vibrations, which can be caused by wind, automobile traffic, wave action, machinery and precipitation, to name a few sources, particularly if for microgravity surveys. These factors will affect data quality and acquisition rates.

Large earthquakes can cause gravimeter oscillations for several days, even if the earthquake occurs thousands of kilometres away from the survey area. In areas of rugged topography the quality of the gravity data can be adversely affected, as modelling the effects of the topography to apply the Terrain Correction is more complex. The need for highly accurate elevation surveying can also be a limiting factor, particularly in forested areas where surveying with traditional or GPS methods is difficult. and can be costly.

Strengths and Weaknesses

The main strength of a gravity survey is that it measures a unique physical property, that is, local density variations in the subsurface. This makes it very useful in constraining the results of geophysical models based on other physical properties, such as electrical conductivity or seismic velocity.

Potential to Combine Technologies

Although there is no potential to combine technologies, gravity data are very complementary to other data sets in developing a geologic model, and are often acquired to support the interpretation of the seismic or magnetic survey results. Because gravity and magnetic fields are related through a mathematical relationship known as Poisson's Relation, if the same body causes both fields it is possible in those circumstances to perform joint interpretation.

Commercial Availability

There are a number of specialised geophysical contractors that offer land based gravity surveys in the Canadian market. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Fugro Ground Geophysics;
Golder Associates Ltd.; and
Hayles Geoscience Surveys Ltd.

Time Scales

A medium sized gravity survey can require one to several months to complete, and require approximately one month to process.

5.3 Electromagnetic Surveys

Electromagnetic surveys are carried out in either the time domain or the frequency domain. In general, time domain EM measurements are undertaken to provide deep information on the electrical conductivity of the subsurface, while frequency domain surveys are generally used to investigate the shallow subsurface. In this section, the discussion focuses on the "deeper looking" time domain EM methods, while the shallower frequency domain methods are discussed in Section 6.4. The basic principles of EM methods are described in Telford et al. (1990). Further background on time domain and frequency domain EM can be found in McNeil (1980a, 1980b and 1994)

Brief Description

Time domain EM techniques (also TDEM or TEM) are designed to determine variations in electrical conductivity with depth, usually assuming horizontal layering. Measurements are typically made at several time intervals after a transient pulse has been transmitted and generally use a fixed source and receiver.

The principle of time domain EM involves a transmitter sending a current pulse into a loop of wire or metal plates buried in the ground, or the use of naturally occurring fields. The artificial waveform of the current pulse may be a pulse, a step function, ramp or other form which can be considered non-periodic.

Measurements are made when the primary field has stopped changing or has been switched off. While the current is on, a static magnetic field is generated within the subsurface. When the current pulse is switched off, the static magnetic field collapses and induces eddy currents in the earth below the transmitter. By measuring both the magnetic and electric fields at different frequencies, an interpretation of the structure of the subsurface in terms of earth resistivity is obtained.

A number of additional methods fall in this category of electromagnetic methods, these include magnetotelluric methods (MT), audio magnetotelluric methods (AMT) and controlled source audio magnetotelluric methods (CSAMT). The source of the first two is naturally occurring spherics and micro-pulsations, while the source used for the CSAMT method is a man-made signal. These three systems produce or rely on plane wave electromagnetic fields; therefore for CSAMT surveys, the measurements are made in the far field where the generated signal approximates to a plane wave. Of these methods, it is likely that the CSAMT technique may be applied during site screening or characterisation investigation or standard TDEM methods may be more appropriate, with the selection being based on the precise objectives and the required depth of investigation. The advantages of the methods are that the measurements of the secondary field are generally made when the primary field is not present and that the measurements of the secondary field as a function of time are equivalent to continuous wave measurements made over a wide frequency range.

Ground based TDEM methods have the advantage over airborne TDEM methods of generally being able to investigate the subsurface to greater depths. These deep TDEM systems can be utilised for general geologic exploration and site characterisation. Shallower targets include fresh water aquifers, saline water intrusions and mapping groundwater contaminant plumes. At greater depths, targets include mapping the thickness of aquifers, clay layers, assessing water quality, mineral exploration, groundwater exploration, mapping saline intrusions, geothermal exploration and general geological mapping.

Surveys are often conducted as profiles or on a (quasi)grid basis, depending on land access and the presence of metallic objects.

Applicability to Programme

Electromagnetic surveys are probably most applicable to site screening and characterisation in a crystalline rock environment.

Processing and QA/QC

TDEM measurements are often made as soundings (i.e., providing information on the electrical conductivity with depth beneath the measurement point).

The data are processed using inversion or modelling codes to provide a horizontally layered earth model where the resistivity and thickness of each layer is determined. Where a non-layered earth is present the interpretation of TDEM data is more complex. For MT measurements, two apparent resistivity curves result from rotating the tensor impedance.

3D modelling and inversion codes are available to process these data. These are computationally intensive computer programs. Codes are also available to carry out joint inversions of the data with other data sets such as that derived from boreholes.

Typical Accuracies and Resolution of the Acquired Data

As with a number of geophysical methods the accuracy and resolution of the method is dependent on the quality of the data and the ability to invert or model the data appropriately. Further, there has to be a contrast in physical properties (electrical properties) between the target and the surrounding geology for the target to be imaged and modelled.

The modelling of data of this type generally suffers from “equivalence”. That is, without some other constraint, a number of similar models can fit the observed data equally well, so the modelling results are not unique. Take for example, a sounding where the measured data is modelled as a layered earth. Similar models can be generated that fit the observed data by changing the resistivity of the layers and simultaneously changing the layer thickness (e.g., a higher resistivity and a thinner layer would produce a similar response to a lower resistivity and thicker layer). This begs the question: which model is correct?

Fortunately, information such as drill hole data can be used to constrain layer thicknesses and resistivities in the model, such that meaningful and reasonably unique results are obtained from the sounding data, with accuracies that are of the order of metres to a few tens of metres, depending on depth.

Limitations and Constraints

EM methods are adversely affected by the presence of cultural features such as power lines, fences and other metallic objects, essentially any large conductor and in particular, a power source.

Earlier studies have also indicated that EM surveys can be affected by the sea and other large bodies of water. Survey results have been compromised by the coupling of the plane wave field generated by a CSAMT survey with a water body. However, recent developments include the use of electromagnetic methods in a marine environment and include shallow water applications.

Strengths and Weaknesses

Shallow EM surveys have good potential to map important near surface features such as faults. Deep EM surveys can be very useful in characterizing deep geologic structures, particularly in a crystalline rock environment. The main weaknesses are loss of resolution with depth, and the potential for man-made features to cause interference with the survey.

Potential to Combine Technologies

There is little potential to combine EM with other technologies due to the potential for electrical interference problems.

Commercial Availability

There are several companies that provide large scale EM surveys to the Canadian Market. These include two well known Canadian firms that provide services to the mining industry: Crone Geophysics and Exploration Ltd., which specialises in TDEM, and Phoenix Geophysics

Ltd., which specialises in CSAMT methods. There are several other capable vendors, although they are not explicitly mentioned.

Time Scales

It would take on the order of one month to complete a medium sized ground based EM survey and one to two months to process and model the data.

5.4 Magnetic Surveys

Land-based magnetic surveys are conducted using either magnetometers or gradiometers (two sensors one above the other separated by a fixed distance) (Figure 5-4). Site screening objectives of magnetic surveys are generally geological and structural mapping and the investigation of basement structure.

Brief Description

Magnetic surveys measure the magnetic field of the Earth at a point on surface. Magnetic surveys are acquired along lines or on a grid basis. Readings can be taken continuously in "walking" mode, or at fixed station points along the line. Magnetic field readings are measured in units of nanoTeslas (nT).

Figure 5-4: GSM-19 Overhauser "Walking Mag" (TerraPlus Inc.)

The basic principles of the magnetic method are described in Telford et al. (1990). The earth's magnetic field is dipolar, with the field directed vertically downward at the north pole, horizontal northward at the equator and vertically upward at the south pole. In Central Canada (50th parallel), the earth's magnetic field is approximately 60,000 nT in magnitude and is directed at an angle of about 65 degrees from the horizontal. Variations in rock type result in variations in the total magnetic field at any given point, which can be measured by the magnetometer survey and used to infer subsurface geologic structure, both shallow and deep.

Diurnal variations are caused by the spin of the Earth relative to the Sun, and result in cyclical changes over a 24 hour period. Other forms of variations are more erratic, and are caused by unpredictable changes in the Earth's field and solar magnetic storms. In practice, both types of variations can be corrected for by taking measurements at a base station, at regular time intervals throughout the survey or with a dedicated base station instrument, although magnetic storms can occasionally be so intense that it is necessary to suspend acquisition.

Applicability to Programme

A ground based magnetic survey is most applicable to a site screening and characterisation programme in crystalline rock, and will be an important follow up to any airborne magnetic survey.

Processing and QA/QC

Processing of magnetic survey data is relatively straightforward and usually requires merging the data with simultaneously recorded positioning data from a dGPS instrument, and then applying a base station correction for drift, based on synchronizing time stamps on the respective data sets.

The magnetic data are then gridded, contoured and presented as maps. Additional processing may include the calculation of horizontal or vertical derivatives, upward or downward continuation, or Euler deconvolution. Magnetic data can also be modelled using either forward modelling techniques or inversion.

Typical Accuracies and Resolution of the Acquired Data

The accuracy of the measurements are dependent on positioning accuracy and the accuracy and resolution of the instrument. Positioning accuracy with dGPS equipment is typically very good, and instrument resolution is also good, with repeatability better than 5 nT (0.01%). Readings can be averaged together over time to increase accuracy.

Regarding model accuracy and uniqueness, like many geophysical methods, magnetic models are most accurate when other geophysical methods or geological information can be used to help constrain model parameters, either geometric or physical property parameters.

Limitations and Constraints

The limitations of the method are effectively those related to land access and vegetation cover. Other factors affecting the results and data quality are those caused by the presence of ferro-magnetic materials or spurious electromagnetic fields within the sphere of measurement of the sensor; including pipes, power cables, power lines, vehicles and human settlement.

Strengths and Weaknesses

The main strength of the method is the ability to distinguish different rock types based on magnetic susceptibility, making it very useful in characterizing subsurface geology. The method is prone to interference from man-made features at surface, which may limit its usefulness on some sites.

Potential to Combine Technologies

This is a method that does not particularly lend itself well to being acquired simultaneously with other methods due to interference concerns, although the data set obtained by a magnetic survey can be useful when interpreted in conjunction with other geophysical data, including seismic, gravity and/or EM data.

Commercial Availability

There are a numerous geophysical contractors that undertake magnetic surveys in the Canadian market, predominantly for mineral exploration, but also for environmental studies. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Fugro Ground Geophysics;
Golder Associates Ltd.; and
Hayles Geoscience Surveys Ltd.

Time Scales

It would take on the order of one month to complete a medium sized ground based magnetic survey and approximately two weeks to process the data.

6. GROUND BASED SURVEYS (SHALLOW)

Ground based shallow geophysical methods are generally used for specific studies of small areas or sites. These may be required to provide high resolution information on particular faults in a Quaternary sequence, the engineering properties of the soil/rock at a site, or even to provide the depth to bedrock. The depth of investigation of the shallow surface based methods can generally be considered to be within 10 to 100 m of the surface. Whether these methods would be used in site screening is dependent on specific site objectives.

This section describes a range of shallow ground based geophysical surveys that may be applied during a site screening and characterisation programme. Methodologies discussed include seismic refraction, electrical resistivity imaging (ERI), ground penetrating radar (GPR), frequency domain electromagnetics (FDEM), spontaneous potential (SP), and induced polarisation (IP). References for further reading are provided at the end of this chapter.

6.1 Seismic Refraction Surveys

Seismic refraction methods are generally used to determine the depth to bedrock, infer structural information and also the ability to excavate material; these may be the objectives of surveys conducted as part of a site characterisation programme, in addition, the methodology may provide information on the biosphere.

Seismic refraction is used to map geologic structure by using head waves. Head waves involve energy that enters a high velocity medium (refractor) near the critical angle and travels in the high velocity medium nearly parallel to the refractor surface. The objective is to determine the arrival times of the head waves to map the depth to the refractors in which they travel.

Brief Description

The seismic refraction technique measures the seismic velocity of subsurface materials and models the depth to interfaces that exhibit a velocity increase. Soil conditions and geologic structure are inferred from the results, since changes in material type, or soil conditions, are often associated with changes in seismic velocity. Details of the method are described in Telford et al. (1990) and Butler (2005).

The seismic refraction method employs seismic energy introduced into the ground by a seismic energy source, such as explosives, a weight drop or sledge hammer. The seismic energy propagates through the earth as a wavefront that is refracted by higher velocity material through which it passes, resulting in changes in the direction and speed of the wavefront. As the wavefront intersects a high velocity interface, a “head wave” is created that travels in the higher velocity material nearly parallel to the refractor. The energy in this head wave is continually re-radiated from the interface and passes back through the low velocity material to the surface (see Figure 6-1 below).

An array or spread of seismic motion (velocity) detectors (geophones) are placed at selected intervals along the ground surface, the geophones often but not always have variable spacings with closer spacings near the ends of the line. The geophones detect ground motion or velocity (with the motion converted to an electric signal) that is transmitted via a cable to a seismograph where it is recorded. The seismograph is initiated either by a trigger switch mounted on the seismic energy source or by the use of a "shot" geophone situated by the shot point. The seismograph digitises and amplifies the incoming signals thereby recording the arrival time of seismic waves propagating from the source, through the subsurface and returning to the geophones. Seismic wave amplitudes are recorded by a seismograph as a function of travel time, measured in milliseconds. The objective is to determine the arrival times of these refracted waves in order to calculate the velocity of the material and model the depth to interfaces.

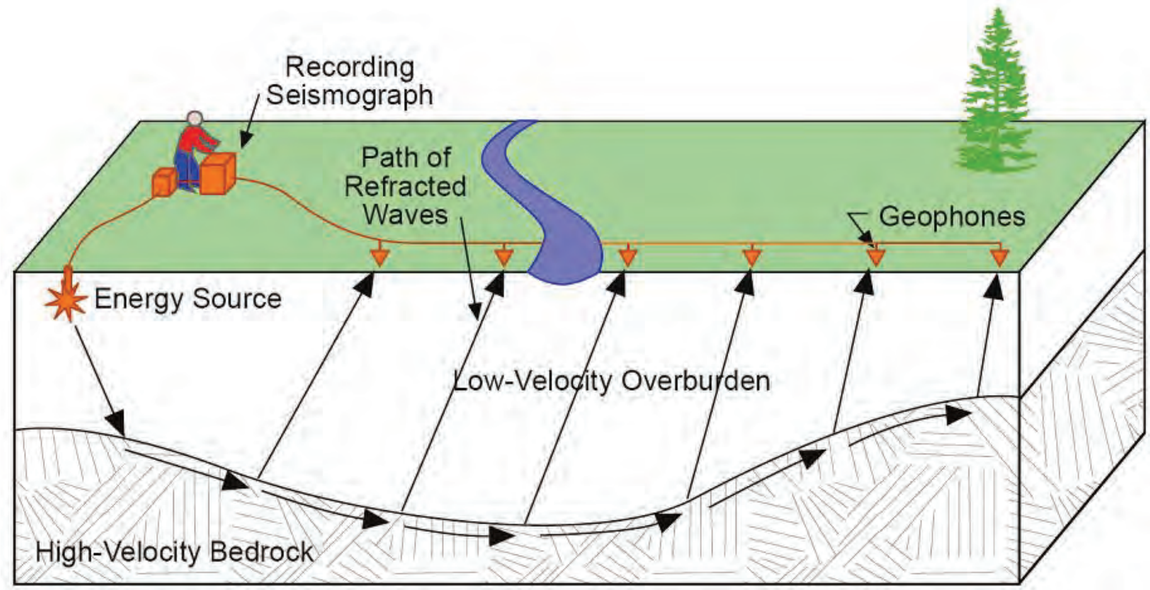

Figure 6-1: Conceptual sketch of the seismic refraction method, showing the field layout and the path of a refracted wavefront (Golder Associates Ltd.)

In seismic refraction, the first arrival time or "first break" of energy is picked up on the seismograms. At geophones located closest to the source, this arrival event is the direct wave travelling from the source to the geophone at the velocity of the upper layer. At the critical distance and beyond, the first event detected is the critically refracted wave which travels along the interface between the surface layer and the layer underlying it, provided that the underlying layer has a higher seismic velocity than the overlying surface layer. This is because a wave travelling along the interface between two layers always travels at the velocity of the faster layer. The time information obtained by picking the first break of energy is used to create a time – distance graph.

To acquire enough travel time data to model the depth to an irregular and dipping interface, the seismic source is deployed at a number of locations that generally include each end of the spread, off each end of the spread, at least at the critical distance and in the centre of the spread, with a seismogram recorded for each shot position. Applications of the seismic refraction method include determining the depth to bedrock, estimating the strength (rippability) of bedrock and mapping subsurface stratigraphy.

Applicability to Programme

Seismic refraction may be useful in site screening and characterisation, particularly in the determination of overburden thickness, and soil / rock strength, if that is of interest. As part of a seismic reflection survey, refraction data (collected simultaneously) will be used to provide "static corrections" for seismic reflection processing.

Processing and QA/QC

The resulting time – distance graphs for all of the recorded data for each spread are analysed. Processing of the arrival times of the refracted wavefront provides for modelling the seismic velocity and depths to subsurface layers. Analysis can be performed using a number of different methods such as the "delay time" method or generalised reciprocal method (GRM) or similar, that allows for the calculation of layer velocity and depth beneath each geophone, even if the ground surface is not flat.

Standard processing is discussed below where an inversion algorithm that uses the delay time method is used to obtain a first approximation depth model. This preliminary model is refined using a series of ray tracing and model adjustment iterations that attempt to minimise the discrepancies between the field measured arrival times and the corresponding times traced through the $2^1/_2$D depth model.

A standard processing route is summarised below.

- First Break Picking;
- Arrival Time Data Input;
    - data entry and editing;
    - shot and receiver geometry and height information;
- Arrival Time Analysis;
    - layer number assignment;
    - seismic refraction modelling;
- Velocity Analysis;
- Depth Model Computation and Refinement; and
- Output.

One shortcoming of some of the codes employed is that they cannot generally handle lateral velocity changes in the subsurface. Where codes do allow this, it is on a large scale, equivalent to the length of the line rather than smaller intervals.

Modern velocity optimisation software is also available that was designed specifically for deriving velocity models from seismic data acquired in areas characterised by strong lateral velocity gradients and extreme variations in topography, but is equally applicable in areas of flatter topography. In such codes, a controlled Monte-Carlo inversion method is used based on forward modelling where models derived from the algorithm are conditionally accepted or rejected based on a probability criterion. The criterion allows the algorithm to achieve a unique, globally optimised model of subsurface velocity structure. The inputs to the program are the arrival time data and the geometrical information of the receiver spread and shot points and also the elevation data. The algorithm requires no *apriori* assumptions of the subsurface structure and makes no assumptions on the orientation of the subsurface velocity gradient and can therefore reveal vertical structures and strong lateral gradients, if present. The resulting velocity model can be interpreted in terms of subsurface structure and can provide velocity information between the off-end shot points and the receiver line.

The resulting velocity models are composed of pixels, discrete blocks each having a constant velocity. The dimensions of the pixels are variable and define the resolution of the image.

Typical Accuracies and Resolution of the Acquired Data

The typical accuracies that can be obtained with this method are of the order of metres and in the case of the velocity inversion the pixels are generally of the order of 2 to 3 m square, therefore defining the resolution.

Limitations and Constraints

The three most common limitations to the seismic refraction method are the "low velocity layer", "hidden layer" and high background noise conditions.

A principle assumption when applying the seismic refraction method is that the seismic velocity increases with depth. A velocity inversion, where a low velocity layer is situated beneath a high velocity layer, will not be detected by the method. The presence of an undetected low velocity layer will make deeper layers appear deeper than their true depth.

Because of vertical resolution limitations of the seismic refraction method there may exist an undetected higher velocity layer (referred to as a "hidden layer") that fulfills the assumption of increasing velocity with depth, but is too thin to be detected. A common example is a thin saturated layer within the overburden above the bedrock. Such "hidden layers" cause the modelled depths below the hidden layer to appear shallower than they are.

In some cases the noise created by cultural activity (machinery, generators, traffic, power lines) can be strong enough to significantly degrade the quality of seismic refraction data. To combat this, modern seismographs allow the user to filter the data and remove many forms of cultural noise. However, in some instances the cultural noise can overwhelm the signal introduced by the seismic source, significantly reducing the ability to image the subsurface. New techniques have been developed which make use of this by using the noise itself as the source, which gives estimates of stiffness from surface wave dispersion.

Strengths and Weaknesses

Seismic refraction can provide accurate depth to bedrock estimates and reliable dynamic measurements of soil and rock strength. Its main weakness is the inability to detect low velocity layers in the subsurface and its limited usefulness in imaging vertical or highly dipping structures.

Potential to Combine Technologies

The potential to combine technologies depends on the objectives of the surveys. Where a seismic refraction survey is being carried out to provide information on the near surface velocity structure that can be used in the processing of the 2D/3D seismic data, then these surveys should be combined.

Where the requirements of the survey are specific to a small area or specific target, the seismic surveys are unlikely to be combined. However, in these cases it is sometimes necessary to acquire other complementary data sets (e.g., ERI). The actual selection of complementary methods being dependent on the target under investigation.

Commercial Availability

There are a number of specialised geophysical contractors that offer shallow seismic refraction surveys in the Canadian market. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Golder Associates Ltd.; and
Hayles Geoscience Surveys Ltd.

Time Scales

Seismic refraction surveys of a medium size are likely to take on the order of several weeks to one month to complete. It will require approximately one month to process the data, depending on the survey size and the type of processing.

6.2 Electrical Resistivity Imaging Surveys

Electrical Resistivity Imaging (ERI) has a wide range of applications, depths of investigation and resolutions. Applications that may be relevant to site screening include mapping overburden thickness / depth to bedrock, soil types, faults and karst features.

Brief Description

Electrical Resistivity Imaging (ERI) is an extension of conventional resistivity surveying, where successively larger electrode spacings are used to investigate the subsurface to greater depths. Principles of conventional resistivity surveying are described in Telford et al. (1990) and Butler (2005).

By moving the electrode arrays laterally as well as changing electrode spacings, a cross-section of ground resistivity with depth can be constructed, enabling subsurface electrical properties to be imaged. The cross-sections can be interpreted in terms of geological structure, indicating geologic layering, structures such as faults, fluid flow, plumes and other buried objects and features. The method may also provide information that could form an input to biosphere studies.

ERI systems generally consist of a resistivity meter (see Figure 6-2 below), either with an integral or separate relay matrix switching unit, a portable computer, cables and steel electrodes. A number of different electrode array types can be used that include; Wenner, Dipole-Dipole, Pole-Pole and Square array and these are either user selectable or programmable.

Figure 6-2: Syscal Junior 72-channel ERI system. (TerraPlus Inc.)

The resistivity imaging technique uses a line of electrodes deployed at equal intervals and connected via multi-core cables to a central switching module. The principle of the electrical resistivity method involves passing a current, *I*, into the ground through two metal stakes (electrodes), C_1 and C_2. The resulting potential difference or voltage, *V*, is measured across a second pair of electrodes, P_1 and P_2. The ratio *V/I* determines the ground resistance. The 'apparent resistivity' (measured in ohm.m), ρ_a, of the ground in the vicinity of the electrodes can be calculated from *V/I* and the spacing between the electrodes and appropriate geometrical factors.

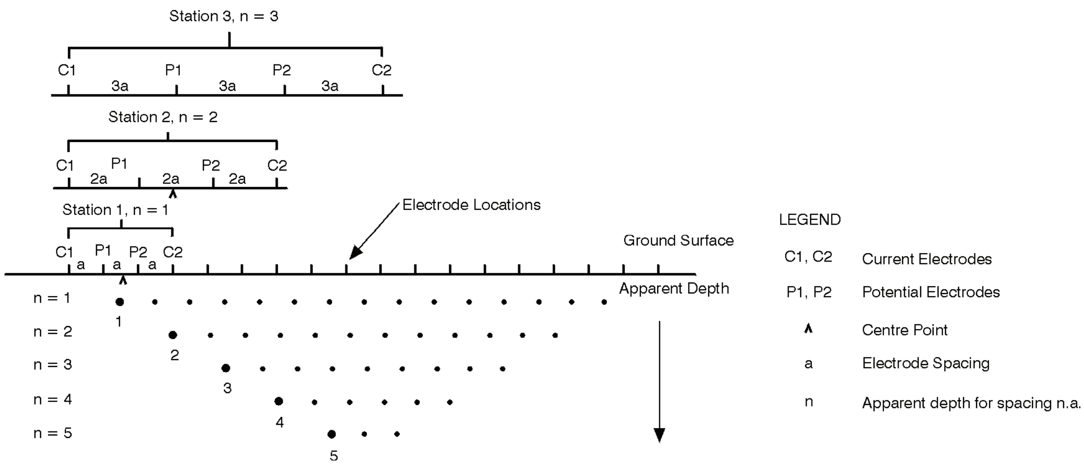

Figure 6-3: ERI measurements in a Wenner configuration using a multi-electrode array. (Golder Associates Ltd.)

With these systems, electrical resistivity measurements are obtained in a continuous profile along the length of the multi-core cable, initially with the unit electrode separation, *a*, set to the largest available multiple of *a*. The electrode spacing is then decreased by a multiple of *a* and a new profile of measurements obtained. This process is repeated at successively shallower levels as the electrode spacings (and hence depth of investigation) decreases, to produce a two-dimensional section of the electrical properties of the subsurface. This arrangement is schematically shown in Figure 6-3 above.

Data acquisition is controlled by a switching sequence that is based on a measurement protocol file that defines which electrodes are used to make the measurements. Resistivity imaging data are acquired using a number of user definable parameters. These include a minimum number of measurements; a convergence criteria based on the variance coefficient of the readings or standard deviation and a maximum number of readings.

Maximum depth of investigation that may be obtained with this method using most commercial equipment is of the order of 60 metres, although deeper surveys could be conducted with modified cables.

Applicability to Programme

ERI can be useful in a site screening or characterisation programme, in determining the depth to bedrock and in identifying shallow fracture systems, if present. It would be particularly useful at the characterisation stage of investigation in a crystalline rock environment.

Processing and QA/QC

Processing includes inspection of the data and removal of “bad” data points that are typically noise spikes in the data. The data are then processed using forward modelling which is routinely undertaken using finite difference modelling to produce an earth model and this uses the observed measurements as an input. A least squares inversion of the data is then carried out that attempts to minimise the Root Mean Square (RMS) error between the model and measured data set. The process is continued until a pre-set (user definable) number of iterations have been completed or the inversion converges on a solution as measured by the RMS error.

A number of different codes exist to process and invert the data including RES2DINV, the most common commercial inversion code of this type. An example resistivity model section generated using RES2DINV is presented on Figure 6-4 below.

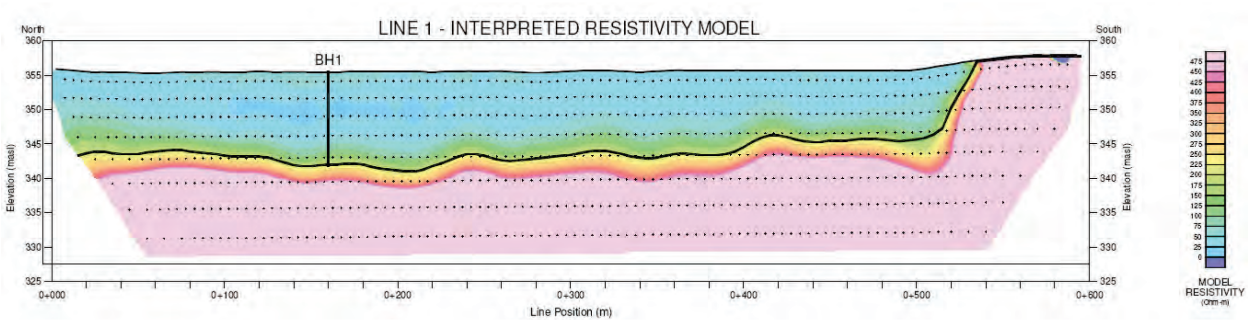

Figure 6-4: Example ERI model section showing the inferred upper bedrock surface overlain by silt and clay soils. (Golder Associates Ltd.)

Typical Accuracies and Resolution of the Acquired Data

The *a* spacing used between the electrodes is typically from 2.5 to 10 metres and this defines the resolution, which may be considered to be half that of the electrode spacing. The spacing between electrodes is selected based on the required resolution and depth of investigation.

Limitations and Constraints

Resistivity imaging derives two-dimensional inversions from a three-dimensional subsurface and can be affected by features slightly offset from the vertical plane joining the line of electrodes. These out-of-plane effects may influence the data and the resulting inversion and this may be considered to be a limitation. Although 3D surveys are theoretically possible, they are generally not practical due to cost and equipment limitations.

The method is adversely affected by the presence of buried conductors as this can generate noise and negative readings in the data that have to be removed. Dry ground surface conditions are also problematic, and may require the application of salt water to the ground surface to reduce contact resistance at the electrodes.

Strengths and Weaknesses

ERI is a versatile and robust method of mapping geology and structures to depths of more than 60 m, including the depth to bedrock and structure within the bedrock. It is slightly more cost effective than seismic refraction in mapping depth to bedrock, and can yield additional useful geologic information. It is somewhat affected by cultural features, but much less so than EM methods.

Potential to Combine Technologies

It is considered that there is limited potential to combine this method with other technologies unless it is necessary to acquire these data in combination with other data sets to meet a specific survey objective.

Commercial Availability

There are a number of specialised geophysical contractors that offer ERI surveys in the Canadian market. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Golder Associates Ltd.; and
Hayles Geoscience Surveys Ltd.

Time Scales

ERI surveys of a medium size are likely to take on the order of several weeks to one month to complete. It will require several weeks to process the data, depending on the survey size and the type of processing. It is faster to process than seismic refraction data.

6.3 Ground Penetrating Radar Surveys

Ground penetrating radar (GPR) surveys have a wide range of applications, depths of investigation and resolutions but the application of the methodology is very site specific and dependent.

Brief Description

Under the right conditions, the GPR technique is a highly versatile geophysical tool allowing a wide range of different subsurface features to be identified and mapped with both extremely high horizontal and vertical resolution. This is dependent on the ability to accurately determine the electromagnetic (EM) propagation velocity and on the centre frequency of the antenna utilised (frequencies available range from 25 MHz to over 1 GHz) and the distance between sampling points.

The basic principles of GPR combine those of electromagnetic (EM) measurements with the acquisition methodologies of seismic reflection. A GPR survey involves using a pulsed electromagnetic field (radio wave) transmitted via a tuned frequency antenna that can penetrate soils, rock, concrete, ice and other common natural and man made materials (see Figure 6-5 below). A detailed description of the GPR method is provided in Butler (2005).

Figure 6-5: Acquisition of 100 MHz GPR data (Golder Associates Ltd.)

The suitability of the GPR method is, however, very site and target dependent. The depth of penetration achievable using GPR is also affected by the ground characteristics and obeys a frequency dependent relationship. As the frequency of the EM radiation increases, so the degree of absorption increases and hence the signal attenuates more rapidly and the depth of penetration is reduced. However, as frequency increases, so the resolution of the technique improves, resulting in a more detailed image of the sub-surface and more accurate depth resolution. The selection of the correct transmitter frequency therefore represents a compromise between maximum resolution and achieving the desired depth of penetration.

The GPR technique is generally unaffected by surface features and can penetrate most materials with the exception of metal and metal gratings. However, the presence of near surface conductive materials (such as clays or conductive groundwaters) greatly reduces the depth of penetration, in some cases effectively reducing penetration depths to zero.

Variations in the electrical properties of sub-surface materials cause EM radiation to propagate at different velocities. Interfaces in the sub-surface representing boundaries between materials with contrasting electrical properties, such as geological or hydrogeological boundaries, reflect a fraction of the transmitted radiation back towards the surface, while the remainder passes through the interface to deeper levels. The reflected radiation (reflection event) is then recorded at a receiver antenna situated close to, or coincident with, the transmitter.

By carrying out a GPR survey along a traverse line, a time-depth cross-section of the shallow subsurface can be constructed. The resultant 2D GPR sections are plots of the recorded radar trace (signal amplitude) plotted in terms of distance along the profile (X-axis) versus two-way travel time (Y-axis), producing a pseudo-depth section. The Y-axis of the radar section is recorded time (nanoseconds) which can be converted to apparent depth once the propagation velocity of the electromagnetic wave through the material is understood, either by estimating or assuming the velocity of propagation of the EM radiation through the subsurface. An example 50 MHz GPR section is shown on Figure 6-6 below.

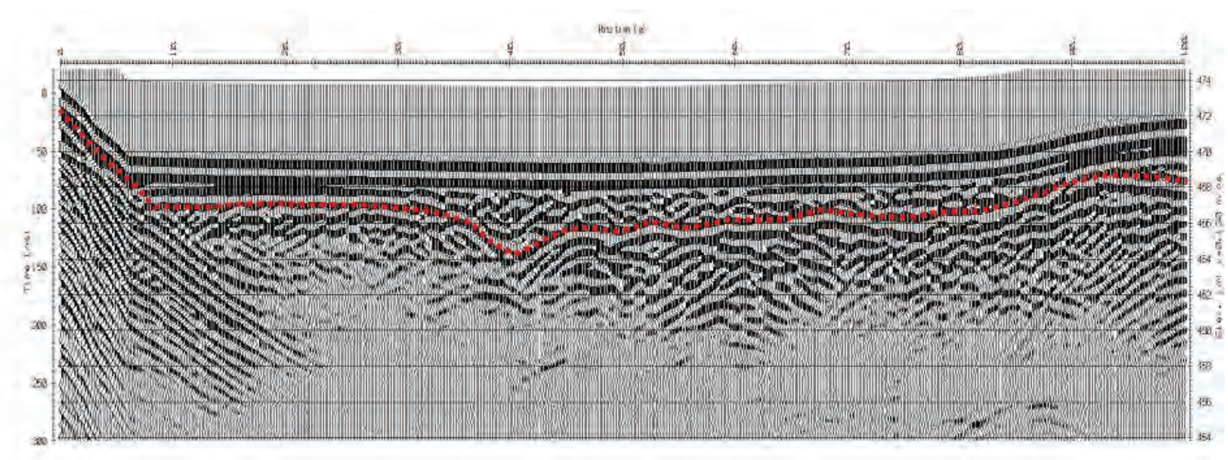

Figure 6-6: Example 50 MHz GPR data used to map the top of bedrock. (Golder Associates Ltd.)

Reflections from subsurface features are produced where there is a change in the electrical properties of the material. These changes occur at the interface between soil and concrete, between soil types, at the water table, or at discrete objects such as pipes, logs, storage tanks and miscellaneous debris. Therefore the depth section, representing electrical properties of the ground, can be interpreted in terms of structure. GPR surveys are often conducted on a grid basis, although linear surveys are also frequently conducted.

Applicability to Programme

GPR will be most applicable in characterizing fracture systems in rock in the near surface in a crystalline host rock environment. It may also be useful in mapping depth to bedrock in sandy environments. It may not be particularly useful as an initial screening tool, but rather as a site characterisation tool for the near surface. GPR is unlikely to be useful in a clay-rich environment.

Processing and QA/QC

GPR survey data are processed using a number of different software packages and the processing is generally not routine but specific to a particular set of circumstances. However, it is possible to generalise and the following processing routines are often included during processing:

- Time-zero adjustment;
- DC removal;
- Amplitude correction;
- Bandpass filtering; and
- Background removal.

Other processing steps may be applied, for example, spatial interpolation and migration.

In both processing and depth estimation, a velocity of electromagnetic wave propagation is used. This value is obtained by either measuring or estimating the value.

Typical Accuracies and Resolution of the Acquired Data

The resolution of the resulting images is in general a function of the central frequency of the antenna used to acquire the data and the spacing between traces. Radar traces may be 2 mm apart or 20 cm or more, dependent on requirements. Thus the horizontal resolution is generally sub metre and often sub centimetre. The vertical resolution is of a similar order although typically in the centimetre range.

The accuracy of the measurements and depth information is dependent on the ability to spatially locate the positions of the lines and thus the traces. It is also dependent on the ability to correctly and accurately determine the radar propagation velocity to enable a correct conversion of time to depth. It is pointed out that radar sections and interpretation may use a constant velocity both with depth and laterally and this is unlikely to accurately represent subsurface conditions where velocities may vary laterally and almost certainly change with depth.

The depth of investigation is dependent on the center frequency of the transmitter, the higher the frequency the lower the depth of investigation but the greater the resolution. Conversely, low frequencies produce greater depths of investigation with lower resolution. Depths of investigation on the order of 50 m can be obtained with low frequency (25 MHz) antennae in clean sands, granite or limestone.

Limitations and Constraints

The GPR method is essentially unaffected by surface conditions with the exception of metal and metal gratings at the surface. These generate strong radar signals that are seen throughout the full time/depth range of the radar section and prevent any information being seen from beneath the metal object or grating.

GPR surveys are adversely affected by the presence of near surface conductive materials (such as clays or conductive groundwaters) which greatly increases the attenuation of the transmitted signal and so significantly reduces the depth of penetration.

Strengths and Weaknesses

Where GPR can penetrate the subsurface, it is a relatively rapid and high resolution imaging technique. Its greatest weakness is the inability to penetrate conductive soils and rocks.

Potential to Combine Technologies

There are considered to be limited possibilities to combine the GPR survey with any other technologies unless it is required to do so in order to meet the objectives for a specific site or target.

Commercial Availability

There are a number of specialised geophysical contractors that offer GPR surveys in the Canadian market. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Golder Associates Ltd.; and
Multiview Inc.

Time Scales

GPR surveys are very rapid and up to several kilometres of coverage can be obtained in a single day, if ground conditions permit. A relatively large survey can be carried out in a week. It is likely to take on the order of several weeks to process a week's worth of GPR data.

6.4 Electromagnetic Surveys

Frequency domain EM survey methods are typically used at fixed frequencies and spacings for shallow investigations. Soundings can be made at a fixed frequency by varying the spacing between transmitter and receiver, or in the case of some instruments, by varying the operating frequency over a range (typically 1,000 Hz to 25 kHz).

Brief Description

EM surveying involves the transmission of electromagnetic energy into the ground at a fixed frequency and the detection of the secondary EM response in order to gain information about subsurface conductivity. A detailed description of frequency domain EM methods is provided in Butler (2005), as well as McNeil (1980a).

The technique is often applied on a grid basis over a site; the survey technique can be used to delineate lateral changes in subsurface conductivity allowing the interpretation of subsurface geology including near surface fracture zones, buried utilities, contaminant plumes and buried metal and/or waste (see Figure 6-7 below).

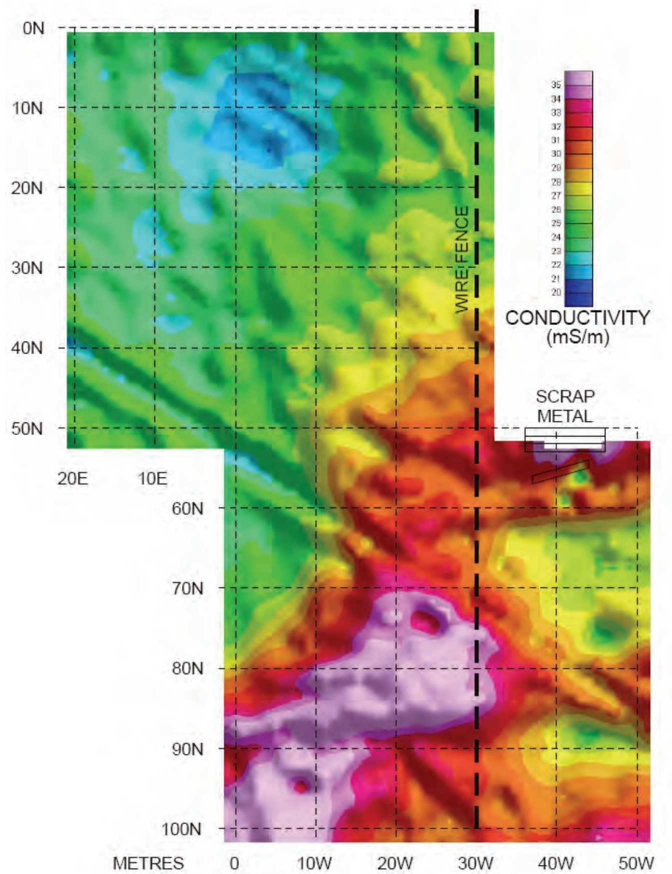

Figure 6-7: Shallow EM survey to locate buried waste. (Golder Associates Ltd.)

Electromagnetic methods require a change or variation in conductivity to exist between the target materials and the surrounding materials or the existence of a distribution in properties of the subsurface for the targets to be imaged.

The theoretical depth of investigation of the method is typically between 1 to 30 m below surface. Dependent upon the type of instrument used, measurements of ground conductivity in milliSiemens per metre (mS/m) and in-phase ratio of the secondary to primary magnetic fields in parts per thousand (ppt) are made at each measurement location. Some instruments, however, only measure the conductivity as the measurement of the primary field is used as a reference to determine the spacing between the receiver and transmitter coils.

Applicability to Programme

Shallow EM surveys may be applicable for specific purposes at the site characterisation stage, but it is unlikely to be a significant component of an investigation at the site screening stage.

Processing and QA/QC

Generally processing is straightforward and mainly involves assigning spatial information to the measured values and then contouring the conductivity and/or phase data to produce maps of the data. Prior to acquisition, the instruments must first be zeroed and the zero checked periodically throughout the survey.

For larger surveys, it will be important to monitor and correct for instrument drift, similar to that done for airborne EM surveys. Either a base station approach or the acquisition of tie-line data works well for drift corrections. Typically both base station and tie-line data are collected as part of the QA/QC process for large EM surveys.

Where sufficient data are obtained to provide depth soundings, these data can be modelled as a layered earth model. It is sometimes necessary to correct the electromagnetic data for the effects of topography.

Typical Accuracies and Resolution of the Acquired Data

The resolution of the method is variable and dependent on the type of equipment used, which affects the spacing between the transmitter and receiver coils and the orientation of the transmitter and receiver coils.

The instrumentation used for EM surveys collects volume averaged measurements and as a general rule-of-thumb, the peak sensitivity is at a depth approximately equal to a quarter of the maximum theoretical depth of investigation. The vertical resolution is generally in the range sub-metre to metre. The horizontal resolution is determined by the station interval which may be as little as sub-metre to several metres and up to intervals on the order of 40 m.

Limitations and Constraints

The survey methodology is adversely affected by the presence of metallic objects beneath the surface, at the surface and also above ground. As with any geophysical technique, a contrast in physical properties between target and host must exist for this method to be effective.

Strengths and Weaknesses

The main strength of EM surveys is rapid data acquisition. The greatest weaknesses of EM surveys are their relatively limited depth penetration and relatively limited vertical resolution (in comparison to imaging techniques like GPR), and their susceptibility to influence by cultural features.

Potential to Combine Technologies

It is considered that there is limited opportunity to combine this survey methodology with other technologies unless it is required to do so in order to meet the objectives for a specific site or target.

Commercial Availability

There are a number of specialised geophysical contractors that offer EM surveys in the Canadian market. These include:

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Golder Associates Ltd.; and
Multiview Inc.

Time Scales

Depending on the spacing, up to several hectares can be surveyed with EM methods in a single day, so a substantial sized area can be surveyed in a week. It will require up to a week to process and interpret a week's worth of EM field data.

6.5 Spontaneous Potential

Spontaneous or Self Potential (SP) is a natural phenomenon created by a number of processes including groundwater flow and seepage, bioelectric activity, heat and varying electrolytic concentrations in groundwater and other geochemical interactions, such as those between sand and clay. SP magnitude varies greatly but generally ranges from a few millivolts (mV) to a several volts; 200 mV would be considered a strong anomaly but magnitudes are generally less than 100 mV. A detailed description of SP is provided in Telford et al. (1990) and Butler (2005).

There are several characteristic regional background SP gradients that commonly occur. One is an SP gradient of the order of 10mV per 300m, which may extend over several kilometres and may be either positive or negative. It is considered that these may be due to changes in diffusion and electrolytic potentials in the groundwater. Another SP regional gradient of similar magnitude appears to be related to topography and is usually negative going uphill and is probably caused by streaming potentials.

Brief Description

The SP fields are created by a number of different processes and, as such, the method can be useful in applications where such flows are related to subsurface targets and examples are reported to include studies of groundwater seepage in the vicinity of dams, reservoirs, wells and faults; investigations of coal mine fires, steam injection, nuclear tests; and surveys to locate environmental contaminants. It is, however, noted that the presence of a near surface clay layer can mask the presence of an SP anomaly.

Although the equipment and field procedures used for SP surveys are relatively simple, considerable care must be taken to ensure that data are reproducible, that sources of noise are recognised and that appropriate data reduction techniques are used to correct for electrode drift and polarisation. Sources of SP noise and error include time variations of measured values, that may be caused by natural telluric currents or grounded electrical machinery, electrode drift and polarisation, topographic effects, buried metal and changes in soil properties.

In essence, the equipment required to undertake such surveys is a pair of non-polarising electrodes (typically porous ceramic pots containing copper electrodes and a copper sulphate solution) and a voltmeter or similar device. The field procedure is similarly straightforward with the electrodes and voltmeter used to either measure SP gradients using a pair of roving electrodes, or else the relative potential at a single roving electrode with respect to a fixed electrode. In either configuration SP readings are taken on a grid pattern over the area of interest. It is considered that acquiring data with one of the electrodes at a fixed location is a better approach, as this usually results in a higher data quality than that obtained by gradient measurements.

Applicability to Programme

While SP is an important physical phenomenon to be aware of in geophysical surveying, in practise, it is unlikely to be a significant geophysical technique in a site screening or characterisation programme.

Processing and QA/QC

The processing of SP data is straightforward and is of a numerical nature; applying corrections for “drift” in the electrodes and the gradients observed in the data set(s).

Interpretation of SP data is carried out using qualitative, geometric or analytic methods. Qualitative methods involve the recognition of typical anomaly patterns in the profile or contoured data and are useful in determining the SP source locations of interest. Geometric modelling can be used to estimate source configurations and depths. Analytical modelling based on concepts of irreversible thermodynamics and coupled flows can provide information about the nature, location and amplitude of the SP sources.

Typical Accuracies and Resolution of the Acquired Data

Based on the authors’ experience using SP to investigate groundwater seepage at earthen dams, the accuracy and resolution of an SP survey is difficult to quantify. In our experience, if there are substantial groundwater gradients, an SP response on the order of 50 to 200 mV may be observed. Spatial resolution is determined by the geometry of the “structure” being investigated, and could be on the order of several metres to 100’s of metres, depending on the structure.

Limitations and Constraints

The main limitation is whether or not the physical process that is under investigation generates an SP anomaly that is larger than other SP background effects. Spurious background SP effects could include natural telluric currents, grounded electrical machinery, topographic effects, buried metal and changes in soil properties. Clearly the presence of human habitation and transport systems, including pipelines, communications and electrical cabling will also add SP noise to the earth system, further constraining the technique.

Strengths and Weaknesses

The main strength of SP is that it can potentially identify groundwater movements, such as dam seepages, in a direct manner. Its weakness is that it is not a very versatile or robust geophysical method.

Potential to Combine Technologies

Although SP data is generally always collected as ancillary data during an IP survey, the potential to combine an SP survey with other methods is limited. SP can be measured in conjunction with an ERI survey, although SP measurements made this way are less than optimal because steel electrodes are typically used and not non-polarizing electrodes.

Commercial Availability

SP is not a common commercial survey, and although it is relatively simple to conduct, it is highly recommended that a geophysical contractor or consultant with demonstrated SP survey experience be retained to complete the work.

Time Scales

It is probable that an SP survey, if utilised, would be very limited in size and scope and would therefore not take very long to complete, several days at most.

6.6 Induced Polarisation

In the earliest galvanic resistivity surveys, it was noticed that there was often times a slowly decaying residual voltage measured at the potential electrodes after the power applied to the current electrodes was turned off. This residual potential effect became known as induced polarisation, or IP. IP has traditionally been used to identify subsurface conductors in precious and base metal mining exploration. IP and in particular, spectral IP (also known as complex resistivity or CR) does have other applications including groundwater and geothermal exploration, hydrocarbon exploration, and contaminant hydrogeology. A detailed description of IP is provided in Telford et al. (1990) and Butler (2005).

Brief Description

The acquisition of IP data is not unlike the acquisition of resistivity or ERI data. In essence, there are several generic types of IP instruments, in one type the decay voltage is measured as a function of time and this is known as time domain IP. As the build up time is also finite, the apparent resistivity, a complex impedance, must vary with frequency, decreasing as the latter increases. Therefore, measuring the apparent resistivity at two or more AC frequencies, generally below 10 Hz, constitutes another method of detection, known as frequency domain IP.

Figure 6-8: Elec Pro 10-channel IP Receiver (TerraPlus Inc.)

In the time domain there are three common forms of IP measurement that can be undertaken; the IP per cent, the decay time integral and chargeability. The simplest way to measure the IP effect with time domain equipment is to compare the residual voltage existing at a pre-determined time after the current is switched off and the steady voltage during the current flow period. The residual voltage is measured after the current cut-off, following the dissipation of the large transients due to the current being switched off and before the voltage has decayed to the noise levels. The residual voltage is much smaller than the steady voltage and the ratio of the two is expressed as mV/V or as a percentage.

Figure 6-9: VIP 3000 IP/Resistivity Transmitter (TerraPlus Inc.)

The alternate method of measuring the IP effect, the decay time integral, is more commonly used in commercially available IP equipment. The potential is measured over a set time interval of the transient decay. If this time integration is very short and the decay curve is sampled at several points, the values of the integral are effectively a measurement of the potential at different times and this is an extension of measuring the IP per cent from which the decay curve shape may be obtained. The most commonly used quantity in time domain IP measurements is chargeability.

In the frequency domain, IP measurements performed are generally the frequency effect and the metal factor. In the frequency domain, measurements of the apparent resistivity are made at two or more frequencies in the range 0.1 to 10 Hz. This is termed the frequency effect and is expressed either as such or as the per cent frequency effect. The IP effect varies with effective resistivity of the subsurface and the metal factor corrects for this variable and is related to the apparent resistivities measured at different frequencies. In theory, as both IP methods measure the same phenomenon, their results should be same. However, the conversion between the two is very complex and it is not, in general, possible to convert from one result to another.

The most commonly used IP equipment operates in the time domain and measures the decay curve, although frequency domain systems are available. The equipment and field procedures for IP surveys are similar to that used in resistivity and this usually results in a combined IP/resistivity survey and occasionally SP may also be measured.

The electrodes used in IP surveys are steel for the current electrodes and non-polarising pots for the potential electrodes. The field procedure is effectively the same as for resistivity measurements and theoretically any of the standard electrode configurations can be used. However, the most commonly used spreads are the Schlumberger or gradient array, the pole-dipole array and the dipole-dipole array.

The results are usually plotted at the midpoint of the spread, although sometimes the midpoint of either the current or potential electrode pair is considered to be the position of the survey station. Frequently, survey lines are surveyed with different electrode separations and consequently both profile and depth sounding information is obtained (pseudo-sections, akin to the ERI method). In addition, SP and apparent resistivity information is obtained for each point.

Applicability to Programme

In a crystalline rock environment, IP data can be useful in characterizing the subsurface geology, if not at the screening stage, then most certainly at the characterisation stage of a site investigation.

Processing

Where data are available for different electrode spacings, the data can be plotted as pseudo-sections, in a similar manner to ERI data. The data are typically processed using 2D inversion codes, such as RES2DINV. Simultaneous inversion of resistivity and IP data sets can be used to construct earth models for determining geologic structure and features such as fractures and faults. Other inversion techniques, such as that developed by Oldenburg and Li (1994), are available in the research community.

Typical Accuracies and Resolution of the Acquired Data

It is difficult to talk of accuracies and resolution, however, the ability to define an anomaly is dependent on the measurement interval but it is likely that the accuracy and resolution would be similar to other resistivity imaging techniques and would therefore be on a metre to tens of metres scale.

Potential to Combine Technologies

There is a potential to combine IP and ERI surveys, although the IP data in this case is not optimal as it is acquired with steel electrodes. Nonetheless, recording IP data in addition to resistivity data during an ERI survey can provide useful additional subsurface information. SP data is generally always collected with IP data.

Commercial Availability

Abitibi Geophysics Inc.;
Clearview Geophysics Inc.;
Fugro Ground Geophysics;
Golder Associates Ltd.; and
Hayles Geoscience Surveys Ltd.

Time Scales

A medium sized IP survey over several km^2 would take on the order of several months to complete, and several months to process. If collected simultaneously with ERI data, the ERI surveyed is slowed by about 30%, to allow for extra time to take the IP readings. Processing time also increases accordingly.

6.7 Further Reading

The following are excellent resources available to the reader, from which can be obtained a more in depth understanding of particular topics in shallow surface geophysical methods, as well as case histories.

> Near-Surface Geophysics - Investigations in Geophysics No. 13, Society of Exploration Geophysicists, 2005. This 756 page book, edited by Dwain K. Butler, is currently the definitive work on near-surface applied geophysics. It contains 31 chapters which cover every major topic in applied geophysics, with individual chapters written by world-recognised experts. It can be purchased on line from the SEG Bookmart at: http://eseg.org/bookmart/.
>
> Application of Geophysical Methods to Highway Related Problems FHWA DTFH68-02-P-00083 September, 2003. This is a 742 page manual on the application of geophysics and non-destructive testing (NDT) to highway related problems, that was developed for the US Federal Highways Administration by Blackhawk GeoSciences. It covers many methods that are applicable to near-surface geophysical investigations. It is available on line at http://www.cflhd.gov/geotechnical/.
>
> Applications of Geophysics in Geotechnical and Environmental Engineering EEGS Short course Handbook, 2001. This handbook written by Dr. John Greenhouse of the University of Waterloo, Canada was used as the basis for a Short Course at SAGEEP in 2001. It provides an excellent theoretical and practical introduction to the subject of

engineering and environmental geophysics. It can be purchased on line at: http://www.eegs.org/pdf_files/publication_order_form.pdf.

Geophysical Exploration for Engineering and Environmental Investigations USACE Engineer's Manual EM 1110-1-1802 August 31, 1995. This is a 208 page manual prepared by the US Army Corps of Engineers on common geophysical methods. It is available on line at http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/toc.htm.

7. REPOSITORY SITES – CASE STUDIES

Geophysical methods are an integral part of every nuclear repository study programme, as geophysical data provide important information about the characteristics of the geosphere that cannot be obtained by any other means. For example, geological structures in the subsurface can be readily mapped over a wide area using non-intrusive geophysical methods, such as seismic reflection or magnetics (depending on the geological environment).

In evaluating the applicability of geophysical methods for screening potential repository sites, it is therefore useful to review the methods used by investigators in the various repository programmes underway in other countries. A variety of host rock environments for potential repository sites have been or are under study by international research groups, as part of their country's long term nuclear waste management programmes. There is significant scientific interaction between these research organizations.

The host rock environments broadly include crystalline rocks and sedimentary rocks (i.e., limestones, clays/shales, volcanic tuffs or salt). In each case, a country's selection of a potential host rock environment is necessarily constrained by the types of geologic environments that occur within their respective country.

The geophysical investigations that have been undertaken as part of the repository programmes for nine countries were examined in this report. They include programmes in the USA, Sweden, Switzerland, Finland, Hungary, Japan, UK, France and Czech Republic.

A more detailed review was then completed for four of the sites, two crystalline host rock sites (in Sweden and the UK) and two sedimentary host rock sites (in the USA and Switzerland). A brief overview of the geophysical studies undertaken at the other sites is also provided in this report.

A summary section discusses the general approaches taken to geophysical studies, the results achieved, lessons learned and the applicability of these geophysical methods to the Canadian programme for both sedimentary and crystalline host rock environments.

7.1 Crystalline Host Rock Sites

7.1.1 Oskarshamn Site (Laxemar and Simpevarp), Sweden

Introduction

Sweden is undertaking site investigations at two different locations: Forsmark and Oskarshamn (see Figure 7-1). Both potential repository sites are located in crystalline bedrock at a depth of approximately 500 m below ground surface. Similar geophysical studies have been conducted at both sites. The Oskarshamn site is discussed in this section. The Oskarshamn site is located along the southeastern Baltic coast of Sweden. Investigations at the site have been ongoing since 2002. There are in fact two subareas at Oskarshamn: Laxemar and Simpevarp; the Simpevarp subarea is located at an existing nuclear power station directly on the Baltic Sea coast, and the Laxemar subarea is located inland, several km to the west of Simpevarp.

The bedrock geology of the site is dominated by granite, granodiorite, and diorite that belong to the 1.8 Ga Transscandinavian Igneous Belt. These Precambrian crystalline rocks have a long and complex geological history. The most important feature in these rocks which requires characterisation are the lineaments (fractures and alteration zones), which are expected to strongly influence groundwater flow.

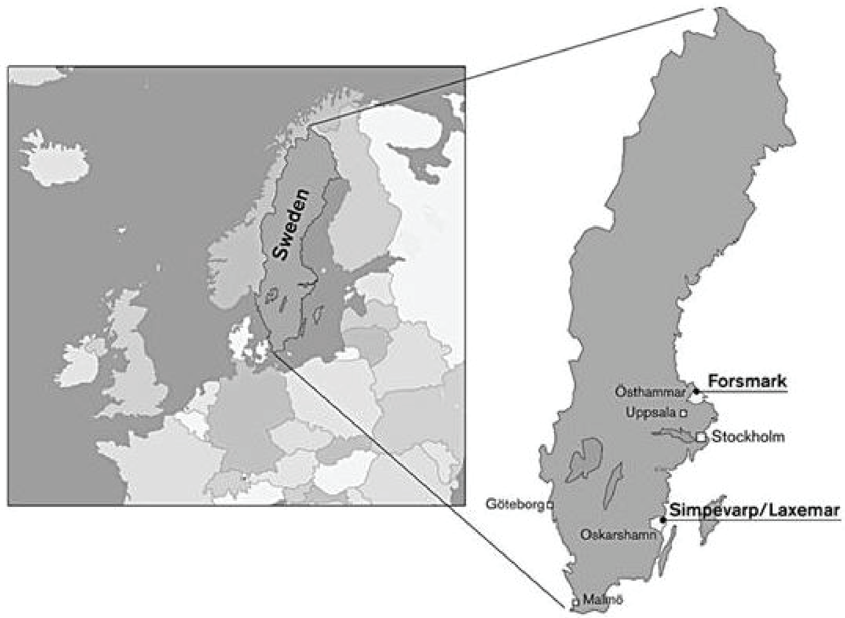

Figure 7-1: Location of the Forsmark and Oskarshamn sites in Sweden. (Lindborg et al., 2006)

Geophysical Methods

A wide variety of surface and airborne geophysical methods have been utilised at the site, primarily directed towards characterizing the different rock types, and perhaps most importantly, delineating lineaments (i.e., fractures) in the rock mass. The geophysical studies at Oskarshamn are a good example of how information from multiple geophysical methods and other non-geophysical data can be integrated and synthesised to develop a more complete understanding of a complex crystalline rock mass.

Another factor contributing to the success of the geophysical programme at Swedish study sites has been the close working relationship between SKB and university researchers, particularly Uppsala University. The importance of this relationship extends to all aspects of the technical studies in Sweden, not just the geophysical investigations.

Airborne Geophysical Surveys

At the beginning of the site investigation, airborne geophysical methods were performed across the entire study area to help obtain geologic and structural information including rock types, the extent of fractures, and zones of deformation. An integrated lineament interpretation was then completed utilizing the airborne geophysical data and topographic data. The geophysical methods included a helicopter borne multi-parameter survey consisting of gamma spectrometry, magnetics, EM and VLF (Rönning et al., 2003, Triumf et al., 2003; Korhonen et al., 2004). This work was later refined through the application of ground based geophysical surveys and surface mapping techniques (see magnetics example on Figure 7-2 below).

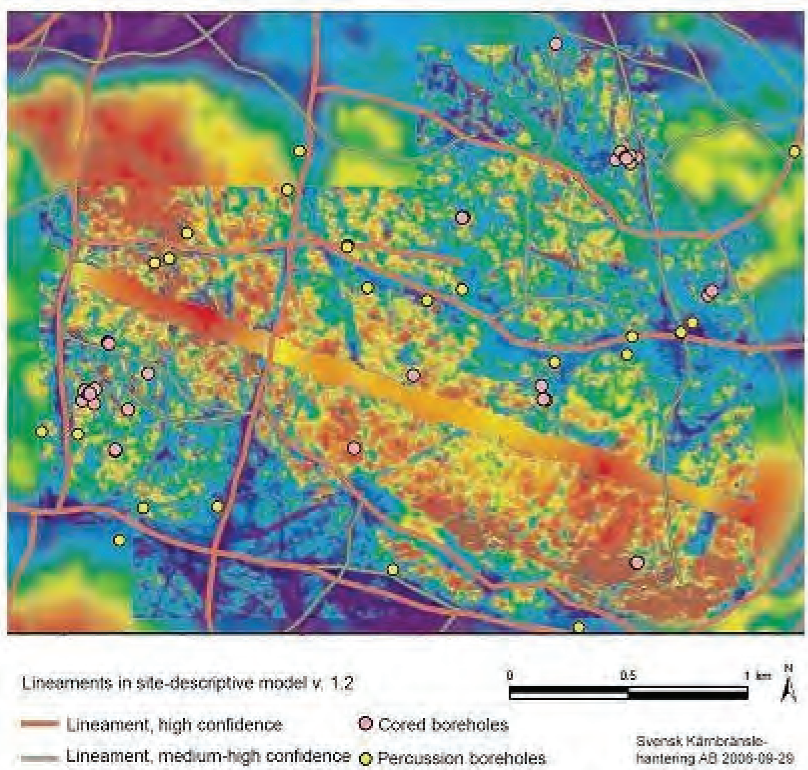

Figure 7-2: Example magnetic survey results, Oskarshamn, Sweden. (SKB: Site Investigation, Oskarshamn, Annual Report 2006)

Ground-Based Geophysical Surveys

Numerous ground based geophysical surveys have since been performed to map the geology and fractures (lineaments) in more detail and follow up on the airborne surveys and previous studies. Gravity and magnetic total field surveys were also carried out to determine the depth distribution of the major rock formations (Rönning et al., 2003; Triumf, 2004).

A series of resistivity soundings have been performed in the Simpevarp subarea to determine the thickness of the soil cover as well as the electrical properties of both the soil cover and the bedrock (Thunehed and Pitkanen, 2003). The survey indicated the presence of a thin soil cover (usually less than 5 m). Lineaments identified during the airborne surveys were investigated in greater detail using both magnetic and ERI (resistivity) profiling.

A ground based horizontal loop electromagnetic survey was also conducted in areas away from major power lines (Thunehed et al., 2004). The resulting resistivity imaging has identified the presence of lineaments, low resistivity anomalies in the bedrock (water bearing fractures) and has helped characterise the rock units and thickness of the overburden (Thunehed and Triumf, 2005).

Magnetic surveys have identified areas of high magnetisation, possibly associated with the presence of mafic igneous rocks such as diorite/gabbro, lineaments associated with high magnetisation, and extensive areas of low magnetisation that are potentially indicative of regional deformation zones.

Considerable effort has been focussed on optimizing high resolution seismic reflection methods for use in imaging fractures and lineaments in crystalline rock (see Figure 7-3 below). These surveys have had some success imaging these features (Juhlin and Palm, 1999; Bergman et al., 2002; Juhlin et al., 2004). These zones may be associated with the presence of greenstone in fracture zones (Bergman et al., 2002). The seismic reflection profiles also provided images of the deeper geologic structures.

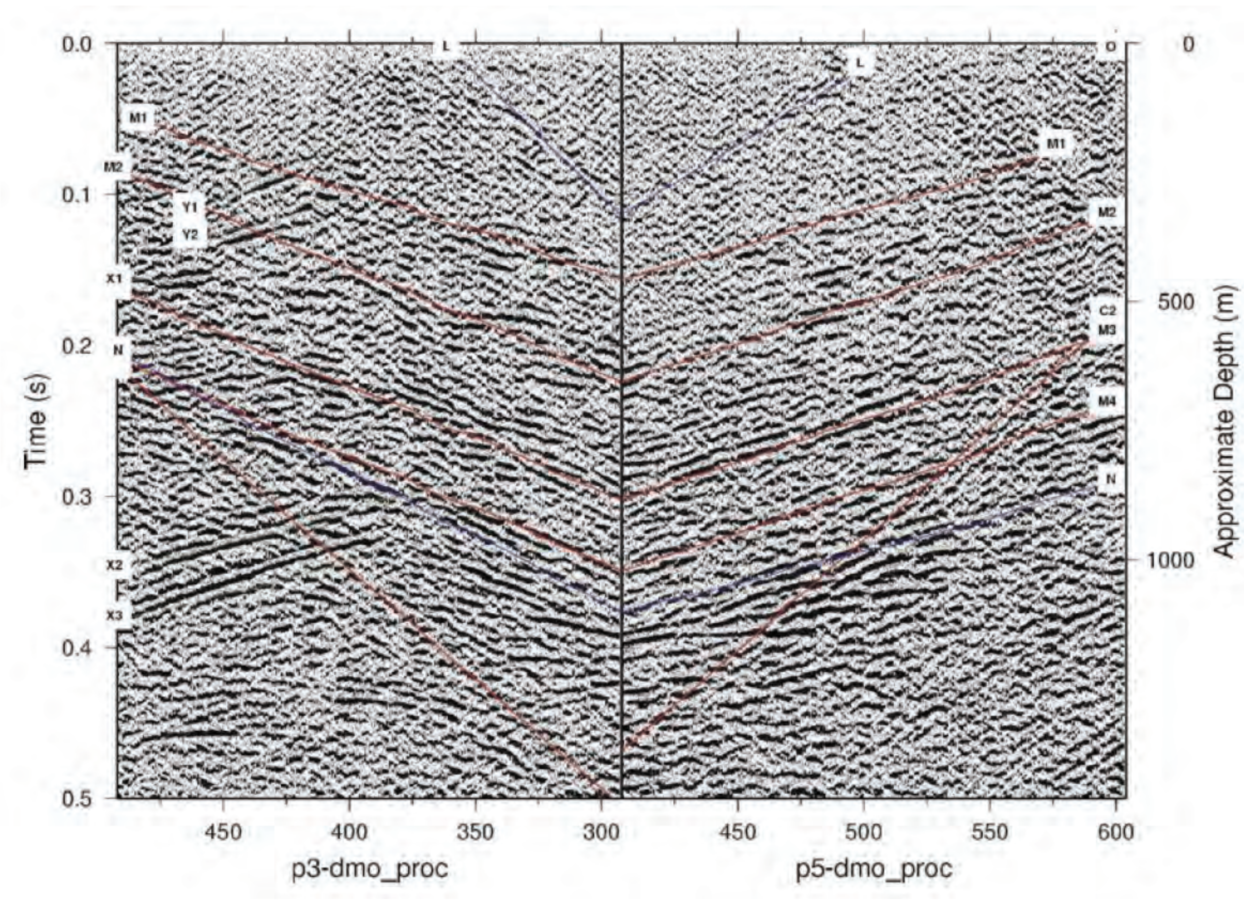

Figure 7-3: 2D seismic reflection results at Laxemar in 2004 showing the correlation between profiles 3 and 5. (Juhlin et al., 2004)

Offshore and land seismic refraction profiles have provided estimates of overburden thickness as well as information in regard to the interpreted lineaments (Lindqvist, 2004). The objectives of another more recent seismic refraction investigation completed throughout the study region were to localise possible tectonic lineaments, determine soil thickness, and gather information on rock quality (Lindqvist, 2007). The soil cover was found to be relatively thin in the study area with thicknesses ranging from 0 to 8 m.

GPR has also been used to image dipping fractures in the bedrock at shallow depths. SKB has also contributed to the expansion of the Swedish National Seismic Network (SNSN). An earthquake assessment has been performed to evaluate the risks of future earthquakes in the vicinity of the two proposed repository sites (Bödvarsson et al., 2006).

7.1.2 Sellafield Site, UK

In the United Kingdom, investigations for a deep radioactive waste repository were initiated by UK Nirex Ltd. (now the Nuclear Decommissioning Authority or NDA) at two sites: Dounreay and Sellafield. Both sites can be considered to be a crystalline basement rock under a sedimentary sequence. Similar investigation programmes were conducted at both sites but through time the focus switched to the Sellafield site (Chaplow, 1994).

Geophysical Methods

A wide variety of surface and airborne geophysical methods have been utilised at the site, primarily directed towards characterizing the different rock types, and perhaps most importantly, delineating lineaments in the rock mass. These studies were conducted in three areas (A, B and C), as noted on Figure 7-4 below.

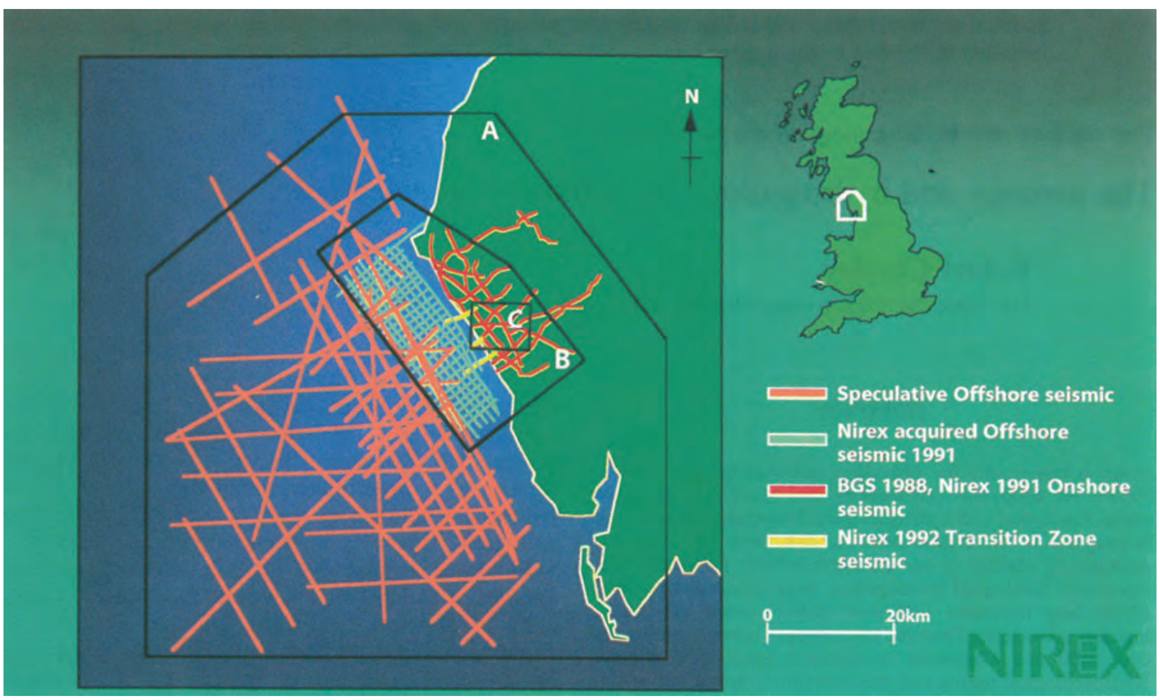

Figure 7-4: Investigation area at Sellafield showing the location of most seismic surveys. (Chaplow, 1994)

An onshore and offshore area (A) of approximately 60 km by 65 km was investigated to gather subsurface information on geological features that might have relevance to a repository safety assessment. This exploited existing published sources of information and commercially available offshore seismic survey data. Additional data, including structural geologic data relevant to seismic hazard studies, were collected from the wider area.

New investigations, including geological and geophysical data collection, were conducted in an offshore and onshore area (B) of approximately 20 km by 30 km within which geological features would have direct relevance to the repository. Detailed investigations were conducted in an onshore area immediately around the potential repository area of approximately 50 km^2 (C). These investigations are summarised in Chaplow (1994).

Airborne Geophysical Surveys

Limited airborne geophysical surveys were conducted as part of the regional investigations (Chaplow, 1994); these included 8,500 line km of airborne magnetic and radiometric surveys. It should be noted that the Sellafield Nuclear facilities are located within the survey area.

Ground-Based Geophysical Surveys

Numerous ground based geophysical surveys were performed to map the geology and fractures (lineaments) in more detail. The ground based surveys included two campaigns of acquisition of 2D seismic reflection data which comprised over 1,950 line km of data. Gravity data were also acquired along many of the seismic lines in conjunction with the seismic survey. In the later stages of the investigation, prior to the cessation of the investigation programme, a trial 3D seismic survey was conducted as a prelude to the design and commissioning of a larger 3D survey. The survey was conducted to test the appropriateness of the survey methodology and to determine acquisition parameters.

A large scale Controlled Source Audio Magnetotelluric (CSAMT) survey was also conducted to investigate the resistivity distribution in the subsurface from which an interpretation of the deep water geochemistry could be produced. In particular, the survey was commissioned to look at and determine the extent of a saline intrusion under the area which was connected to the Irish Sea. The modelling of the acquired data was at the forefront of technology and pushed the boundaries of the 3D modelling capabilities that were available at the time.

Additional more limited studies were focused on specific targets or areas requiring more detailed information. Methods used in these studies included high resolution 2D seismic reflection surveys to investigate a specific near surface fault to look at palaeo- and neo-tectonics. ERI and GPR surveys were also performed to address specific aspects of the near surface Quaternary geology that make up the biosphere.

Although outside of the scope of this report, it is worth noting that extensive borehole geophysical investigations were also conducted, most notably relevant to the surface geophysics, were the Vertical Seismic Profile (VSP) surveys. These surveys used a number of different geometries and included zero- and far-offset surveys, walkaway and walkabove surveys (other terms are sometimes used synonymously). One important use of the VSP data was its correlation to the surface 2D seismic data.

Acoustic emission/microseismic monitoring equipment were deployed in some of the boreholes as a prelude to a facility wide network being installed if the investigations continued. As a component of this, additional seismic monitoring stations were established in the vicinity.

7.2 Sedimentary Host Rock Sites

7.2.1 Yucca Mountain Site – Volcanic Tuff, Southern Nevada, USA

Introduction

The Yucca Mountain site is located adjacent to the Nevada Test Site in Nye County, Nevada, about 160 km northwest of Las Vegas (see Figure 7-5). The mountain consists of a series of ridges extending 40 km from Timber Mountain in the north to the Amargosa Desert in the south (DOE, 2002).

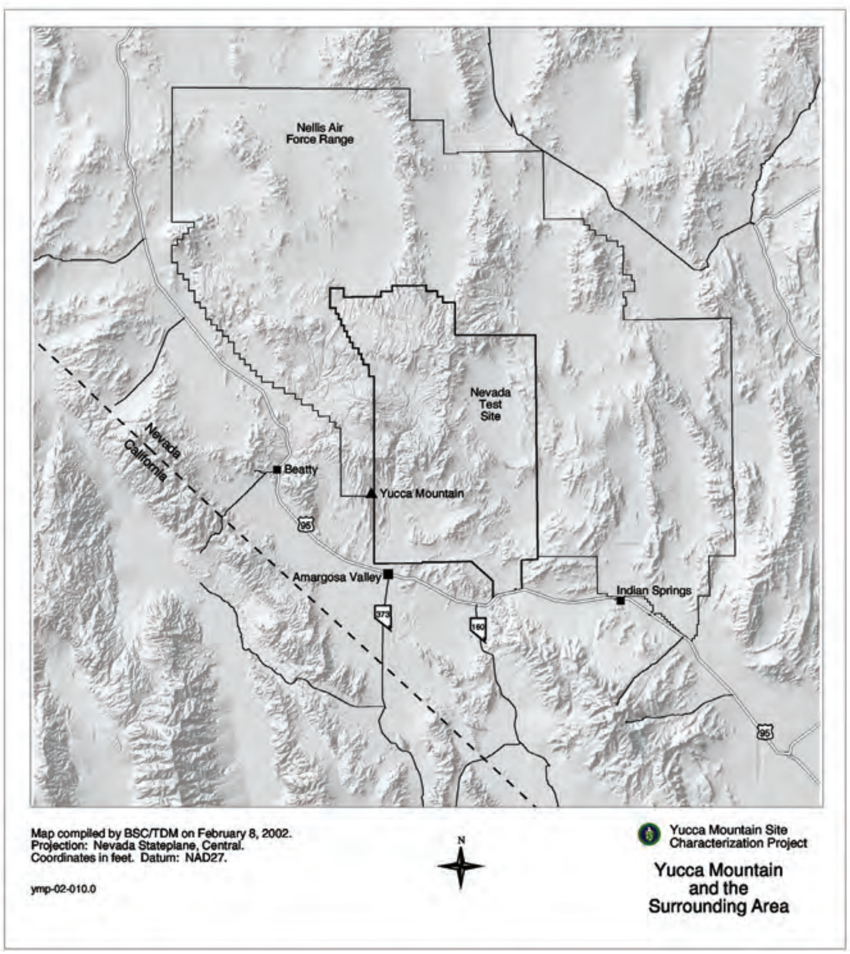

Figure 7-5: The Yucca Mountain site and surrounding lands, Nevada, USA. (www.ocrwm.doe.gov)

The site is a somewhat unique and relatively complex geologic environment in comparison to most other potential repository study sites, and its rocks are relatively young in geologic age (see geologic map and cross sections on Figures 7-6 and 7-7, respectively).

For the purposes of this report, we have classified it as a sedimentary host rock environment, as the strata exhibit mostly sedimentary rock characteristics. Strictly speaking, it is a volcanic and sedimentary environment. The water table at Yucca Mountain is approximately 500 to 800 m below the surface of the mountain at the potential repository location. The underground facility will be located in the unsaturated zone, about 200 to 500 m below the surface and, on average, about 300 m above the water table (DOE, 2002).

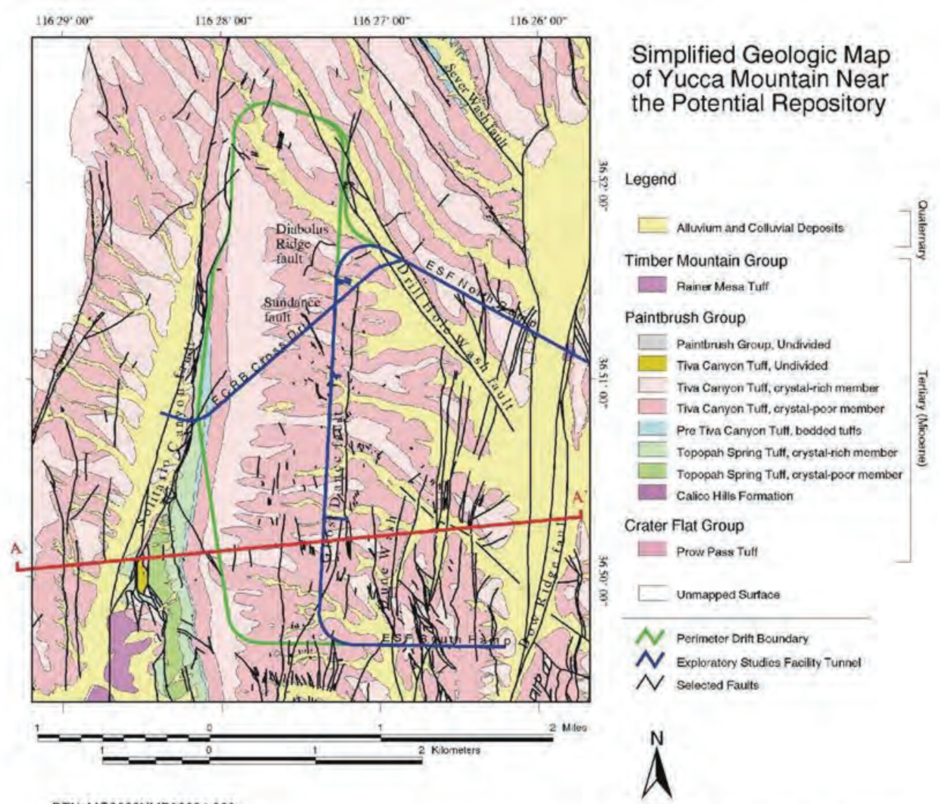

Figure 7-6: Geologic map of Yucca Mountain Area, Nevada, USA (DOE, 2002 modified from Day, Dickerson et al. 1998)

The potential repository would be located in volcanic tuff that was deposited between approximately 11 and 14 Ma ago by eruptions of volcanic ash from calderas to the north. Individual layers of tuff thin from north to south. Most of these volcanic rocks are ash flow tuffs of two types, welded and nonwelded, that formed when hot volcanic gas and ash erupted violently and flowed quickly over the landscape (DOE, 2002). The composition of the rocks at Yucca Mountain ranges from rhyolite to dacite or latite. In the immediate vicinity of the potential repository, the stratigraphically highest volcanic unit present is the Rainier Mesa Tuff of the Timber Mountain Group (DOE, 2002).

The Rainier Mesa Tuff is found in only a few locations in the faulted valleys east and west of the crest of Yucca Mountain. Beneath the Rainier Mesa Tuff, other volcanic rocks (known as pre-Rainier Mesa bedded tuffs) are also locally present.

Most of the surface of Yucca Mountain above the potential repository location is composed of the volcanic rocks of the Paintbrush Group. As a result of faulting over the last 13 Ma, these layers are all tilted slightly to the east. The Tiva Canyon Tuff is a large volume, regionally extensive ash flow tuff that has been dated at approximately 12.7 Ma. The thickness of the Tiva Canyon Tuff ranges from 50 to 175 m; it is approximately 100 m thick near the potential repository site.

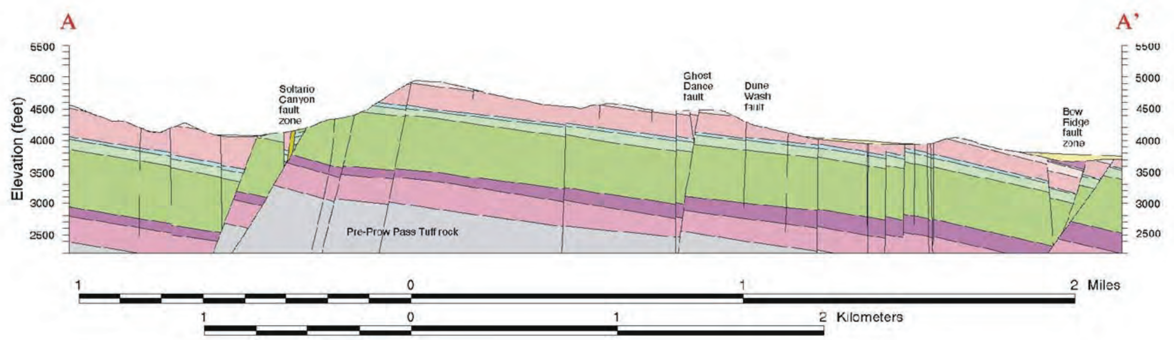

Figure 7-7: Cross section showing the distribution of volcanic rocks at Yucca Mountain (DOE, 2002 modified from Day, Dickerson et al. 1998)

A layer of nonwelded tuff underlies the Tiva Canyon Tuff near the site of the potential repository. This nonwelded layer includes two separate ash flows, the Yucca Mountain Tuff and the Pah Canyon Tuff. In the vicinity of the potential repository, the total thickness of the nonwelded units ranges from 30 to 50 m (DOE, 2002).

The lowermost unit in the Paintbrush Group is the Topopah Spring Tuff, which would be the host rock for the potential repository. The Topopah Spring Tuff was formed by an eruption about 12.8 Ma ago and has a maximum thickness of about 375 m near Yucca Mountain. An important characteristic of the layers is the presence and abundance of lithophysae, which are small, bubble-like holes in the rock caused by volcanic gases that were trapped in the rock matrix as the ash flow tuff cooled. Like the Tiva Canyon Tuff, the Topopah Spring Tuff is fractured throughout; these fractures provide the main pathway for water to flow through the rock unit.

Beneath the Paintbrush Group, the Calico Hills Formation is a series of mostly nonwelded rhyolite tuffs and lavas that were erupted approximately 12.9 Ma. The formation thins southward, from a total thickness of about 290 m north of the repository block to 40 m south of it. None of the tuffs of the Calico Hills are densely welded; therefore, they generally have higher matrix porosities than the Topopah Spring Tuff. Because the rock has higher ductility, the fractures that are common in welded tuffs are less common in the Calico Hills Formation.

The geologic units below the water table contain older volcanic rocks composed mainly of welded and nonwelded ash flow tuffs. These older units can be up to 1,000 m thick below

Yucca Mountain. The volcanic rocks are underlain by the Palaeozoic limestones and dolostones. Near Yucca Mountain, the older volcanic rocks and the Palaeozoic rocks lie deep beneath the surface, but they are found at much shallower depths (and even at the surface) to the south (DOE, 2002).

Geophysical Methods

Geophysical methods have played an important role in the characterisation of the geology at the Yucca Mountain site, as noted by Oliver et al. (1995). In fact, geophysical surveys helped answer many of the most important geologic questions, including (1) the depth to and nature of the Palaeozoic basement, (2) the potential presence of faults, (3) the deep groundwater table, and (4) deep geologic structures that shed light on the possibility of future nearby volcanic activity.

Geophysical methods that have been used to study the Yucca Mountain site include: gravity surveys, airborne and ground based magnetic surveys, magnetotelluric surveys, seismic reflection and seismic refraction surveys and teleseismic tomography studies. Of particular relevance and interest are the early geophysical studies undertaken at the site selection stage.

The Yucca Mountain site is a good example of how multiple geophysical techniques which measure a variety of different physical properties (i.e., seismic velocity, electrical resistivity, density, magnetic field) can be combined with limited geologic information from deep drilling to develop an understanding of a relatively complex geologic environment, and answer important, relevant geologic questions.

Gravity

Gravity investigations began at Yucca Mountain in 1977 to help characterise the general geologic and tectonic setting, although previous gravity studies had been conducted in the area dating back to 1957. These studies showed that Yucca Mountain does not have a basement core, but that it is characterised by a gravity high along its east edge and a gradual westward gravity decrease of approximately 20 mGal across Yucca Mountain towards Crater Flats. This gravity trend has been modelled and indicates a westward increase in the depth to the Palaeozoic basement rocks, from approximately 1 km in the east to 3 to 4 km to the west. These and other data eventually helped develop the low-angle fault model of the geology for the site (Ponce and Oliver, 1995).

Gravity investigations have helped support additional conclusions about the geology of the area. North of Yucca Mountain, several circular gravity lows of up to 50 mGal in magnitude helped reveal the presence of a series of calderas, the largest of which is the Timber Mountain Caldera. The gravity survey indicated the absence of these anomalies in the vicinity of the site, in particular beneath Jackass Flats (Ponce and Oliver, 1995).

Gravity methods were also helpful in locating and delineating north-striking concealed faults near the east side of Yucca Mountain and in Midway Valley where extensive surface facilities are planned (Ponce and Oliver, 1995).

It is important to recognise that gravity interpretations in and of themselves do not produce unique results. However, when combined with other data sets such as depths to geologic contacts from drilling or seismic data, and rock densities from drilling or seismic velocity data, gravity models can be constrained and thereby yield very useful results.

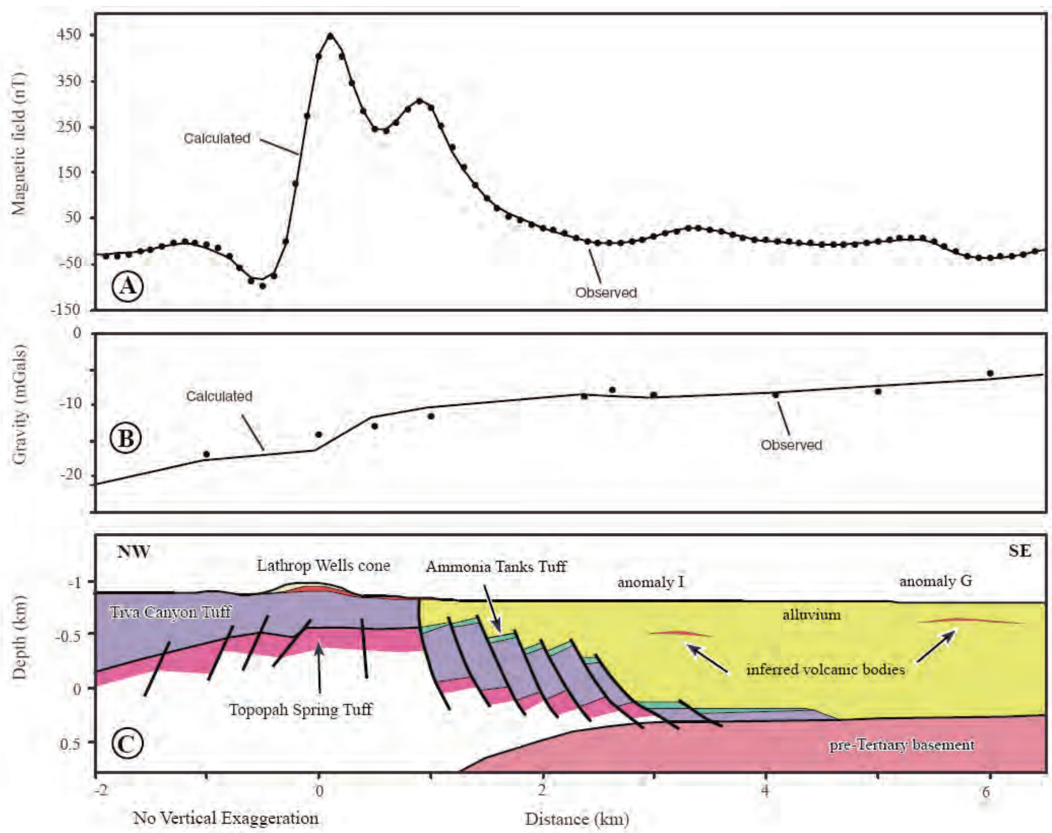

Figure 7-8: Geophysical models showing fits between observed and calculated (A) magnetic and (B) gravity profiles and (C) a geologic interpretation of inferred subsurface structure at Yucca Mountain. Note the anomalies I and G, which are inferred to be basaltic volcanic bodies. (O'Leary et al., 2002)

Magnetics

Regional aeromagnetic surveys of the area and ground based magnetic surveys at the study site have also been used to answer important questions about the geology of Yucca Mountain (Figure 7-8) (Oliver et al., 1995; O'Leary et al., 2002).

The most prominent magnetic feature in the region is a magnetic high extending from southeast to northwest, just north of the site. This magnetic high is associated with exposed Tertiary-aged granitic rocks at Wahmonie, and with (altered) magnetite-bearing Palaeozoic shales in the Calico Hills area. This suggests that where the magnetic high crosses Yucca Mountain, there is likely a change in basement rock type, from the dolomite encountered by drilling in the beneath the east-central part of the site, to a rock type such as granite or altered shale (Oliver et al., 1995).

Gradient analysis of the magnetic data indicates the Palaeozoic basement contact beneath this area of Yucca Mountain to be approximately 2.2 km beneath the surface, and is one of the only sources of evidence of the basement depth beneath the northern part of Yucca Mountain. This finding has important implications on structural and mineral assessment models for the area (Oliver et al., 1995).

Several local dipolar magnetic anomalies have been detected within Crater Flat and the nearby Amargosa Desert. The largest of these anomalies was drilled in 1991, which indicated the presence of basalt at a depth of 104m below surface (Oliver et al., 1995). The ability to detect basaltic centers with magnetics has made important contributions to estimates of the potential for future volcanic activity in the region (Oliver et al., 1995).

Results of potential-field modeling indicate that isolated, small-volume, volcanic (basalt) bodies embedded within the alluvial deposits in these areas produced the anomalies. Their physical characteristics and the fact that they tend to be aligned along major structural trends provide strong support for the hypothesis that these anomalies reflect buried basaltic volcanic centers (O'Leary et al., 2002).

Magnetic methods have also proven useful in locating concealed faults, since several layers of the tuffs that form the Paintbrush Group have large remnant magnetisations, both normal and reversed (Oliver et al., 1995).

Aeromagnetic data for the area has also been used to estimate the depth to the Curie isotherm. The curie isotherm under Yucca Mountain has been estimated to be at a depth in excess of 25 km (Oliver et al., 1995).

Magnetotellurics

Several magnetotelluric surveys have characterised the subsurface resistivity structure of the site and determined its relationship with the subsurface geology and deep regional tectonic processes (Klein, 1995). The gravity, magnetic, and magnetotelluric surveys have also suggested the presence of unconcealed faults, as well as the location and extent of calderas, basaltic centers, and plutons.

Seismic Refraction

Five deep seismic refraction profiles in the Yucca Mountain vicinity, acquired in 1983 and 1985, have provided valuable insight into upper crustal velocity structure near the site (see Figure 7-9). The five profiles, when combined with geologic and other geophysical data have provided a three-dimensional view of the structural setting.

The inferred pre-Tertiary surface in the study area is inferred to have a maximum depth of approximately 3.5 km beneath Crater Flat and forms an asymmetric, westward deepening structure located between the east flank of Bare Mountain and as far east as eastern Yucca Mountain. The Tertiary volcanic section beneath the eastern flank of Yucca Mountain, as shown by the dashed line on Figure 7-9, is estimated to be 1.25 km thick along the east-west seismic refraction profile (Mooney and Schapper, 1995).

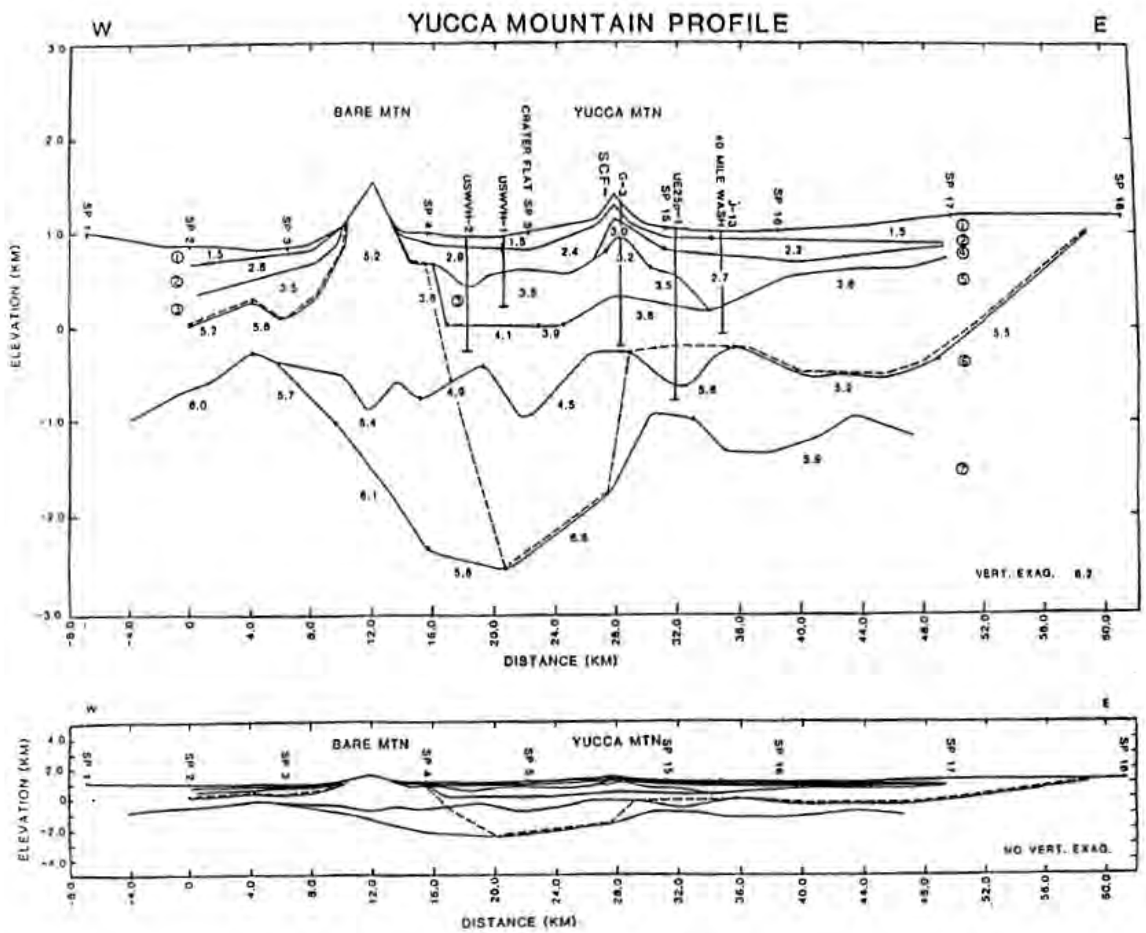

Figure 7-9: Crustal velocity model along the Yucca Mountain seismic refraction profile (Mooney and Schapper, 1995).

Seismic Reflection

A number of “shallow, intermediate and deep” seismic reflection surveys have been conducted at the Yucca Mountain site and the surrounding area beginning in the 1980’s and through the mid-1990’s by various contractors and researchers. The work is summarised in Oliver et al. (1990), Brocher (1995) and Brocher et al. (2002). The data was acquired using a variety of energy sources, including Mini-Sosie, Vibroseis, and explosives.

The survey results did provide some images of deeper geologic structure and faults, and helped characterised the geometry of the pre-Tertiary/Tertiary contact (Brocher, 1995; Brocher et al., 2002), although in some cases the data quality was not optimal.

Teleseismic Tomography

Teleseismic tomography uses the energy from distant earthquakes to reconstruct seismic velocity perturbations in the upper crust and mantle. The compressional wave phase teleseismic data in the region of the Yucca Mountain site offered important constraints on the physical properties of the lithosphere and hence the tectonic processes that have generated them. Travel time tomography provided valuable information regarding the extent and status of deep magmatic systems (which appear to now be cooled and therefore inactive), the presence of some localised zones of partial melt at shallower depth, and the location of tectonic structures (Evans and Smith, 1995).

7.2.2 Zürcher Weinland Site – Opalinus Clay, Switzerland

Introduction and Site Geology

NAGRA is investigating the Opalinus Clay as a potential host rock for a deep geological repository for high-level and long-lived intermediate-level waste. The Zürcher Weinland site is located in northern Switzerland (Figure 7-10).

Figure 7-10: Location map showing the Zürcher Weinland site, Switzerland. (NAGRA, 2000)

The rock layers of the Opalinus Clay were formed around 180 Ma ago by deposition of fine mud particles in the Jurassic Sea. Favourable properties such as an extremely low hydraulic permeability, a regionally homogeneous structure and a thickness of approximately 100 m make the Opalinus Clay potentially suitable as a repository host rock (Figure 7-11). The formation also occurs over a depth range which is reasonable from an engineering point of view (i.e., down to around 900 m below ground surface). Added to this is the fact that, in the Tabular Jura, which dips below the Molasse Basin towards the south-east, the Opalinus Clay is largely undisturbed tectonically (NAGRA, 2000; Marschall et al., 2005).

Long after the Opalinus Clay had been deposited, the high mountains of the Alps and, further to the north, the Folded Jura, were formed. The Tabular Jura remained unaffected by this folding of the earth's crust and the rock formations – including the Opalinus Clay – are still in the same location as when they were formed. Neither the volcanic eruptions in the Hegau region some 15 million years ago nor the glaciers of the many ice ages which advanced through the landscape had the effect of altering this situation. Only the uplifting of the Black Forest had an influence, in the form of a slight tilting of the layer stack (NAGRA, 2000; Marschall et al., 2005).

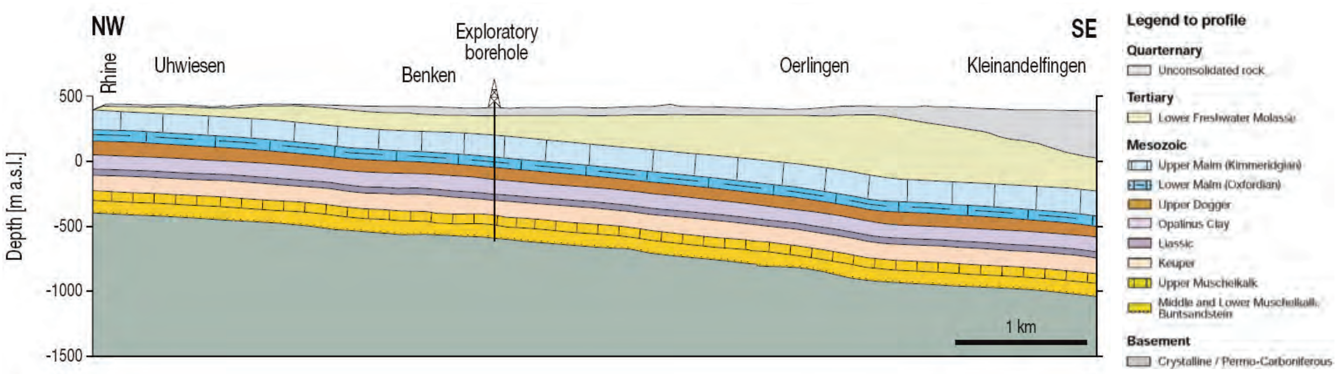

Figure 7-11: A geological profile through Zürcher Weinland showing the major geologic units. (NAGRA, 2000)

Geophysical Methods

Geophysical methods have been very successfully used in the site investigations undertaken by NAGRA in their repository research programme. This review focuses on the implementation of 2D and 3D seismic reflection surveys as a key geosphere characterisation tool in a sedimentary rock environment, the Opalinus Clay. A variety of other geophysical techniques were also used at the site selection stage, which are discussed briefly.

Seismic Reflection

In 1991 and 1992, NAGRA carried out 2D seismic reflection surveys in northeast Switzerland to help assess the continuity of the Opalinus Clay formation. Using the results of the 2D surveys, an area of approximately 50 km^2 in the north of Canton Zürich was identified for detailed investigation.

A 3D seismic reflection survey was carried out in this area in 1997 (Figure 7-12). Together with the Benken borehole, the results from the 3D survey provided a sound basis for determining whether the requirements for safe disposal of high-level waste can be fulfilled (McKinley and McCombie, 1995). A very concise account of the 3D survey work is provided in NAGRA's Technical Bulletin 33 (2000). Key aspects of the planning, field work and data processing, based on that account, are summarised below.

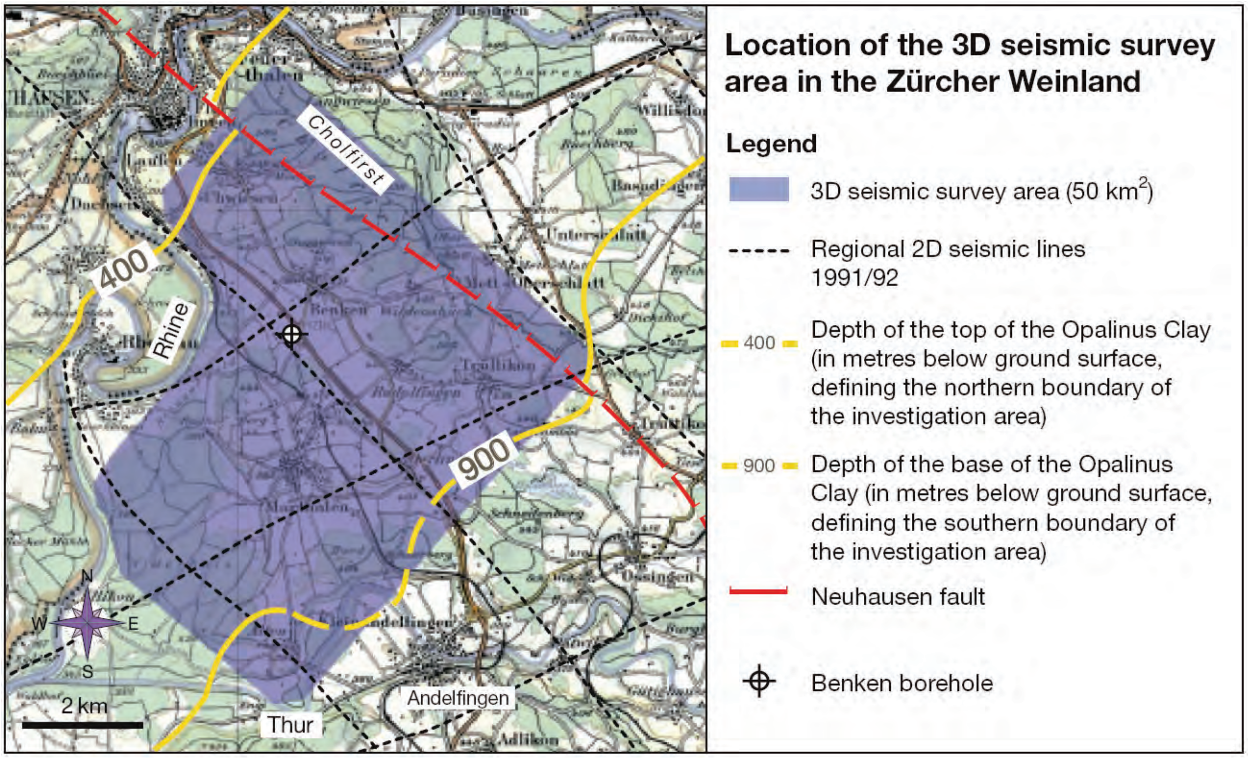

Figure 7-12: Location of the 2D and 3D seismic surveys at the Zürcher Weinland site. (NAGRA, 2000)

Survey Design and Planning

The survey was designed to achieve 20-fold coverage (theoretical) with a 15 m bin size. This required a 180 m line spacing and 30 m shot and receiver spacing over the 50 km^2 study area. Within the study area, there were 10 villages, approximately 18 km^2 of forested lands, and approximately 24 km^2 of agricultural lands.

Implementation of the 3D survey required a great deal of careful planning. GIS mapping and recently acquired orthorectified aerial photographs allowed the team to plan precisely the location of the seismic stations that could be utilised in practise, and thereby achieve actual data coverage that was as close as possible to the theoretically planned coverage.

Before the work could begin, land access agreements were arranged by a team of 7 people, who were successful in obtaining agreements with 98% of the 1,700 individual land owners. The work was carried out in the winter months to minimise the disruption to agricultural operations.

Data Acquisition

The 3D seismic survey required approximately 4 months of field work to complete. An array of three Vibroseis trucks were used at about 23% of the source points (along roads and access trails), with small explosive charges detonated in shot holes at the remaining source points (softer ground and forested areas). Interestingly, the Vibroseis trucks used a pseudo-random excitation signal, rather than a swept sinusoid, in order to minimise the potential to generate resonances within building structures and cause damage. Signals in the frequency range of 10 to 85 Hz (3 octaves) were effectively recorded.

The recording system used 480 live channels on 8 lines of geophones, recording data over a rectangular area approximately 900 by 1260 m in size. A total of 29,000 geophones were connected to more than 60 km of cable at any given time during the survey. Approximately 4 million individual traces were recorded during the survey.

Each shot point and geophone group was surveyed for location using a combination of differential GPS and a Geodyne 30 navigation system (where dGPS satellite coverage was obscured by trees or tall structures).

Following the completion of data acquisition, clean-up teams collected any materials left behind during the survey, grouted all of the shotholes, and restored the ground surface to its original condition.

Data Processing

Processing was then carried out in the following sequence:

- Reading in the field data
- Sorting into bins
- Minimum phase transformation of the Vibroseis data
- Spherical divergence correction
- Surface-consistent deconvolution and amplitude adjustment
- Ground static corrections
- Frequency/wave number filter and subsequent residual static corrections
- Dip move-out correction (DMO)
- Velocity analysis and normal move-out correction (NMO)
- Stacking
- Deconvolution after stacking
- 3D migration
- Zero-phase transformation
- Spectral amplitude balancing

The resulting 3D dataset was then ready for analysis.

Data Analysis and Results

The high resolution 3D seismic data set was used to address a number of important geologic questions regarding the continuity and competence of the Opalinus Clay.

Correlation to Regional Data The 3D seismic data set was correlated to the previous 2D survey and, in turn, to the Weiach borehole some 13 km from the 3D survey area. This established a direct link between geologic formations and the seismic data set, even before the Benken borehole was drilled. The results of the Benken borehole further established this correlation.

Identification of Faults and Discontinuities A novel coherence algorithm was applied to the entire 3D seismic data set, which allowed for the systematic identification of anomalies that were potentially indicative of faults and discontinuities. This was a very powerful analysis approach that was used to build stakeholder confidence in the continuity and competence of the Opalinus Clay.

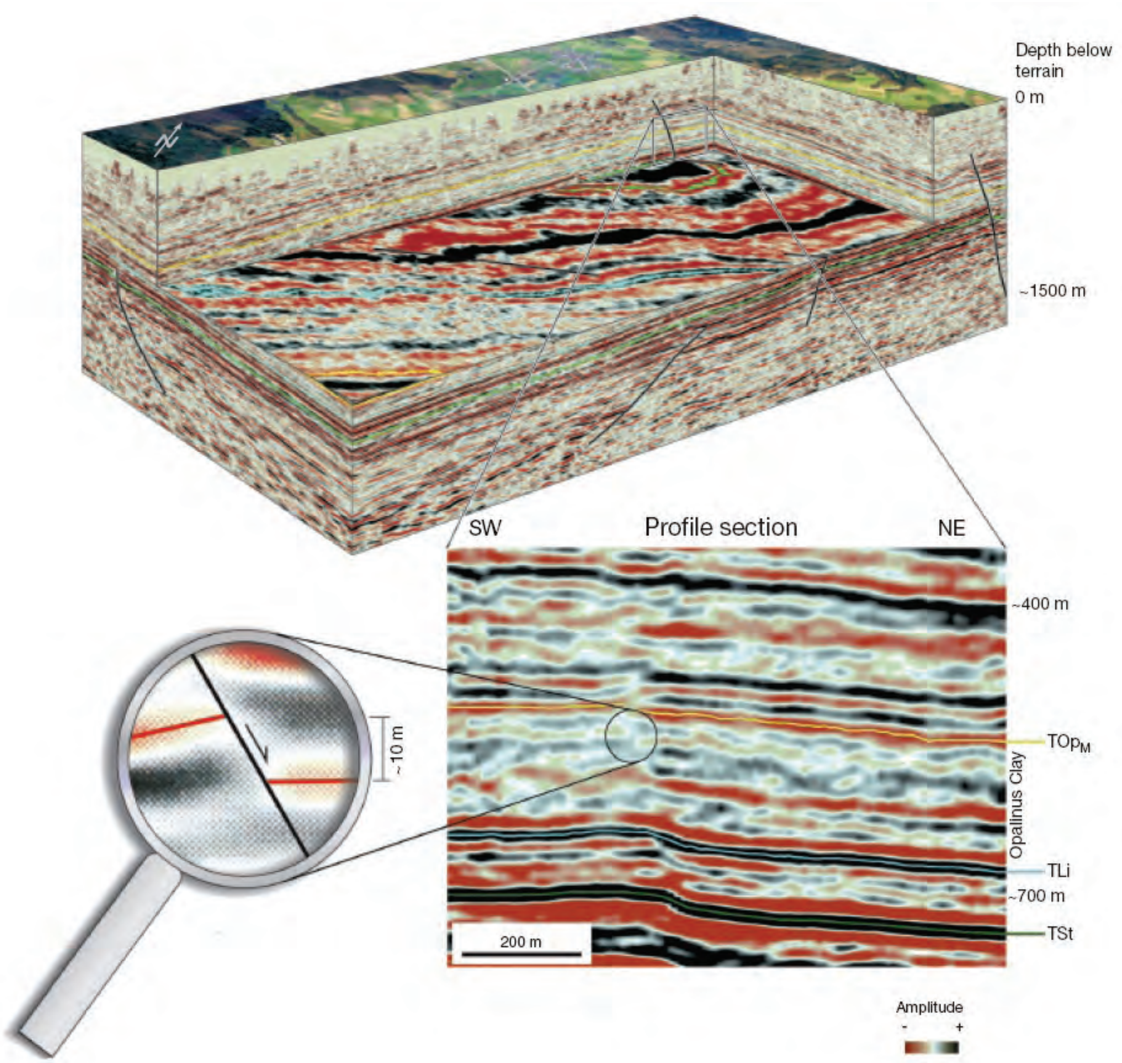

Figure 7-13: 3D seismic image of the Zürcher Weinland site. (NAGRA, 2000)

Structural Geology and Tectonic Interpretation The seismic data set and the derivative coherence data set were then analysed to develop a detailed three-dimensional understanding of the structural geology of the site (Figure 7-13). This involved advanced analysis and visualisation techniques, including seismic attribute analysis. The results provided an understanding of the structural geology at an unprecedented level of detail.

The structural model developed from the 3D seismic data set confirmed that the Opalinus Clay was in a remarkably undisturbed state, with the only fault of significant displacement being the north-west to south-east trending Neuhausen fault. The predicted general thickness of the Opalinus Clay (100 to 120 metres) was also confirmed by the 3D seismics and the results from the Benken borehole. The Neuhausen fault was previously know to exist and is considered to be the westernmost marginal fault of the Bonndorf-Hegau-Bodensee graben.

The Wildensbuch flexure is situated north of the Benken borehole and merges with the Neuhausen fault at Wildensbuch. Several individual fault elements were identified along the flexure from the seismic data, where the strata are displaced to the NNE to NE. The maximum vertical displacement at the level of the Opalinus Clay is approximately 13 m. These minor faults have an extensional character and reach partly into the Malm.

Using the results from the 3D seismic survey, it was possible to compile a structural dataset for the geology of the Zürcher Weinland which is unique in terms of its degree of detail. The identification of an extensive, tectonically undisturbed Opalinus Clay deposit forms an important basis for evaluating the feasibility of safe geological disposal of high-level waste in Switzerland.

Other Geophysical Methods

A variety of other geophysical methods have been used by NAGRA as part of their repository research studies (Blümling, personal communication, 2008) and are summarised in this section.

Seismic Refraction

Several deep seismic refraction profiles were surveyed as part of regional investigations in the 1980's. The seismic refraction results provided an understanding of seismic velocities in the area, the depth to the top of Permo-Carboniferous crystalline basement, and additional insight into the structure of the deep Permo-Carboniferous trough. Shallow refraction profiles at the Wellenberg site in the 1990's were used to map sediments in the valley (up to a few hundred meters in thickness) and provided subsurface information pertaining to a landslide site.

Gravity

Approximately 5,000 gravity measurements were made in the 1980's and 1990's and processed to yield Bouguer anomaly and residual anomaly maps. The residual anomaly map showed a negative anomaly along the Permo-Carboniferous trough. The gravity data was also used to validate previous depth estimates of the crystalline basement in the area of the Permo-Carboniferous trough. A microgravity survey was carried out locally and was successfully used to detect sink holes.

Seismicity

NAGRA has collaborated with the Swiss Seismological Survey to improve the density of their seismic monitoring network in areas of interest, which has resulted in an improved ability to actively monitor natural seismic activity.

Microseismicity

Microtremor measurements were made in 2001 in cooperation with Japanese partners to predict S-wave velocity distributions in the top few hundred metres of the subsurface, with limited success.

Aeromagnetics

Aeromagnetic surveys were carried out in the early 1980's. The survey results were not favourable and it was not possible to infer the depth to the Permo-Carboniferous crystalline basement or the depth of the Permo-Carboniferous trough.

ERI, GPR and VLF

Small scale investigations have been carried out at a variety of sites with some but limited success.

7.3 Other Sites

7.3.1 Bure Site, France

An overview of relevant activities undertaken at the Bure underground research laboratory (URL) operated by ANDRA is presented herein, based on ANDRA Activity Reports from 2000 to 2003 and on direct knowledge of the investigations. The Bure and the URL in particular are located in a mudrock/clay environment. The site is located in the Paris Basin (Figure 7-14) and is well known to ANDRA from detailed mapping and various investigations undertaken by the oil exploration industry.

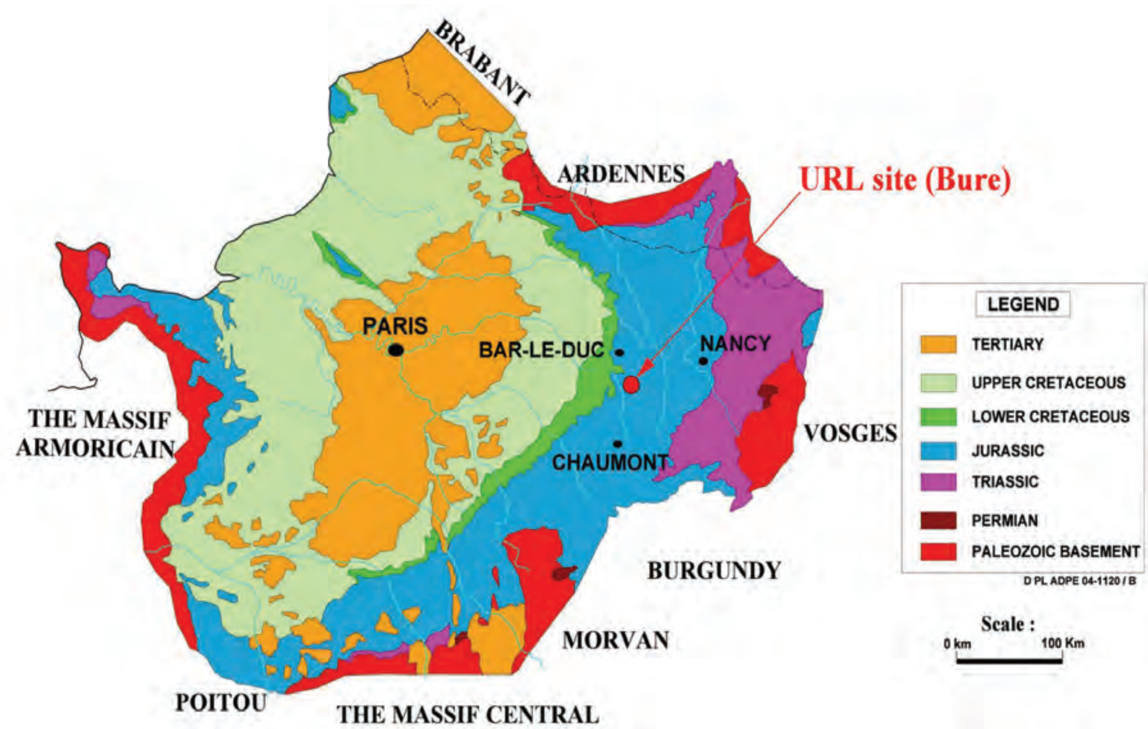

Figure 7-14: Site of the ANDRA Bure HRL (www.andra.fr)

Geophysical Methods

2D and 3D seismic reflection have been the most important surface based geophysical method used by investigators at the Bure site (ANDRA, 2000). This includes the use of existing data at the preliminary stages, as well as new surveys during the later stages of site selection and characterisation. Over the period 1989 to 1994 ANDRA collected and reinterpreted existing geoscientific data, including 1,300 km of seismic data and geophysical data from 68 regional boreholes.

Between 1994 and mid-1995 two deep boreholes were drilled 15 km apart and used for a series of testing programmes that included vertical seismic profiling. During this time, a systematic search was made of other existing data sources and sets. Following this phase of activity, the site of the Bure laboratory was determined and additional boreholes were drilled and seismic data acquired over the period mid-1995 to mid-1996. The additional seismic data comprised the acquisition of three high resolution 2D seismic lines reducing the 4 km grid to a local mesh of 2 km.

An additional 4 deep boreholes were drilled and long term monitoring including the acquisition of electromagnetic data (six years of data) commenced. One of the conclusions that was reached at this time was there was an absence of seismicity and the area was in a stable geodynamic context. Between 1999 and 2002, a 2 km by 2.1 km 3D seismic survey was completed to provide enhanced imaging at depths of between 200 and 800 m below surface (ANDRA, 2001).

7.3.2 Uveghuta Site - Granite, Hungary

The Üveghuta site is located near the village of Bátaapáti, in southern Hungary (Figure 7-15). 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).

Figure 7-15: The Üveghuta site in southern Hungary (GeoEye Inc.)

Regional tectonic and structural investigations around the proposed site were completed using a variety of geophysical methods, including gravity, magnetic, magnetotelluric, and seismic (Vertesy et al., 2004). A variety of ground based geophysical methods have also been used during the site selection phase (Vertesy et al., 2004) to characterise the overburden and to delineate the granite volume including resistivity, electromagnetic (TDEM), and magnetic methods (Vertesy et al., 2004). In the geological context of the site, the magnetic survey has identified the contact between the granite and adjacent geology. The investigation of the homogeneity of the interior of the granite body was conducted using 3D seismic tomography, magnetotelluric soundings, and resistivity.

In their report, Toros et al. (2004) suggest that the thick loess cover makes traditional electromagnetic and seismic methods impractical for the investigation of the interior of the granite body. Instead, they used borehole radar, cross-hole tomography, and shear wave reflection profiling to provide information on the composition, structure, and fracturing of the granite.

Results from these techniques have been jointly interpreted with geological and hydrogeological data. Seismic refraction and 2D seismic reflection surveys were also used to determine the upper crustal velocity structure in the vicinity of the site and to image major structural features.

7.3.3 Olkiluoto Site - Granite, Finland

An initial screening of over one hundred Finnish sites was made primarily using satellite imagery, aeromagnetic and gravity data (McEwens and Aika, 2000). The goal was to screen potential sites based on the inferred absence of large scale faults and fracture zones within the crystalline bedrock.

Based on these initial screening results, a more refined study phase was conducted using existing geological maps, aerial photos, and regional geophysical data. Further screening based on a variety of criteria led to the selection of the Olkiluoto site (Figure 7-16). The proposed Olkiluoto site is located in the Precambrian crystalline granite/gneiss bedrock along the southwest coast of Finland. The crystalline basement is covered by a thin soil overburden that ranges in general between 2 and 7 m thick with a maximum thickness of 20 m.

Construction of the Onkalo underground rock research facility at the Olkiluoto site began in 2000, following approval by the Finnish Parliament. Geophysics has played an important role in site investigations (McEwens and Aika, 2000). A wide range of geophysical methods have been used to characterise the overburden and the bedrock.

Magnetic and gravimetric measurements were done mainly for lithological mapping. Ground magnetic surveys have been conducted in 1989 and 2004 with a 50 m line spacing covering a large part of Olkiluoto Island. In 2007, a new ground magnetic survey was carried out at greater resolution at three test sites within the investigation area to enhance the existing anomalies and correlate them with known geological and geophysical features (Tarvainen and Lahti, 2008). VLF was used at some of the preselected sites but not at the Olkiluoto site because of interference from power lines (McEwens and Aika, 2000).

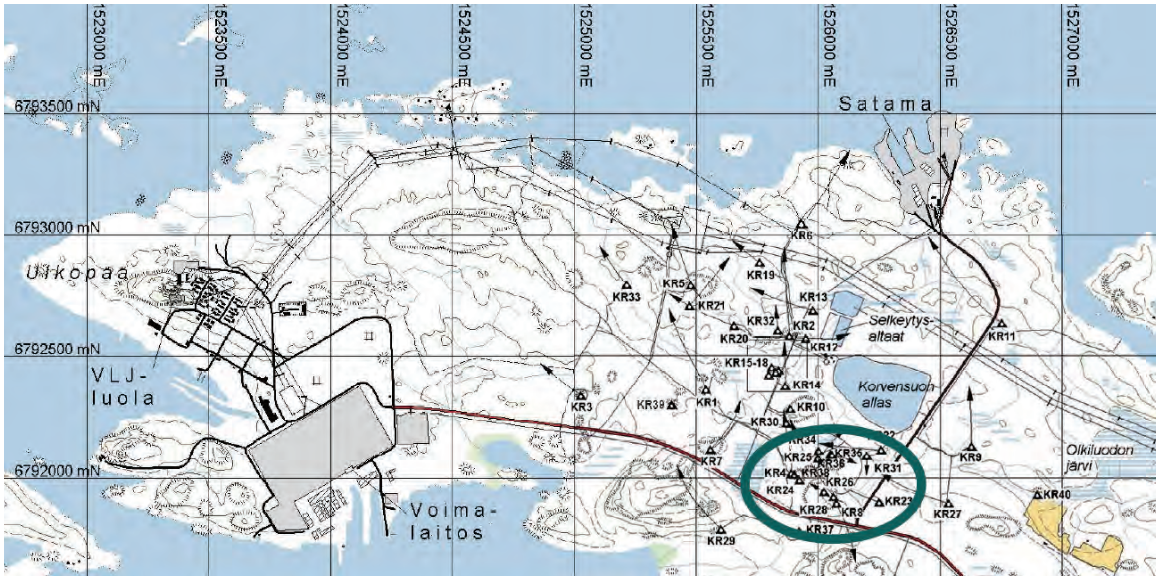

Figure 7-16: Map showing the location of the Olkiluoto site and the Onkalo underground rock characterisation facility. (POSIVA, 2007)

GPR was completed at all the preselected sites including Olkiluoto to provide information on the thickness of the unconsolidated deposits and the homogeneity of the bedrock surface. Seismic refraction surveys were carried out at only a few preselected sites (not Olkiluoto) to investigate the distribution of seismic velocities along lines where anomalies have been previously detected in earlier airborne and ground geophysical methods. Electromagnetic and seismic surveys were selected because of their good resolution and because they allow the investigation of large volume of granite. These two methods provided information on bedrock fracturing. Vertical seismic and vertical radar profiling surveys offered a detailed image of the bedrock around the various existing boreholes.

Acoustic seismic soundings carried out offshore over a large area (150 km^2) west of Olkiluoto allowed the mapping of the sea bottom and bedrock topography and the imaging of lineaments associated with fracture zones (Kuivamäki, 2005). Six seismic reflection profile lines were surveyed offshore to image fracture zones in the bedrock and to provide information on the 3D structure of reflecting horizons. Recently, a 3D seismic reflection study was done to image the presence of geological and structural features in the crystalline bedrock (Juhlin and Cosma, 2007). The presence of saline groundwater and conductive zones were mapped using “Mise a la masse” techniques (Lehtonen and Heikkinen, 2004). Seismicity has been estimated for all the preselected sites indicating the presence of zones of high and low seismicity in southern Finland (Saari, 2000).

7.3.4 Site Screening in Granitic Rock, Czech Republic

In 2003, the Radioactive Waste Repository Authority (RAWRA) in the Czech Republic conducted an airborne geophysics programme at six sites: Lubenec-Blatno, Božejovice-Vlksice, Pačejov Lodhéřov, Rohozná, and Budišov, all situated in granitic crystalline rock (Figure 7-17).

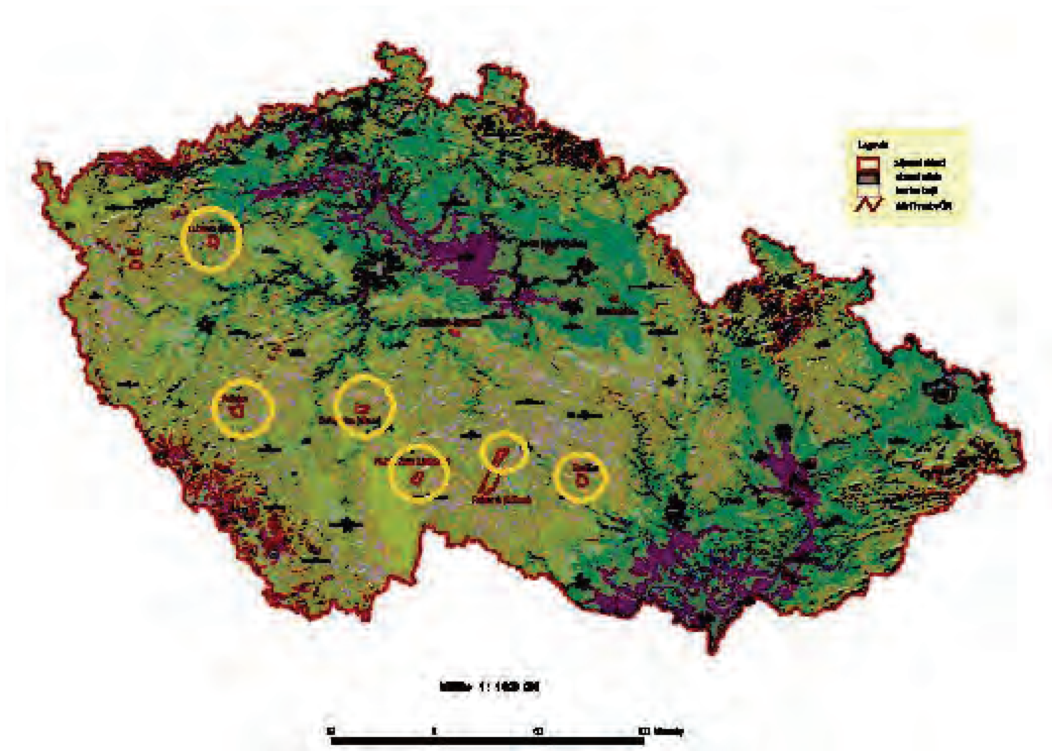

Figure 7-17: The six survey areas where airborne geophysics was conducted in southern and western parts of the Czech Republic. (McPhar Geosurveys Ltd., 2004)

A total area of nearly 240 km^2 was surveyed using helicopter based magnetometer, gamma spectrometer and frequency domain EM systems (McPhar Geosurveys Ltd., 2004).

The acquisition systems used were a Geometrics G-823 caesium magnetometer, a Pico-Envirotech GRS-410 gamma-ray spectrometer, and a Geotech frequency domain “Hummingbird” EM system (8.8 kHz to 34 kHz), along with a high resolution dGPS system and radar altimeter for positioning. Example magnetic survey results are presented on Figure 7-18.

After some initial challenges including deteriorating weather, coordinating schedules around military flight exercises and a moderate geomagnetic storm, a total of 1,845 line km were flown at the six sites over a 2 week period in November, 2003. These data were then used to develop an understanding of the geology and structure in the area and target anomalies for ground-based follow-up investigations. Although, there was significant interference in highly developed areas due to cultural features, in particular with respect to the magnetic and EM data sets, the survey was a great success.

Further site specific investigations are currently on hold, in view of the current negative public attitude towards the project (RAWRA, 2008).

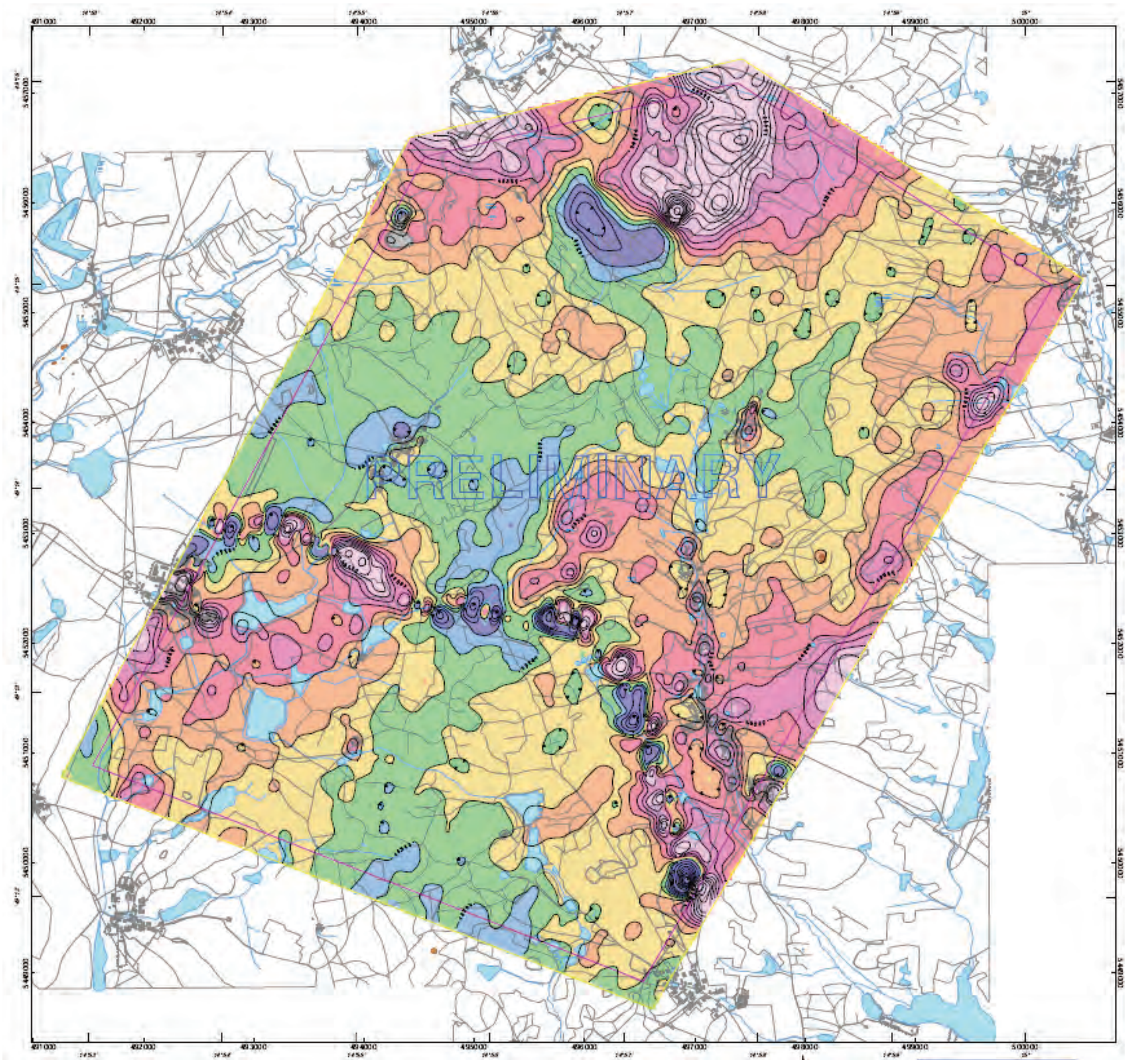

Figure 7-18: Example total magnetic field survey results, Czech Republic. (McPhar Geosurveys Ltd., 2004)

7.3.5 Mizunami / Shobasama Site - Granite, Japan

The Tono Geoscience Center has undertaken a research programme to develop the Mizunami Underground Research Laboratory project. This project is located at the Shobasama site in Mizunami city. The Shobasama site is located in the hilly country between the Kiso and Toki Rivers, where the Mizunami and Seto Groups overlie the Toki Granite.

The site is bounded to the northwest by the Mino-Hida Mountains and to the southeast by the Mikawa Mountains. The geology of the area consists of sedimentary rocks of the Mino Belt (Jurassic to Cretaceous), granites and rhyolite (Cretaceous), and later sedimentary rocks (JNC, 2001). The primary focus of the laboratory is to study the crystalline rock type as a potential host rock for a deep geologic repository.

Several ground and airborne geophysical investigations were conducted at the site. An aeromagnetic survey was used to delineate the geometry of the Toki granite and image linear magnetic features as potential faults. EM, magnetic, VLF-EM and gamma ray spectrometric helicopter borne surveys imaged a linear VLF anomaly along the Shoma River and provided information on the overburden depth.

A seismic refraction survey was carried out across the northern part of the Mizunami site to image faults and fracture zones within the granite and to resolve the unconformity at the base of the sediments. The structure of the granitic basement was further investigated by a seismic reflection survey which imaged reflective zones possibly associated with fracture zones. Vertical seismic profiling also provided complementary information on fracture zones.

The granitic basement was imaged as a high resistivity layer using a magnetotelluric survey (McCrank, 2002).

7.4 Summary

This section summarises the general approaches taken to geophysical studies at other repository sites, the results achieved, lessons learned, and the applicability of these geophysical methods to the Canadian programme for both sedimentary and crystalline host rock environments.

7.4.1 Approaches to Date

Geophysical methods have been an integral part of geosphere characterisation in all repository studies. Many surface and airborne geophysical methods have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development, and the available technology at the time.

The development and advancement of geophysical methods has been a journey of scientific discovery for repository site investigators, using state-of-the-science techniques and in some cases developing new techniques or at least optimizing and adapting existing methods for new applications and environments. Some examples of state-of-the-science approaches are the use of high resolution 3D seismic reflection by NAGRA at the Zürcher Weinland site in the Opalinus Clay sedimentary rock environment and the adaptation of high resolution seismic reflection methods in an effort to image crystalline rock environments by SKB and POSIVA at their sites, situated in Precambrian bedrock.

Geoscientific advancements have been accomplished through collaboration with other repository research groups, sharing ideas and best practices, and through strong, long term, working relationships with universities and other scientific organizations. There are many good examples of close collaboration between waste management agencies, universities and scientific organizations, such as the collaboration with SKB and Uppsala University in Sweden, and that of the US DOE and the USGS in the United States.

7.4.2 Best Practices – Sedimentary Host Rock

Based on the case studies reviewed in this report, it could be argued that, in general, sedimentary host rock environments can be more readily characterised by geophysical methods than crystalline rock environments. The most important geophysical technology applicable for this purpose is high resolution seismic reflection. Both 2D and 3D seismic reflection survey techniques developed for oil and gas exploration are relatively mature technologies that can be readily adapted to the characterisation of sedimentary rocks for the purposes of constructing a deep geologic repository.

Sedimentary rocks are stratified; this horizontal layering can be readily imaged with seismic reflection methods. Reflectors in the stratigraphic sequence can be used as marker horizons, which can be traced laterally over distances of many kilometres. Detailed analysis of these marker horizons in the seismic reflection data can yield tremendous and compelling insight into the continuity of the rock, the location of faults, and the tectonic history and stability of the region. These are all very relevant to modelling the geosphere and ultimately making the case for safe deep geological repositories. Seismic reflection can simultaneously provide detailed resolution on a scale of metres and confidence and understanding on a scale of many kilometres. An excellent example of this is the recent use of seismic reflection by NAGRA at the Zürcher Weinland site, which has set a new benchmark for the comprehensive characterisation of a sedimentary host rock environment.

Other geophysical methods will also be applicable to answering site specific questions about a particular sedimentary host rock environment. One example would be the use of techniques such as seismic refraction, gravity, magnetotelluric and teleseismic surveys to address issues related to deeper tectonic stability and volcanism, as was the case at the Yucca Mountain site. A variety of shallow geophysical techniques have also been used to characterise near surface features as part of detailed geosphere characterisation to support the safety case.

7.4.3 Best Practices – Crystalline Host Rock

Crystalline rock environments are more challenging to characterise with geophysical methods, as they have often undergone great changes since their original formation, which can result in very complex lithology and structure. Crystalline rocks invariably contain heterogeneities in the form of intrusions, alterations and fractures. Important features such as fractures are often subtle to detect, and while they may occur in one or two dominant orientations, they often occur in many orientations.

The techniques geophysicists most commonly use to investigate crystalline rocks for mineral exploration are primarily intended to identify the presence of base metals, which are typically electrically conductive and/or magnetic. What is most required for rock mass characterisation in the siting of a deep geological repository are geophysical tools that can detect and characterise, if present, fracture networks in the rock, as these are critically important to the geosphere model and development of the safety case.

While there have been significant advances in this technical area of geophysics, driven mainly by mining engineering and waste engineering, the problem is considerably more complex than in the sedimentary rock environment.

The geophysical programmes underway in Sweden and Finland by SKB and POSIVA are both good examples of the state-of-the-science in this area. Both programmes utilise a combination of geophysical methods to characterise the crystalline rock mass and potential structures within it, including magnetic, EM, TDEM, VLF, ERI, gravity, radiometric, seismic refraction, magnetotelluric, GPR and seismic reflection methods.

Of these, seismic reflection holds the most promise as the tool to image fractures, although the subtle impedance contrast and potentially complex orientation of fractures makes this very challenging. Part of the solution to this problem is the use of borehole seismic reflection and surface to borehole seismic reflection methods, which have been developed by northern European countries in the last decade. One of the pioneering companies in the area of seismic reflection in complex geometries is Vibrometric Oy, based in Finland. It should however, be noted that there has been considerable advances in the processing of seismic data and also the application of interpretative processing, in particular the use of coherency analysis which is used in automated interpretation (fault strand picking) of seismic data and has been very effectively applied in basement studies. These methods were unavailable at the times when these case studies were conducted and if applied now may result in different conclusions being drawn.

7.4.4 Case Studies - Lessons Learned

A sedimentary host rock environment is likely to be more readily characterised by geophysical methods than a crystalline rock environment. This does not in any way mean that a crystalline rock environment could not be a suitable host site for a repository, only that the characterisation effort required is likely to be significantly more substantial.

A comprehensive geophysical study plan needs to be developed prior to initiating field investigations. The geophysical study plan must be well integrated into the overall programme and should be designed to collect specific data for a specific purpose.

High resolution seismic reflection imaging (2D and 3D), when feasible, is likely to be the single most important surface geophysical characterisation tool for characterizing the geosphere and supporting the safety assessment.

A geophysics QA/QC plan needs to be developed prior to initiating any field investigations and this QA/QC plan needs to be sufficiently robust so as to meet the standards required to support the safety assessment for the repository.

Sites with existing infrastructure have the potential to cause unacceptable levels of interference with geophysical surveys that are necessary to complete the geosphere characterisation and support the safety case.

Collaboration with other repository research groups will be important in developing a sound geophysical investigation programme. There is a real opportunity to learn from past experiences and share new experiences and best practices. Repository programmes in other countries have also forged strong links to their universities. There exists considerable geophysics and remote sensing expertise at Canadian universities that could provide technical support.

8. CONCLUSIONS

This report presents a discussion of the available geophysical techniques that could be used at early stages of site evaluations for a deep underground repository for nuclear waste. The techniques considered in this report include satellite, airborne and surface based techniques, with the surface based techniques being subdivided into shallow and deep geophysical methods. The shallow geophysical methods described are, in general, designed to focus on small areas where a particular specific issue needs to be addressed. While these geophysical techniques may not be used in a reconnaissance survey to initially screen potential sites, they may be of value if a feature is observed in the wider surveys that require a specific targeted investigation.

This report presents a state-of-the-science review of the geophysical and remote sensing techniques and methods available, and highlights some of the ongoing research in applicable areas. The report provides guidance on the benefits that specific techniques may provide along with some constraints.

Although geophysical techniques are generally well established, continued advancements in microelectronics and computing power have and will continue to advance the state-of-the-science in applied geophysics. The volume and quality of geophysical data that can be practically and cost effectively acquired will continue to increase over time. Similarly, with computing power growing exponentially comes the ability to process larger volumes of data and perform more complex calculations than before. Innovations in other scientific fields will find new applications in geophysics. An example is the application of algorithms originally developed in medical screening and imaging which are now used in seismic processing and imaging.

Details on the accuracy and resolution of geophysical methods are provided. These are guidelines as they are dependent on many investigation specific factors, including depth of the target, geology and topography, to name a few. Without knowledge of these, further specifics cannot be provided.

A discussion of data processing is included in the report, although it is noted that processing for some methods is considered proprietary information by contractors who are not always willing to provide full details. Additionally, while this report outlines typical processing, there are considerable additional processing and interpretative processing methodologies that can be applied to geophysical data following standard processing. Some of the available additional processing techniques are also discussed in brief, in addition to some of the research work that is being carried out. However, the requirements for applying different processing methods are dependent on the geologic environment and the geological features to be imaged. The complexity of the site and surface conditions will also influence the type of additional processing that may be required. As such, the discussion of the additional processing methodologies is not exhaustive, but does provide some guidance on the more appropriate methods that could be applied and are more likely to be included or required.

Canada is well advanced in geophysical exploration for hydrocarbons (sedimentary rock environments) and at the forefront in geophysical exploration for mineral deposits (crystalline rock environments). As such, the equipment and the contractors required to perform the geophysical surveys and techniques discussed in this report are commercially available in the

Canadian market, recognizing that this is a specialty area, so the number of qualified providers is small. Canada is also well advanced in satellite imagery and remote sensing techniques, making these methods also readily available.

The report has also reviewed the geophysical investigations undertaken in some other countries around the world as part of their site characterisation programmes for a deep geologic repository, essentially looking from the perspective of the two geological environments most closely related to the Canadian programme: sedimentary and crystalline host rocks. This review complements the sections on geophysical techniques, as it illustrates the application of these methods in a relevant context.

What is perhaps most apparent is that the selection of geophysical methods has been dependent on the geology. At the characterisation stage, there has also been more reliance placed on geophysical methods in a sedimentary rock environment, whereas in a crystalline rock environment the emphasis has been on investigation by drilling and geophysical surveying. This is in part due to the inherent complexities of many crystalline rock environments, but also in part to the perception that geophysical techniques used to study sedimentary rocks are more maturely developed. While this may have been the case a decade ago, we suggest that this is truly only a perception, as geophysical techniques traditionally used in a crystalline rock environment have progressed considerably and geophysical techniques that have mainly been applied to a sedimentary rock environment are in fact directly applicable to a crystalline rock environment, with minimal adaptation.

Geophysical methods and remote sensing have been an integral part of the geosphere characterisation in all repository studies. Many satellite, surface and airborne techniques have been employed at the site screening stage. The method selection has been a function of the specific geology of the site, the questions that need to be answered to support conceptual geosphere model development, and the available technology at the time.

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