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Geophysical surveying techniques to characterise a site for a geological disposal facility: A review of recent developments and NDA's proposals

Final, March 2011

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Preface

The Environment Agency is responsible in England and Wales for regulating disposals of radioactive waste. The Nuclear Decommissioning Authority (NDA) is responsible for planning and implementing geological disposal of higher-activity solid radioactive waste. The NDA has established a Radioactive Waste Management Directorate (RWMD), which it will develop into an effective delivery organisation to implement geological disposal.

Any future permit to dispose of solid radioactive waste to a geological disposal facility (GDF) in England and Wales will be granted by the Environment Agency (EA), subject to the production of an acceptable environmental safety case. Guidance on the development of such safety cases and the expectations of the environment agencies is outlined in Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation (GRA).

The programme to implement the GDF will take many years. At present our role is to provide advice on regulatory issues. We have entered into an agreement with NDA to provide, and charge for, such advice during the early stages of the development of a GDF. Our scrutiny of the work by RWMD during these early stages enables us to:

- advise on the requirements for, and preparation of, future submissions to the regulators;
- improve our understanding of the safety and environmental performance of proposals for the GDF and provide our views on improving safety and environmental protection;
- provide guidance on regulatory issues that may arise;
- inform stakeholders of our requirements;
- inform RWMD of the work it will be required to carry out to meet our regulatory requirements during future stages;
- reduce the risk of unnecessary expenditure or delays during the formal regulatory stages.

This review was produced under the terms of the agreement between the Environment Agency and RWMD. This review was carried out under contract on behalf of the Environment Agency.

Environment Agency

Contents

Executive summary

This review was carried out by RSK STATS Limited on behalf of the Environment Agency (EA), under the terms of an agreement between the EA and the Nuclear Decommissioning Authority's Radioactive Waste Management Directorate (RWMD). It provides the contractor's view of RWMD's generic work on the application of geophysical surveying techniques to characterise candidate sites for a geological disposal facility (GDF). It includes a summary of the capabilities and limitations of relevant geophysical surveying techniques, and a critical review of RWMD's strategy for applying these techniques in its Geosphere Characterisation Project (GCP).

Licensing a GDF will be a staged process under the Environmental Permitting (England & Wales) Regulations 2010. RWMD will need to apply to the EA for a permit before it starts intrusive investigations at a candidate site. RWMD's application, at that stage, will include an initial site evaluation supported by information gathered using geophysical techniques. The EA will evaluate the evidence supporting RWMD's application and if satisfied that the proposals meet our regulatory requirements we will issue a permit. Thus, regulatory control will be established very early in the development of a GDF. This review will help the EA decide whether RWMD has used appropriate techniques to understand as much as possible about the sub-surface characteristics of a potential site before it disturbs the site. This is one aspect we will consider before we grant a permit to allow RWMD to progress to the next stage of intrusive investigations.

Geophysical surveying gathers subsurface data without disturbing a site and can be used to develop an initial understanding of the sub-surface conditions, in order to define and focus subsequent (more disruptive) investigations. Seismic reflection is likely to be the main geophysical surveying technique used at the site scale. Other geophysical surveying techniques could yield valuable additional information at the regional and the site scales.

Several geophysical surveying techniques are currently being investigated and developed to improve data acquisition and interpretation. These improvements should result in more accurate surveys and the ability to make better use of integrated acquisition and interpretation strategies in future.

RWMD's generic approach for using geophysical surveying to characterise a candidate site is set out in its GCP Status Reports, and is discussed further in two technical reports. RWMD intends to design its investigations based on a model typically used for oil-field investigations. Relatively low resolution regional surveys will be undertaken and the descriptive site model for a specific and smaller area of interest will be refined by more detailed surveys. However, RWMD has also proposed that it might construct some boreholes in the early stages of the investigation irrespective of geophysical data.

RWMD's plans do not demonstrate explicitly the flexibility that is likely to be required to address the many challenges in characterising a site. In most circumstances it is better to gather and interpret adequate geophysical data before drilling boreholes. RWMD should clarify how it will integrate and use information from interpreted geophysical data and borehole investigations.

RWMD recognises that developing a data management system and making it interact with visualisation and interpretation software is a considerable technical undertaking. RWMD will need to plan carefully how it will incorporate disparate geophysical data sets and interpretations with data and interpretations from other disciplines and test them thoroughly under operational conditions.

We have identified some specific recommendations, as a result of this review. These are not listed in any order of priority:

1. RWMD should embed the possible use of time-lapse geophysical surveys into its generic approach by first considering the role they could play throughout the development of a GDF. RWMD should identify any requirement for specific time-lapse geophysical surveys as early as possible after the selection of potential sites so that each survey in the sequence can be planned and integrated into the programme of site works.
2. Whilst recognising that RWMD’s present study is generic, we would expect RWMD to build in as much flexibility as practically possible when it reviews the terms of the generic site characterisation programme or develops a site-specific programme.
3. RWMD’s site characterisation programme should ensure that geophysical surveys precede and inform any borehole drilling, unless the technical requirements of a specific site dictate otherwise. The geophysical and borehole investigations should be fully integrated to optimise the detail, accuracy and coverage of the geological model.
4. RWMD should develop and test the data management system and any visualisation and interpretation software in operational mode using typical data sets before they are used in a site characterisation project. This will test the functionality of the system and software and help to train operatives.
5. RWMD should monitor the latest practical developments in geophysical techniques, and seek opportunities to incorporate relevant research and development into their programme.
6. The EA should continue to review RWMD’s generic site investigation programmes and any subsequent proposals developed for a candidate site or sites.

1 Scope and objectives

In 2001 Government initiated the Managing Radioactive Waste Safely (MRWS) programme to find a practicable solution for the UK's higher activity radioactive wastes. The Committee on Radioactive Waste Management (CoRWM) was established and, following extensive consultation, recommended to Government a long-term management strategy based on deep geological disposal following a period of robust interim storage (CoRWM, 2006).

Government accepted CoRWM's recommendation of geological disposal, coupled with safe and secure interim storage, along with a programme of ongoing research and development, as the way forward (UK Government, 2006). After further consultation the UK Government, in conjunction with the devolved administrations for Wales and Northern Ireland, produced the white paper *A Framework for Implementing Geological Disposal* (Defra, 2008) which sets out the UK Government's framework to implement the management of higher activity radioactive wastes.

The Nuclear Decommissioning Authority's (NDA's) Radioactive Waste Management Directorate (RWMD) is responsible for planning and implementing geological disposal. RWMD is developing an understanding of disposal in different geological environments and considering various design concepts for disposal of higher activity radioactive wastes and nuclear materials that may be declared as waste.

This report presents a systematic review of the geophysical surveying techniques that could be relevant to siting a geological disposal facility (GDF) in a range of geological environments in England and Wales and RWMD's proposed application of geophysical surveying techniques to characterise candidate sites as expressed in its generic work.

The objectives of this review are:

- To identify and describe the geophysical surveying techniques available, and assess their limitations, the information acquired and the geoscientific understanding that can be obtained from them; and,
- To review RWMD's strategy and proposed deployment of geophysical surveying techniques.

This review provides references as illustrative examples to support the text. It was not our intent to provide a comprehensive review of the available literature.

Section 2 of this report provides the background to the policy and regulatory frameworks. Section 3 discusses geophysical surveying techniques and summarises their potential application. Section 4 reviews RWMD's proposed strategy for the use of geophysical surveys. Section 5 provides conclusions and recommendations. Descriptions of geophysical surveying techniques and an appraisal of their potential application are contained in Appendices A and B.

2 Background

2.1 UK Policy

The White Paper, *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal* (Defra, 2008) provides the key elements of the policy framework for the long-term management of higher activity radioactive wastes in England, Wales and Northern Ireland[1].

- The UK's higher activity radioactive waste should be managed in the long-term through geological disposal in a facility between 200 and 1000 metres below ground.
- This will be preceded by safe and secure interim storage until a GDF can receive waste.
- There will be ongoing research and development to support optimised delivery of the geological disposal programme, and the safe and secure storage of the radioactive waste in the interim.
- The UK Government will pursue an approach to site selection based on voluntarism (that is, a willingness to participate) and partnership with local communities.
- The NDA is the body responsible for planning and implementing geological disposal in the UK.
- The arrangements will be subject to strong independent regulation by the statutory regulators.
- Scrutiny and advice to the Government on the implementation programme will be provided by CoRWM.
- The approach will be open and transparent, involving the public and stakeholders throughout the implementation process.
- The GDF will be implemented on a staged basis, with clear decision points allowing review of progress and assessment of costs, affordability, value for money, safety and environmental and sustainability impacts before decisions are taken on how to move to the next stage.

The staged approach to implementing geological disposal (Figure 1) will progress in a series of stages, beginning with a call for expressions of interest (via a screening stage), followed by a decision to participate from a volunteer community,

[1] The Scottish Government is not a sponsor of the current phase of Managing Radioactive Waste Safely, its policy for higher activity radioactive waste was published January 2011. It states that higher activity radioactive wastes should be managed in near-surface facilities as near to the site where the wastes were produced as possible.

desk-based assessment studies, and surface investigations, before development of a GDF and eventual underground operations.

Stages 4 and 5, which will include detailed desk-based and surface-based site characterisation studies, are of particular interest to this review. During these stages RWMD might review and reinterpret appropriate existing geophysical surveys, and could commission new surveys before starting any intrusive characterisation activities (i.e. drilling boreholes) that may disturb the site.

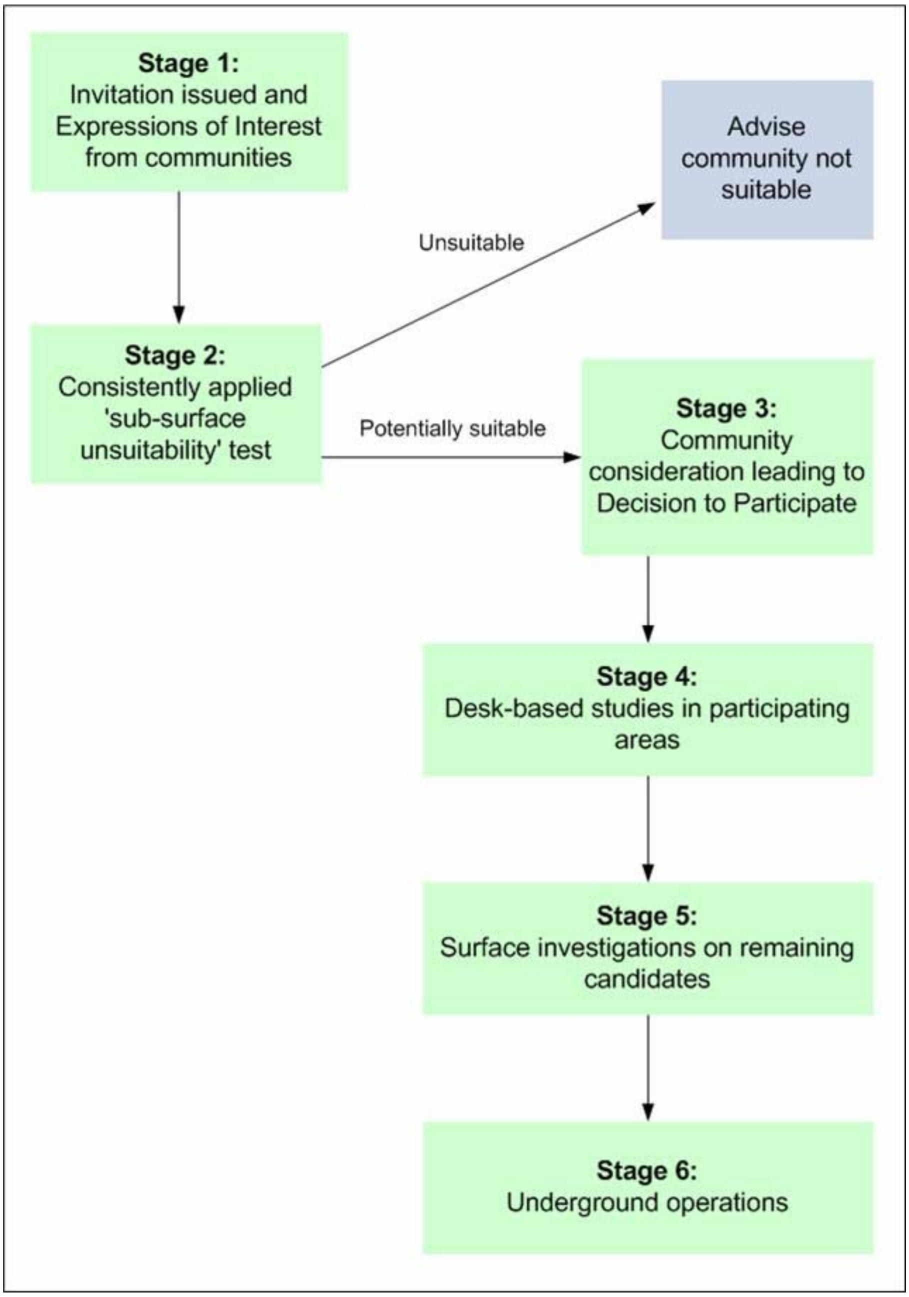

Figure 1. MRWS Site Selection Process

2.2 Regulation of site characterisation

The Environment Agency is responsible in England and Wales for regulating disposals of radioactive waste. RWMD will require a permit from the Environment Agency before it disposes any wastes to a GDF[2].

The Environment Agency's guidance (Environment Agency and Northern Ireland Environment Agency, 2009) describes the regulatory expectations that a developer of a GDF is required to meet. Requirement 11 addresses site investigation, and states the *"developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction."*

Using legal powers provided by the Environmental Permitting (England & Wales) Regulations 2010, the Environment Agency will regulate development of a GDF using a process known as "staged regulation". "Staged regulation" recognises the need to establish regulatory over sight very early in the development of a GDF and to maintain it throughout the development process. Staged regulation will involve a series of regulatory 'hold points' at important stages in developing a GDF. Figure 2 shows an indicative process for staged regulation[3]. A developer will need regulatory approval to proceed beyond a 'hold point' but work at a particular stage will not need to stop completely. A developer may continue to gather information while we consider an application to vary an environmental permit to allow development to proceed to the stage beyond the 'hold point'.

The first regulatory hold point will be before the start of surface-based intrusive site investigations, such as drilling boreholes, to investigate the geological conditions at one or more candidates sites. The developer must have an environmental permit before proceeding with intrusive site investigation. Figure 2 shows that the developer is expected to submit an Initial Site Evaluation report to support an application for an environmental permit for intrusive activities. We will base our decisions, including whether to grant such a permit, on this Initial Site Evaluation report.

At this stage, geoscientific understanding is likely to be based on information derived from existing sources and from non-intrusive surveying techniques, such as geophysics.

One of the regulatory aims, at this hold point, will be to check that any proposed intrusive site investigation will not compromise the integrity of a candidate site to

[2] In addition the developer of a disposal facility for solid radioactive waste will need to produce environmental statements as part of the environmental impact assessment (EIA) process. Under the EIA process, the planning authority is required to consult us and we shall give our views on the developer's environmental statements.

[3] **Note:** Since publication of the Guidance on Requirements for Authorisation, the preferred term has become staged regulation (rather than staged authorisation as used in the guidance).

the unacceptable detriment of the long-term environmental safety case for a possible GDF.

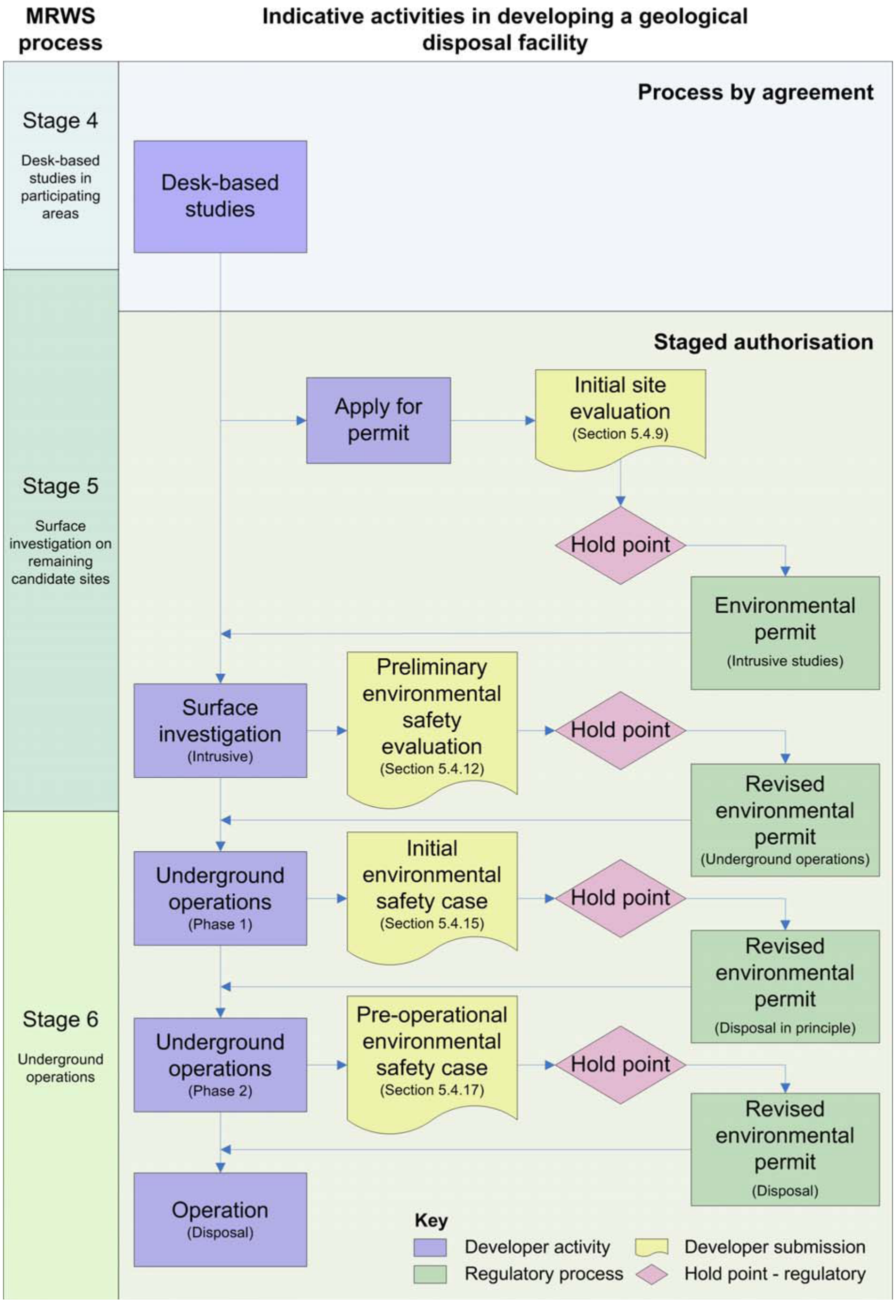

Figure 2. Process for staged regulation of a geological disposal facility (**N.B.** The section numbers in the figure relate to the Guidance on Requirements for Authorisation (Environment Agency and Northern Ireland Environment Agency, 2009), rather than to this report)

3 Geophysical surveying techniques

The following sections describe the geophysical techniques available to characterise a site for a GDF, and considers how they may be applied under different geological conditions.

3.1 Overview of geophysical surveying techniques

Geophysics studies the structure and physical conditions of the subsurface by measuring its physical properties. Variations in subsurface properties are interpreted (often using numerical techniques) to derive information, such as the likely or inferred presence of sub-surface geological structures. More reliable interpretations are likely to achieved by using supporting data (e.g. from boreholes).

Several different geophysical techniques exist. The advantages in using these techniques, particularly in the early stages of a characterisation programme include:

- they use non-intrusive[4] methods to get subsurface data at depth (which are not likely to disturb a candidate site, unlike intrusive methods);
- they can cover large areas or volumes of ground relatively quickly so they can be more efficient than intrusive activities, in terms of time and cost; and,
- they can help to define and focus subsequent investigations.

A geophysical survey will be planned to detect a particular feature, such as a geological structure, or the distribution of ground water. In areas where very little information is known about the subsurface, geophysical surveying can be used as a useful ‘reconnaissance’ tool to obtain an overview. The specific techniques to be deployed, and details of how they will be used will be tailored to the physical properties that need to be measured, and the resolution and depth of investigation required. Data may be acquired by the consultant that designed the survey, or by specialist subcontractors, who may also undertake the initial data processing. The data processing required depends on the type of data acquired, but typically includes some immediate quality control and visualisation of the raw acquired data. Initial processing will remove any low quality or spurious data, and will typically also attach location information. Subsequent processing and interpretation may take some time to complete, and will draw on information from other geophysical data; direct observations from any existing boreholes; and/ or sampling, to develop an interpretative model of the subsurface. Interpreting

[4] For the purposes of this report non-intrusive is taken to mean activities that are unlikely to result in significant or long-lasting damage to the protective capacity of a potential site for a GDF (i.e. they do not require or include the construction of boreholes or other significant excavation to significant depth).

information from some geophysical techniques may additionally involve a process of inverse modelling; a common scientific technique which is used to derive initial data values based on knowledge of the result, which in this case is the interpretative model. Undertaking such inverse modelling of geophysical survey data enables a consistency check to be made on the assumptions made during the development of the interpretative model.

An individual geophysical technique detects the contrasts in a sub-surface physical property. A particular volume of ground can be looked at in different ways, using a combination of two or more techniques, to build up a more complete and accurate picture. In the simplest sense, taking the results of three techniques in isolation can tell you three separate things about the subsurface. However, combining and comparing the results from two or more techniques allows much more information to be extracted than would be possible by analysing the individual techniques alone. For the example used here, comparing the results from each of the techniques with each of the others can tell you 9 separate things. Therefore, using a combination of geophysical data sets often allows a more detailed and robust interpretation to be made. Subsequent data from borehole records or exploratory excavations would add significant detail to this information and constrain the number of possible geophysical interpretations.

A summary of the geophysical surveying techniques, currently in use that may be relevant to the characterisation of a candidate site for a GDF is provided in Table 1.

A detailed description of specific techniques and discussion of their capabilities and limitations can be found in Appendix A. This review has drawn heavily on the experience of the author and discussions with a number of international experts. More detailed introductions to the theory and application of the geophysical techniques discussed here can be found in standard texts such as Reynolds (1997) and Kearey *et al.* (2002).

Table 1. Summary of geophysical surveying techniques relevant to characterisation of a candidate site for a GDF

Technique	Application	Limitations	Recent Advances and current research
Seismic Reflection Measures reflection of seismic waves and relates them to contrasts in sub-surface units (e.g. density)	Can be used to determine geological boundaries and indicate the presence and distribution of small scale faults and fractures relevant to the mechanical stability of the rock mass and the flow of fluid or gas.	Applicable to a wide range of geological environments. Resolution possible of 5-10m at depths of 500m to 1000m. Land-based surveys are more difficult to undertake than marine surveys due to the logistics of data acquisition and the sometimes complex near-surface weathered rock (and soils). For this reason land based surveys may yield lower resolution or less reliable data.	Advances in computational power have significantly enhanced 3D seismic interpretation (e.g. fracture permeability) and are also increasing the ability to infer rock properties. Cableless acquisition will simplify the deployment logistics for land surveys and may help to reduce impacts on the environment. Seismic interferometry is currently a major area of research and significant advances could be made in the next few years.
Seismic Refraction Measures refraction of seismic waves and relates them to boundaries between contrasting sub-surface units	Normally used to identify major sub-horizontal contrasts such as the top of bedrock.	Certain near-surface geological conditions such as the presence of a shallow high velocity layer (e.g. a massive limestone or an igneous sill) may restrict the effective penetration of the technique.	Advances in data inversion resulting in more accurate and detailed models of velocity variations.
Surface wave profiling Measurements of surface seismic waves are related to properties of sub-surface units	Used to determine major changes in geology with depth such as the top of bedrock.	Resolution is lower than the other two seismic techniques (reflection and refraction). Good continuous depth coverage relies on the ability to record a wide range of frequencies and may require long recording times.	Current research is addressing data processing to recover low amplitude or low frequency signals, and the capability of software to interpret the measured dispersion curves to provide a robust geological interpretation.

Technique	Application	Limitations	Recent Advances and current research
<u>Micro-gravity</u> Measures differences in the Earth's gravitational field and relates them to variations in the density of geological materials in the subsurface	Can determine the thickness of sedimentary sequences, variations in depth to basement rocks, and presence of large geological structures (such as faults and folds) And discrete high density features such as igneous intrusions.	Land based systems require quiet (low vibration) stable ground conditions. Marine and airborne systems are subject to the weather and navigational restrictions of their respective platforms.	Recent improvements in instrumentation allow more rapid and accurate surveys. Current research includes the development of gradiometer and tensor instruments.
<u>Magnetics</u> Infers the presence of magnetic, or magnetically susceptible materials, from disturbances to the local magnetic field	Can determine regional distribution of geological units and large scale geological structures, especially where they displace basement rocks.	Man-made infrastructure including buildings, roads, power lines and pipe lines generate significant magnetic anomalies that may mask the signals of interest.	Recent research has advanced the software to analyse and interpret the data. Joint inversion with gravity data becoming commonplace.
<u>Electromagnetic: Time Domain</u> Measures induced electrical currents and relates them to changes in sub-surface properties	Detects major changes in electrical conductivity with depth associated with the presence of significant bodies of fluid, major geological units, or mineralization.	Does not work in rocks with high electrical resistivity. Data is interpreted as a vertical profile of varying resistivity with depth and more than one equally valid interpretation may be possible.	The acquisition of multiple components of the electric and magnetic field, at multiple locations coupled with improved data analysis and modelling software have led to better constrained models.
<u>Electromagnetic: Frequency Domain</u> Measures induced electrical currents and relates them to changes in sub-surface properties	Provides information on the shallow geology, recent soil deposits or to determine the presence of man made ground.	Typically limited to the upper few 10's of metres.	Recent R&D has improved the effectiveness of airborne systems.

Technique	Application	Limitations	Recent Advances and current research
Electromagnetic: Magneto-Tellurics Measures variations in magnetic and electrical fields and uses their ratio to infer changes in sub-surface properties	Determination of major geological units, and for the identification of fluids.	Requires space on the ground to deploy the receiver array and (for CSAMT only) the transmitter dipole. Measurements can be disrupted by man made infrastructure, especially conductive features such as power cables and pipelines.	Faster data processing and data acquisition systems are now available. Recent advances have been made in the capabilities of marine systems.
Direct Current Electrical Resistivity Measurements of an applied direct electrical current are used to determine the resistivity of the ground.	Determination of geological units and fluids	Depth penetration is limited by the distance that current can be driven through the ground, typically to a maximum of 100m or so. Resolution decreases quickly with depth.	Faster and more stable data acquisition systems are now available. Increased computer power has increased the size of the data set it is possible to interpret.

3.2 Potential application of geophysical surveying techniques to different geological environments

A site to host a GDF has not been proposed or selected at the time of publication of this report, hence the geological setting of a GDF is unknown. Therefore, this review considers nine different geological environments which are representative of the range of plausible host environments in England and Wales (Metcalfe and Watson, 2009) to highlight the technical issues relevant to geophysical surveying.

On the basis of the appraisal reported in Appendix B it is likely, although not certain, that seismic reflection will be the dominant geophysical investigative tool at the site scale. Dependent upon the geological environment, and the specific geological and logistical challenges of the characterisation project a number of other geophysical techniques could yield valuable additional information both at the regional and the site scales. As the ground models develop, the information and detail required will change as will the application and targeting of the suite of geophysical tools. In this evolving investigation the role of the geophysical experts is key to ensure geophysical techniques are used appropriately and efficiently, and to ensure they are effectively integrated with other sources of information, and to keep abreast of new developments and to encourage their implementation accordingly.

A fuller description of the geological environments is presented in Appendix B. Also included in Appendix B is an appraisal of the potential application of geophysical surveying techniques to each representative geological environment. It should be noted that this is not intended to be used as a guide for designing geophysical surveys as part of a characterisation programme. Appropriate experts will need to assess the specific technical application of geophysical techniques at the survey design stage for a specific site.

4 RWMD's strategy for the use of geophysical surveys

4.1 The Geosphere Characterisation Project

The Geosphere Characterisation Project (GCP) was commenced in October 2004 by Nirex and has been continued by RWMD following its formation[5]. RWMD's stated objectives for the GCP (NDA, 2008) are to:

- Maintain and develop the understanding of approaches to the design and implementation of information-led investigations (surface-based and underground investigations, etc) and input this knowledge and understanding into discussions with key stakeholders, as necessary;
- Undertake sufficient preparatory work such that, if required, surface-based investigations could be implemented at a selected site(s) in a timely and efficient manner; and,
- Support other activities where knowledge of geological and hydrogeological issues are relevant.

The stages of the GCP (Nirex, 2005) are shown in Figure 3.

The methodologies applied in the GCP are generic so that they remain relevant regardless of the specific challenges that may be presented by candidate sites. Because candidates sites are not known or assumed within the GCP it is generic and there are several uncertainties relevant to planning and implementing future geophysical surveys. The lack of a site means that it cannot be known for example:

- whether the geophysical surveys will be restricted to land-based and airborne, or whether marine surveys will also be needed
- what sort of challenges the terrain will offer
- how the exact surveys will need to be optimised for the specific geological conditions.

Notwithstanding these limitations the GCP provides an opportunity to review RWMD's proposals in this area.

[5] The ongoing RWMD project relating to site characterisation is now called the "Preparations for Surface-based Investigations Project".

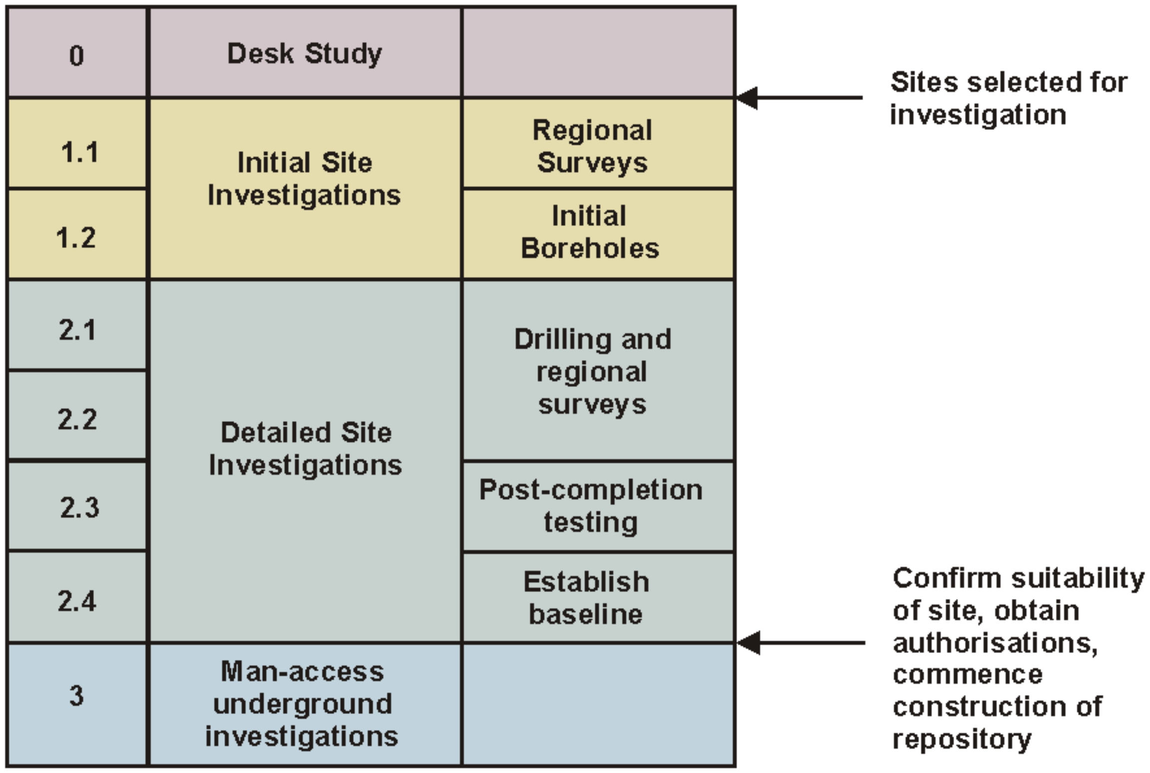

Figure 3. Stages in the GCP (Nirex, 2005)

The aim of the GCP is to demonstrate an understanding of the key considerations for characterising potential sites in preparation for when sites have been identified as potential hosts for a GDF. RWMD's ongoing generic studies within the GCP are reported in a number of reports. The reports below are particularly relevant to the use of geophysical surveying techniques for characterising sites and are referred to throughout this review:

Geosphere Characterisation Project: Status Report: October 2007 (NDA, 2008)

Geosphere Characterisation Project: Status Report: October 2006 (Nirex, 2006)

Geosphere Characterisation Project: Status Report: March 2005 (Nirex, 2005)

Data Acquisition Report: Surfaced-based geophysical techniques (Golder Associates, 2008)

Geophysical Characterisation, Strategic Overview (Golder Associates, 2006)

We reviewed these reports and met with RWMD to discuss its strategy for using geophysical techniques in the site characterisation process (Tuckwell and Thomson, 2009). The review and discussions are reflected in Section 4.2 of this report. We have made some recommendations which are highlighted in the text where they arise and are summarised in Section 5.

It is also relevant to note that the central tenets of the Geosphere Characterisation Project (i.e. Nirex, 2005) pre-date the June 2008 publication of the government White Paper (Defra, 2008). The ethos of 'volunteerism and partnership' and the staged site selection process that define the MRWS Site Selection process (e.g. Figure 1) are not yet explicitly recognised within the GCP.

4.2 Proposed use of geophysics within the GCP

RWMD's generic approach for using geophysics to characterise a potential site is set out in Nirex (2005), and is discussed in later documents, in particular those commissioned from Golder Associates (2006 and 2008).

RWMD anticipates that geophysical surveying techniques will contribute significantly to the descriptive models of the geology of the site that are developed and reviewed iteratively throughout the characterisation programme.

RWMD proposes to design the investigations in a manner similar to that typically followed for oil field investigations. Initially relatively low resolution regional surveys will be undertaken. Then a descriptive site model will be refined by more detailed surveys for a specific and smaller area of interest in which the disposal facility is to be located.

Nirex (2005) describes stages of data acquisition and use of geophysical techniques, related to the descriptive site model (the Stages refer to those indicated in Figure 3):

- Stage 0 comprises desk studies to compile and integrate available information, including collating, reprocessing and interpreting existing geophysical data. Regional geophysical data sets held by the British Geological Survey (e.g. BGS, 2005) will also be available for use, together with other British Geological Survey data.
- Stage 1.1 includes using airborne and ground geophysical surveys to provide 'regional' geological information.
- Stage 1.2 continues geophysical surveys and begins to use down-hole and cross-hole geophysics to support the geophysical surveys undertaken in Stage 1.1.
- Stage 2.1 uses high resolution geophysical surveys (e.g. 3D seismic reflection surveys) targeted on the area of the proposed GDF.
- Stage 2.2 comprises continued cross-hole and down-hole geophysics (these are not considered within the scope of this review).

During Stage 1 regional geophysical surveys will be designed to characterise a sufficiently large area in order to identify a 10km^2 target area representative of the best potential volume to site a GDF. In Stage 2 site specific surveys will characterise in maximum detail the potential volume of rock within which the disposal facility will be located.

The geophysical characterisation strategic overview (Golder Associates, 2006) outlines an approach based on investigating basement rocks under sedimentary cover. The report notes that if the geological environment is different from this the details of specific geophysical techniques or survey parameters may be different but the proposed methodology would not be. The report emphasises that geophysical investigations must be "*embedded in a holistic approach"*, that is to say that it is necessary not only to consider the development of geological models, but also the uses of the data from the geophysical investigations in the development of other models and performance assessment. Furthermore the report notes that the need for long term or time-lapse surveys should also be identified and planned for at an early stage. The report also suggests that the proposed methodology is for regional surveys followed by more detailed local surveys (perhaps implemented as a campaign of airborne geophysics with some surface gravity profiles and 2D), followed by a 3D seismic reflection survey of the specific volume in which it would be proposed to locate a GDF.

Golder Associates (2006) summarises the minimum geophysical surveying requirements for a site characterisation programme as follows:

- Regional Investigation
    - Satellite and airborne geophysics
    - 2D seismic surveys
    - Gravity surveys
- Site survey
    - 3D seismic surveys
    - Gravity surveys
    - Electromagnetic surveys
    - Seismic monitoring network
    - High resolution near-surface geophysics

Golder Associates (2006) develops the proposals outlined in Nirex (2005) in which there is an emphasis on the need for a detailed understanding of the requirements of acquisition and processing to ensure that appropriate surveys are undertaken. Within the GCP RWMD has developed a 'needs based' approach to site characterisation that it proposes may help to acquire, use and refine comprehensive data. In some areas RWMD should provide more clarity on the potential applications of a technique within a generic or site-specific characterisation programme. For example, the potential use and requirements of time-lapse surveys are not strongly represented in RWMDs generic approach detailed in the existing GCP status reports. However, we note it is also important to ensure that the approach is reviewed when the project progresses and as activities move from a generic to site specific basis.

Recommendation 1

RWMD should embed the possible use of time-lapse geophysical surveys into its generic approach by first considering the role they could play throughout the development of a GDF. RWMD should identify any requirement for specific time-lapse geophysical surveys as early as possible after the selection of potential sites so that each survey in the sequence can be planned and integrated into the programme of site works.

4.2.1 Relationship of geophysical surveying to borehole construction

Geophysical survey techniques offer a way of getting information to support a submission for permission to start intrusive investigations without disturbing the site (or existing characteristics). A key consideration is the timing and extent of borehole construction and the degree to which such activities are guided by geophysical surveys.

RWMD has suggested that it will design geophysical surveys using existing information which it identifies from the Stage 0 desk studies. At a meeting RWMD noted that the reprocessing of existing geophysics data sets is included within the early stages of GCP (Tuckwell and Thomson, 2009). RWMD suggested that it would place emphasis in the early stages on reprocessing existing data rather than acquiring new data because acquisition costs are much greater than reprocessing costs. We note that pre-existing data may have been acquired for different purposes, and perhaps some time ago, and RWMD will need to consider the relative value of a new survey specially designed for the purpose, using modern equipment and software.

The GCP Status Reports state that RWMD will use regional geophysical surveys to feed into a preliminary geological model and that the emphasis at Stage 1.1 will therefore be on 2D seismic and airborne gravity and magnetic surveys (e.g. Nirex, 2005). However, RWMD stated (Tuckwell and Thomson, 2009) that it believes it may be possible (depending on the local geological conditions) to drill some boreholes before geophysical surveys have been performed in order to define the general stratigraphy. RWMD proposes that results from the geophysical surveys will then be used to define the geological structure, which may then be investigated by subsequent boreholes. RWMD envisages that perhaps only a subset of the borehole locations will be defined using geophysical surveys because some locations may be readily identified based on existing information from Stage 0. RWMD states that this would enable some boreholes to be constructed in an initial 'ramping up' phase before data from geophysical surveys are available.

RWMD’s current plans to integrate geophysical surveying into the investigation programme aim to allow drilling work to proceed continuously for cost efficiency reasons (e.g. Nirex, 2007). Therefore, there will be ongoing tension between the time needed to interpret the geophysics and to refine the geological model, and the need to determine where the next boreholes are to be drilled. The revised program presented in Nirex (2007, Section 6.3.6) seeks to address these tensions in part by slowing down the investigation, primarily by reducing the number of drilling rigs deployed concurrently.

Within the detailed investigations in Stage 2 RWMD intends to limit the number of boreholes drilled in the potential volume of rock within which a GDF would be located (e.g. Nirex, 2005). RWMD proposes that it could progress 3D seismic surveys while drilling boreholes outside, but immediately surrounding, the GDF potential volume. Depending on the locations of the pre-existing 2D seismic lines in relation to this area of detailed investigations, RWMD may run some additional 2D seismic surveys to enhance the coverage.

We consider RWMD's ability to optimise a site investigation programme in the context of evolving technical challenges and a variety of geological, environmental and logistical challenges will require considerable flexibility. The staged approach currently proposed in the GCP appears quite rigid and it is not obvious how flexibility has been or could be built in. Obtaining a thorough coverage of interpreted geophysical data before boreholes are drilled is, in most circumstances, considered technically beneficial. This approach is not implicit in RWMD's plans. The mechanism for planning and carrying out geophysical surveys to feed in to the holistic characterisation programme has not yet been addressed at a practical level.

Recommendation 2

We recognise that RWMD's present study is generic, and we expect RWMD to build in as much flexibility as practically possible when it reviews the terms of the generic site characterisation programme or develops a site-specific programme.

Recommendation 3

RWMD's site characterisation programme should ensure that geophysical surveys precede and inform any borehole drilling, unless the technical requirements of a specific site dictate otherwise. The geophysical and borehole investigations should be fully integrated to optimise the detail, accuracy and coverage of the geological model.

4.2.2 Managing data and its interpretation

RWMD proposes that all geophysical data sets will have associated metadata. Metadata includes information that defines how the data have been treated after they have been acquired. These would be delivered to the characterisation project team through interpretative reports. These reports would include statements on the limitations, uncertainties and resolution of the interpretation, together with any underlying assumptions made. Independent quality control would be set up to review the geophysics data sets and interpretations, and RWMD intends to subject its work to peer review via the supply chain. RWMD's High-Level Advisory Panel includes expertise in geophysics who would provide an overview of RWMD's planning and procedures (e.g. for interpretation).

RWMD anticipates that data will be interpreted and integrated into a coherent model by a panel of experts (a Joint Interpretation Panel or similar). Multiple geological models may be taken forward in order to assess uncertainty (i.e. the multiple working hypothesis approach), particularly in the early stages. Opportunities will exist to revisit existing and acquired data in cycles of processing and model refinement.

RWMD intends to subject its characterisation programme to peer review. We note that this is an important and valuable oversight role. We stress that, for it to be successful, it must be resourced adequately, with sufficient time allowed for the reviews to feed effectively into the iterative development of the characterisation work. The value of peer review work would be greatly reduced if the characterisation programme had moved too far into the next iteration before the reviews could report and/or RWMD could consider their feedback, or if there was insufficient time for the respective experts to complete their work to the required standard.

The overall characterisation programme is underpinned by the strategy for data management and visualisation. RWMD's data management strategy is set out in Tessella (2007). RWMD intends to keep the database of data and information separate from project management and interpretation tools. The advantage of this approach is that it simplifies data management, and reduces the technical requirements of the visualisation software.

Modern visualisation tools integrate map and 3D volume data with borehole and other subsurface data in 2D and 3D. Users can manipulate a volume of surface and subsurface geochemistry, geophysics, and geology data in 3D within a single or transparently linked interactive environment. These tools are very powerful, and provide invaluable insights into what the data mean.

The information fed in to such software must be controlled, and quality and format criteria must be applied consistently. This poses a potential operational problem for a new or untested system. A visualisation system used purely to interrogate interpretations from individual surveys and investigations uses typically the best information that can be attributed to the data set at that time. The construction of conceptual models takes this one step further, and requires alternative interpretations derived from separate data sources to be considered and any conflicting interpretations to be resolved. When a model is refined in an iterative way it will be necessary to revisit certain interpretations and to understand the confidence that can be placed on the interpretation and the data on which it is based. Interpretations that are well constrained by reliable data and therefore considered 'fixed', and those based on data with scope for reinterpretation or dismissal in the light of better data, should be identified.

There are a number of strategies to achieve this. An approach used by the petroleum industry is to progress multiple interpretative models (Bond *et al.*, 2008). When new data become available the range of concepts and interpretational models are refined. Non-viable interpretations are removed in each iteration, and viable concepts are attributed a risk or confidence level. Confidence levels for interpretations based on geophysical data would refer to the limitations of the data originally obtained, and the improvements achieved by revising and refining the interpretations, as additional controls and calibration points become available.

Recommendation 4

RWMD should develop and test the data management system and any visualisation and interpretation software in operational mode using typical data sets before they are used in a site characterisation project. This will test the functionality of the system and software, and help to train operatives.

4.2.3 Research and development

RWMD's research strategy includes a theme on site characterisation (NDA, 2009). RWMD noted that its approach to research and development related to geophysical surveying is generally reactive.

Many geophysical techniques are subject to research and development in various industry and academic sectors. Advances may be made in future years that could be relevant to site characterisation. In particular this could include the development of new acquisition platforms for airborne gravity and magnetic data and the joint inversion of airborne data to define geological structure. Seismic attribute analysis, velocity anisotropy and interferometry are of considerable interest to the petroleum industry and show great promise in delivering subsurface information relevant to site characterisation.

RWMD should monitor developments in geophysical techniques, and seek opportunities to support relevant research and development.

Recommendation 5

RWMD should monitor developments in geophysical techniques, and seek opportunities to incorporate relevant research and development into their programme.

4.2.4 Environmental impacts

RWMD may need to justify using certain surface geophysical techniques, such as 3D seismics, that can affect the environment. RWMD may also have to produce an acceptable EIA to support its proposals.

RWMD and the regulators should consider the need for an EIA and the possibility of any environment impact from the use of geophysical surveying techniques at an early stage so that any necessary lead in times for permissions can be built into the investigation programme. We note that recent literature has reported the use of cableless surveying (Chitwood *et al*. 2009) and such advances in acquisition methodology may result in less environmental impact.

5 Conclusions and recommendations

This report has presented an overview of modern geophysical techniques, and has discussed their potential benefits and limitations for characterising GDF sites. The report has also evaluated their application to geological environments representative of those found within England and Wales.

Geophysical surveying is advantageous in that it can acquire subsurface data without the need to disturb a site. In the early stages of a characterisation programme geophysical surveying can be used to develop an initial understanding of sub-surface conditions which can help define and focus subsequent investigations. We consider it is likely, although not certain, that seismic reflection will be the dominant geophysical investigative tool at the site scale and that a number of other geophysical techniques would be expected to yield valuable additional information both at the regional and the site scales.

Several techniques are the subject of ongoing research and development to improve data acquisition and interpretation in order to enable surveys which are more accurate and make better use of integrated acquisition and interpretation strategies.

RWMD is responsible for undertaking a characterisation programme that is technically robust, minimises environmental disruption, and provides value for money. The extent to which RWMD intends to use geophysical surveying in meeting these goals is not clear from its strategy and status reports.

RWMD's plans do not demonstrate explicitly the flexibility that is likely to be required to address the many challenges in characterising a site. In most circumstances it is better to gather and interpret adequate geophysical data before drilling boreholes. RWMD should clarify how it will integrate and use information from interpreted geophysical data and borehole investigations.

RWMD recognises that developing a data management system and making it interact with visualisation and interpretation software is a considerable technical undertaking. RWMD will need to plan carefully how it will incorporate disparate geophysical data sets and interpretations with data and interpretations from other disciplines and test them thoroughly under operational conditions.

We have identified some specific recommendations, as a result of this review. These are not listed in any order of priority:

1. RWMD should embed the possible use of time-lapse geophysical surveys into its generic approach by first considering the role they could play throughout the development of a GDF. RWMD should identify any requirement for specific time-lapse geophysical surveys as early as possible after the selection of potential sites so that each survey in the sequence can be planned and integrated into the programme of site works.

2. We recognise that RWMD's present study is generic, and we expect RWMD to build in as much flexibility as practically possible when it reviews the terms of the generic site characterisation programme or develops a site-specific programme.
3. RWMD's site characterisation programme should ensure that geophysical surveys precede and inform any borehole drilling, unless the technical requirements of a specific site dictate otherwise. The geophysical and borehole investigations should be fully integrated to optimise the detail, accuracy and coverage of the geological model.
4. RWMD should develop and test the data management system and any visualisation and interpretation software in operational mode using typical data sets before they are used in a site characterisation project. This will test the functionality of the system and software, and help to train operatives.
5. RWMD should monitor the latest practical developments in geophysical techniques, and seek opportunities to incorporate relevant research and development into their programme.
6. The EA should continue to review RWMD's generic site investigation programmes and any subsequent proposals developed for a candidate site or sites.

Glossary and list of abbreviations

Bathymetric	Relating to measurements which are taken to record the depths of water bodies such as lakes or oceans (the below water equivalent to topographic measurements of land surface).
Bedrock	Compacted, hardened rock which is normally overlain by weathered rocks and soils.
Competent	A rock layer which possesses sufficient mechanical strength or stiffness to enable it to flex without significant shear when subjected to stresses.
CoRWM	Committee on Radioactive Waste Management.
CSAMT	Controlled Source Acoustic-frequency Magneto-Tellurics (see also Electromagnetic: Magneto-Tellurics).
Cultural interference	Signals or anomalies recorded by a geophysical instrument that relate to manmade features or activities, and not to the natural subsurface variations of interest to the survey.
Data inversion	The process of determining a model of the subsurface that is calculated to match the geophysical anomalies recorded in the data.
Direct Current Electrical Resistivity	Direct (DC) electrical current is driven between a pair of electrodes, with the resultant potential difference measured by two further electrodes to determine the resistivity of the ground.
Disposal	Disposal is the Emplacement of waste in a specialised land disposal facility without intent to retrieve it at a later time; retrieval may be possible but, if intended, the appropriate term is Storage. We shall regard the time of emplacement as the time of disposal, even if the facility is eventually closed many years later.
Electromagnetic: Time-Domain	Involves generating an electromagnetic field which induces a series of currents in the earth at increasing depths over time. These currents, in turn, create magnetic fields. By measuring these magnetic fields, subsurface properties and features can be deduced.

Electromagnetic: Frequency Domain	Involves generating an electromagnetic field which induces current in the earth which in turn causes the subsurface to create a magnetic field. By measuring this magnetic field, subsurface properties and features can be deduced.
Electromagnetic: Magneto-Tellurics	The measurement of the Earth's electric and magnetic fields over a range of frequencies to enable imaging at large depths. When an artificial source is used the technique is referred to as Controlled Source Magneto-Tellurics. Controlled Source Acoustic frequency Magneto-Tellurics refers to an implementation which records data in the acoustic frequency range.
Geological Disposal Facility	An engineered facility for the disposal of solid higher activity radioactive wastes.
Geophysics	A branch of earth sciences which studies the structure and physical conditions of the Earth's subsurface by the quantitative observation of its physical properties.
Geophysical surveying	The study of variations in physical parameters of geological strata in order to determine sub-surface structures. Methods may involve the study of ambient fields (e.g. gravity) or the effects of applied fields (e.g. seismic) and are non-intrusive.
Geosphere Characterisation Project	A generic project being undertaken by RWMD to assist in planning and preparing for the site characterisation that would be required to support the development of a future GDF.
Ground Penetrating Radar	A system that transmits electromagnetic waves at radar frequencies into the ground and records the arrival of reflections back at the surface.
Higher Activity Radioactive Waste	Radioactive waste having a radioactive content exceeding 4 gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma activity and any radioactive wastes below these thresholds that are unsuitable for near-surface disposal.
ILW	Intermediate Level Waste. Radioactive waste exceeding the upper activity boundaries for low level waste (LLW) but which does not need heat to be taken into account in the design of disposal facilities.
LIDAR	Light Detection And Ranging. An optical remote sensing technique which uses the transmission of a light pulse (e.g. laser) to produce 3D images such as topographic maps of the land surface.

MRWS	Managing Radioactive Waste Safely is a Government initiated programme to find a practicable solution for the long-term management of the UK's higher activity wastes.
Magnetic surveying	The measurement of the Earth's magnetic field to locate local variations caused by magnetic or ferrous materials
Magneto-Tellurics	See Electromagnetic: Magneto-Tellurics
Metadata	The descriptive information embedded inside an data file or other type of file
Micro-gravity	The measurement of the Earth's gravitational field to locate variations caused by local differences in the density of materials in the subsurface
NDA RWMD	The Nuclear Decommissioning Authority's Radioactive Waste Management Directorate, which now has many of the responsibilities that were formerly associated with Nirex.
Nirex	Nuclear Industry Radioactive Waste Management Executive was a body established in 1982 to develop a long-term solution for the disposal of the UK's radioactive waste. Staff and resources were transferred from Nirex into the NDA in March 2007.
Non-intrusive	Activities that are unlikely to result in significant or long-lasting damage to the protective capacity of a potential site for a geological disposal facility (i.e. those that do not require or include the construction of boreholes)
Seismic attribute analysis	A measure of a characteristic of a seismic signal derived from the seismic data. Typical attributes include the amplitude, frequency or phase of the seismic wave.
Seismic interferometry	The analysis of correlated seismic noise signals obtained from one or more recording locations to construct images of the subsurface seismic properties.
Seismic waves	Seismic waves are waves that travel through the Earth's subsurface as a result of an earthquake, explosion, or some other process that imparts a short duration impulsive disturbance.
Seismic reflection	The recording of the arrival of seismic waves generated at or near the surface and reflected back to recording instruments from the interface between materials with contrasting seismic (elastic and density) properties

Seismic refraction	The recording of the arrival of seismic waves that are refracted along the interface between materials with contrasting seismic (elastic and density) properties
Site characterisation	Surface and sub-surface investigations to determine the suitability of a site to host a disposal facility for radioactive waste and to gather information about the site to support an environmental safety case.
Stakeholder	People or organisations, having a particular knowledge of, or interest in, or being affected by, radioactive waste, examples being the waste producers and owners, waste regulators, non-Governmental organisations concerned with radioactive waste and local communities and authorities.
Surface wave profiling	A technique which measures the velocity of surface (Rayleigh) waves of different frequencies to calculate the elastic shear stiffness values at different depths in the subsurface.
Tectonised	The geological description of a rock that has been subjected to significant deformation due to forces generated by the movement of the earth's crust.
Time-lapse	The recording of multiple data sets at the same location at different times in order to determine change.
VLF	Very Low Frequency – An electromagnetic geophysical technique that measures the local properties of very low frequency radio transmissions to relate variations to the electrical conductivity of the ground.

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Appendix A. Geophysical surveying techniques

A.1 Seismic Reflection

A.1.1 Overview

Elastic energy injected into the ground by an impulse or vibrating source will propagate through the ground as elastic or seismic waves. There are two types of wave that propagate through a solid. A pressure wave, of which a sound wave is one example, where the particle motion causes dilation and compression in the direction of propagation of the wave. The second wave type is the shear wave, in which the particle motion is perpendicular to the direction of the propagation of the wave front. The pressure and shear waves are also referred to in shorthand as p-waves and s-waves respectively.

Where a wave encounters a contrast in acoustic impedance (determined by the elastic properties of a material and its density) a proportion of the wave energy will be reflected. Recordings of the seismic waves reflected back to the surface can then be processed to construct an image representative of the subsurface.

Any geological boundary can represent a contrast that would generate a reflection. As such the technique can provide detailed information on the geometry of sedimentary sequences, structural faults, igneous intrusions and evaporite deposits. Dependent upon the nature of the data additional information can be derived from the seismic velocity absorption or anisotropy of individual units.

A.1.2 Application

The technique is likely to be useful in a wide range of geological environments because of its ability to produce an image of the subsurface that can be tied directly to a geological model. Details of individual geological units can be traced across the survey volume, and structural features can also be mapped. In addition, advanced processing can be undertaken to obtain other characteristics of the seismic waves that can be linked to specific physical properties of the rock mass such as fracture density and orientation, porosity and rock mass strength. These wave characteristics are called “attributes”, and examples of seismic attributes include the amplitude, frequency or phase of the seismic wave

A.1.3 Limitations

The ability of a seismic data set to image a geological feature is largely a function of the frequency content of the seismic data, with a higher frequency content leading to greater resolution. The frequency content of a seismic data set is controlled by the seismic source type. Large explosive charges have higher energy low frequencies than smaller explosives. Frequency sweep sources such as Vibroseis land trucks or tuned air guns rely on the control provided by a known source wave containing a range of frequencies and the frequency content will depend on the system and configuration deployed.

Higher frequencies provide higher resolution, but are more quickly absorbed by the earth and so have limited depth penetration. The theoretical resolution of features within a data set is equal to one quarter of the wavelength of the seismic signal. In practice other factors affect the signal to noise ratio and reduce the resolution achieved.

In the upper 500m to 1000m resolutions of between 5-10m are achievable (Gillot *et al*., 2005; Peters and Hendrick, 2006). Sub-meter resolutions are achievable in the upper 50-100m (Brabham *et al*., 2005; Gutowski *et al*., 2008; Tokarev *et al*., 2008).

Horizontal resolution is determined by the acquisition geometry, with the highest horizontal resolutions achieved by the collection of a 3D data set that can be processed to properly compensate for the lateral propagation and reflection of the seismic energy.

The accuracy to which the seismic method can recover structural and stratigraphic information is controlled by the inherent limitations in the technology and the geological environment in which the seismic survey is conducted.

Land-based seismic reflection surveys tend not to produce as high quality data as marine surveys, primarily because of data collection is much slower and there are various additional complications associated with acquiring and processing seismic data from a dry undulating terrestrial environment. Data acquired in areas with irregular topography, a complex near-surface structure, and a complex subsurface require a detailed model of the near-surface variations to be constructed in order that spurious reflections, refracted wave and surface wave (ground roll) signals that may mask reflections of interest can be effectively removed (Yimaz, 2007). In such cases additional seismic refraction data should be acquired in order to constrain the shallow velocity structure of the ground, and to help process and remove refracted and surface wave arrivals.

Particular geological features at depth can also significantly influence the expected data quality. For example, a basalt horizon will represent a strong contrast that will generate a strong reflection, reducing the proportion of energy that propagates to deeper levels. Interbedded coal sequences with multiple seams can make it very difficult to extract clean high-resolution images of the sedimentary sequence at depth since the seismic energy may suffer transmission loss as it passes through. Some of these imaging difficulties can be surmounted by using particular acquisition geometries and more advanced data processing algorithms.

A.1.4 Acquisition and Processing

The source type and the geometric configuration of the receivers used for each acquisition project depends on a number of variables specific to a particular area. For example, in the marine environment the choice of a tuned air gun array will depend on the known sub-sea geology, data from previous seismic surveys, the depth at which the main features of geological interest exist, the desired frequency output of the source array, the amount of energy or power required and so on. For the land environment, the source choice is normally between drilled dynamite shot holes or mechanical vibrators. Again, the choice will depend on the specific geology and characteristics of the prospect area but can also be influenced by non geophysical issues, such as terrain, safety issues (especially for explosive use and storage) and local environmental concerns.

Seismic data should not be considered in isolation from all other geological and geophysical information. The more information that is fed into the seismic interpretation process the better the outcomes.

Some lithological and structural information may be available from core observations and image log interpretation, but these data are only valid in the vicinity of the borehole, and when extrapolated beyond this can lead to erroneous prediction of the overall geology. Even though geostatistical methods can help to reduce the uncertainty associated with spatial predictions by taking into account the geological heterogeneities, a 3D “attribute” is necessary in order to accurately characterise features away from the control points (Freundenreich *et al*., 2006; Kozlov *et al*., 2009).

Fracture systems aligned in preferential directions induce a directional (or azimuthal) dependence of the seismic properties such as velocity and reflection amplitude (Freundenreich *et al*., 2006; Wand *et al*., 2007; Singh *et al*. 2008). This directional dependence can cause seismic waves to split in preferential directions related to the alignment of the fractures. It can also affect the amplitude of compression waves depending upon the direction of propagation. An analysis of the anisotropy effects observed in 3D seismic data can therefore provide insight into the fracture characteristics. Methods based on shear wave splitting analysis are well established, but currently shear wave data are relatively expensive to acquire and process.

Shear wave propagation is sensitive only to rigidity and density, while pressure wave propagation is sensitive to rigidity, density and compressibility. Interpreting both pressure and shear wave reflectivity offers the potential ability to discriminate lithology, porosity, and fracturing. The group of attributes for mapping fracture swarms is well established. Coherence, curvature and anisotropy attributes routinely extracted from seismic data are useful tools for mapping faults and zones of increased fracture density. Such attributes can be considered as indirect indicators of fracture permeability as both faults and fractures are likely to act as pore fluid conduits.

A.1.5 Recent and Future Advances

In recent decades the greatest advances have come in the speed and scale of acquisition that is possible, together with the availability of the computational power required to process 3D volumes of data. What could be achieved 20 to 30 years ago with 2D seismics is now relatively routinely achieved with 3D seismic data volumes. 4D or time-lapse seismic surveys allow comparison of data sets acquired at the same location at different times to determine changes in the seismic properties of the subsurface.

Recent developments in advanced 3D seismic interpretation and converted-wave seismology focus on detecting more subtle stratigraphic features such as thin or interbedded sedimentary sequences, locating fluids and gas, and mapping lithology away from borehole locations (Roche *et al*., 2005).

Seismic attributes that can be considered as indirect indicators of fracture permeability are well documented and accepted by the hydrocarbon industry. For matrix permeability, several attributes have recently been proposed that are sensitive to the rate of seismic p-wave induced fluid-flows between fractures and equant matrix pores which in turn affect the amplitude of p-wave returns (Kozlov *et al*., 2009). These effects are strongly frequency dependent. It is not possible to calibrate these multi-variate patterns quantitatively against fracture and boundary permeabilities. Instead seismic attributes can be calibrated by bulk scale piezo-conductivity and hydraulic conductivity at such time in the site investigation where they can be established by direct measurement.

Developments in land seismic recording systems, sensor technology and data processing are such that the use of multicomponent data for exploration and development is now possible and economically viable (Criss *et al*., 2005). Multicomponent systems record the seismic waves in three component directions, two horizontal and one vertical. This allows the three-dimensional shape of the arriving seismic wave to be recorded and analysed. Recent work on full-wave imaging and the acquisition technologies promise improved resolution, more efficient noise suppression and higher quality seismic images. The use of three-component sensors permit the application of advanced signal processing methods including multicomponent singular value decomposition techniques which enable phase identification and separation of specific surface wave types from the recorded wave field. The recording of the full wave field therefore has the potential to allow the component waves to be isolated and interpreted, and as such compression waves, shear waves, and complex conversions between the two can be combined to give a more complete reflection image. This also opens up the potential to calculate and map seismic attributes relevant to physical and hydraulic rock properties.

The benefits of multicomponent recording may be increased when sensors are deployed using the latest generation of cable free continuous recording instruments which can handle a more diverse range of acquisition geometries at the same time as reducing environmental exposure (Heath, 2007; Chitwood *et al*. 2009). Cableless technology has less impact on the terrain, making it better suited for access to environmentally sensitive areas and densely populated urban environments.

Currently at proof of concept stage is a technique called seismic interferometry. The principle is that the observed seismic noise wave field at a number of detectors can be used to synthesise the wave field which would have been generated if, instead of having a detector at one of the sites there was an active source. Potentially therefore, active sources are not needed at all because the information about the subsurface is already contained in the noise wave field and can be extracted with appropriate processing. A number of theoretical papers have been published on the topic, but as yet only limited practical experiments have been reported. Interferometry is, however, the subject of considerable academic and industry interest (Wapenaar *et al*., 2008), and it is possible that significant practical advances could be made in the next few years.

A.2 Seismic Refraction

A.2.1 Overview

Seismic energy is injected into the ground and recorded in a similar way to the seismic reflection technique. In this instance the waves of interest are those that are refracted along the boundary between units with contrasting seismic velocities. Detection and analysis of these arrivals can provide information on the distribution of seismic velocity properties within the subsurface, which in turn can be interpreted in terms of a geological model.

The technique is typically deployed to identify major sub-horizontal contrasts such as the top of competent bedrock. The velocity information obtained can be used to evaluate mechanical rock properties.

A.2.2 Application

This technique may be useful in determining the depth to bedrock, or geometry and distribution of geological units. It may provide shallow information not easily obtained using seismic reflection, and may be specifically required as part of a seismic reflection survey in order to calculate and compensate for near-surface heterogeneity.

Acquiring both pressure wave and shear wave measurements allows the calculation of the shear and bulk elastic moduli. Azimuthal variations in seismic velocities associated with geological bedding, or fracture orientations can also be determined.

Typically refraction data are acquired for relatively shallow depth (up to 100m) to determine, for example, the thickness of drift deposits. It may also be useful in the context of deep geological disposal to use the technique to investigate greater depths for example to determine the location of basement rocks. The technique is also commonly used to determine large scale (10's of kilometres) crustal and lithospheric structure.

The resolution of the technique varies both with the deployment geometry and the geological conditions, and should be considered carefully for each case. It is possible to run relatively simple calculations to predict the expected response and therefore to determine the detectability of a particular feature at depth, however it is more usual to use the seismic refraction technique to locate major contrasts in the subsurface (such as competent bedrock and deeper basement rocks). Velocity models derived from seismic refraction feed in to the processing of seismic reflection as described in Section A.1.

A.2.3 Limitations

The technique relies on the reconstruction of the path taken by individual "rays" of seismic energy between the source and the receiver. The resolution achieved is determined by the coverage of these measured ray paths, which in turn is determined by the density of source and receiver pairs deployed. The depth penetration is principally a function of the energy imparted by the source and the length of the spread of receivers. Longer offsets allow energy to have the opportunity to propagate to greater depths before returning to the surface.

Certain geological conditions may restrict the effective depth penetration of the technique. For example, the occurrence of 'seismically fast' shallow layers such as massive limestones or basaltic igneous layers will act to channel the seismic energy, and as such may prevent useful information from being obtained from features at greater depths.

Although the method has a strong ability to image the subsurface, there is a common problem of non-uniqueness. Refraction data always include some ambiguities due either to noise or to complex geological changes. The travel time data therefore have the potential to be equally well matched by more than one model of the subsurface.

A.2.4 Acquisition and Processing

Acquisition is typically undertaken as a series of 2D sections. Survey design should be tailored for the expected geological features and the depth from which information is required. Computer predictions of the expected signals received from theoretical ground models can be used to inform these decisions if necessary.

Processing and interpretation of the results relies on the inversion of the arrival time of the energy at each recording position to achieve a velocity model of the subsurface. This model can be generated automatically by specialist software, or can be influenced by the geophysicist applying conditions of particular layering, velocities or other information such as known boundaries identified from available borehole logs.

A.2.5 Recent and future Advances

There have been two main foci of recent research into seismic refraction. Firstly the utilisation of the technique to determine the deep crustal structure of continental and oceanic lithospheric plates, which considers a much greater depth than that relevant for a GDF. The second focus has been to improve the interpretation of the shallow (upper 10s or 100s of meters) velocity structure in order to obtain better seismic reflection images (Yimaz, 2007).

Of relevance to the application of the technique in the context of deep geological repositories are the advances in the inversion of the data to produce robust and unique geological models (Kanli, 2009). Increasingly sophisticated algorithms, including genetic and evolutionary routines, have been developed to test large numbers of ground models and to automatically refine them to produce a small number of possible solutions (Rawlinson *et al*., 2009). To better constrain the possible models produced it is also possible to integrate the inversion of surface wave data (Dal Moro, 2008). This provides valuable ancillary data to inform the selection of a suitable solution to the refraction data inversion, and also allows the possibility to detect low velocity layers that would otherwise be invisible to the refraction survey.

A.3 Surface wave profiling

A.3.1 Overview

Surface wave seismic is a profiling technique. Rather than recording body wave information, surface wave profiling techniques such as MASW (multichannel analysis of surface waves) measure surface waves at a range of frequencies. The velocities of the waves are determined by the elastic shear modulus of the ground and its density.

Longer wavelength, lower frequency, signals sample the ground to greater depths, and therefore by measuring at a range of frequencies a profile of velocity with depth can be recorded.

Ambient noise typically contains a broad range of frequencies that can be used as the input source for this technique. Not all frequencies across the useful spectrum are necessarily present within the natural ground noise, and as such an active source (vibration or impulse/explosion) can be deployed.

Elastic properties will be determined by the collection and inversion of the seismic surface wave data and an assumption about the density of the ground materials. The output of the survey is a series of profiles of elastic shear modulus (shear stiffness) that can be combined to produce cross sectional or 3D representations of shear stiffness which can be interpreted in terms of a geological model.

A.3.2 Application

This method maps the shear wave velocity distribution in the subsurface, and has the advantage that it can obtain data from depth without the need to deploy geophones over large horizontal distances at the surface. The technique can utilise ambient noise present within the ground, or can measure the propagation of waves generated by artificial sources such as weight drops or explosions. It is not always practical to generate very low frequency energy artificially, and as such typically investigations to depths greater than 50m or so utilise only natural noise sources.

Resolution is determined by the contrasts of particular layers within the subsurface and can be estimated in advance by forward modelling. Discrete layers at depth can be difficult to resolve, and the technique is most useful for the identification of major changes in the geology with depth such as the upper interface of bedrock or basement rocks.

If density data are available or can be readily estimated the velocity data can be converted to elastic shear stiffness.

A.3.3 Limitations

In a similar way to the seismic refraction technique, it is possible that a number of somewhat different ground models can provide an equally good fit within the uncertainties inherent to the recorded data.

Good continuous depth coverage relies on the ability to record suitable amounts of energy at all frequencies within the range of interest. It is not necessarily the case that these ground vibrations will be present, and long recording times may be necessary to capture reliable signals that can be inverted and interpreted in terms of a useful ground model.

A.3.4 Acquisition and Processing

Recorded data are analysed to determine the wavelength of each frequency present within the data, and also the velocity at which that frequency propagates. In processing the data as a first approximation the velocities from each profile can be assigned to depths equal to one third of the wavelength. More robust ground models are then typically modelled as a stack of homogeneous linear elastic layers, and the parameters to be determined in refining the ground models are the layer thicknesses and shear wave velocities. Adjacent profiles can be merged to give continuous cross section images of the shear velocity of the subsurface and will identify lateral as well as vertical changes.

A.3.5 Recent and future advances

Instrumentation requirements for this method are no more demanding than for other seismic techniques with the exception of the memory needed to store long data records from continuous recordings which may be up to several hours long. Memory storage is now cheap and presents no challenge to the technique.

Recent research has concentrated on obtaining coherent dispersion curves from either a small number of recording locations, from weak signals, or from very low frequencies (Parolai, 2009; Foti *et al.*, 2009). The other focus has been on the inversion of the dispersion curve to provide a robust geological interpretation, including the combined inversions and interpretation of seismic refraction tomography data and surface wave profile data (Foti *et et al.*, 2009).

Future developments are likely to present further incremental improvements in the ability to acquire and interpret useful data from significant depths in more difficult environmental and geological conditions.

A.4 Micro-gravity

A.4.1 Overview

Gravity measurements at or near to the Earth's surface vary with location due to a number of factors. Within each observation is the contribution made by the density, volume and distribution of materials in the subsurface. In order to isolate these, all other contributions must be calculated and removed. What remains is a gravitational anomaly map constructed from a spatial grid of observations at which relative differences in the gravity measured, termed ‘anomalies’, are apparent. These anomalies relate directly to the density distribution of the subsurface and can be interpreted in terms of a geological model.

Examples of detectable density contrasts are voids (e.g. mine workings, karst features), volcanic intrusions, mineralised zones, salt intrusions, sedimentary cover and depth to basement, and geological structures such as large scale folds and faults.

A.4.2 Application

The micro-gravity technique will principally be of use in informing the large scale geological model by detecting major geological features. Where density can be correlated with geotechnical parameters for example in fractured of voided rocks gravity may also contribute to the mapping of these parameters. Gravity data can be of particular use in determining the thickness of sedimentary sequences, in mapping variations in the depth to higher density basement rocks, and in detecting large geological structures such as folding and faults. Discrete high-density bodies such as igneous intrusions, or mineralisation can also be readily detected in most circumstances.

A.4.3 Limitations

Certain practicalities may restrict the abilities of the systems to obtain good data. Land based surveys require firm ‘quiet’ ground conditions, and can suffer from nearby sources of vibration such as busy roads, construction sites, or trees or wooded areas where wind noise is transmitted into the ground.

Marine and airborne systems are subject to the weather and navigational restrictions of their respective platforms, but are otherwise able to operate over any ground or subsea conditions.

Land based surveys have the advantage of providing the highest resolution data both in terms of spatial resolution (access permitting) and measurement accuracy, with practical resolution limits typically in the region of 0.01 mGal. The measurement accuracy of marine systems is in the region of up 0.5 mGal, and of airborne systems is in the region of 0.8 mGal. Gradiometer systems deployed by aircraft or boat offer increased resolution, especially for shorter wavelength anomalies such as those expected to be generated by density contrasts in the upper 1000m of the subsurface. The accuracy of gradiometer measurements is constantly improving with the development of new instrumentation, but is typically in the region of 10 Eötvös (1 mGal/m = 10,000 Eötvös).

Another important difference between land, marine and airborne surveys is the height at which observations are made. The greater the distance from the density contrast the weaker and longer wavelength the measured anomaly. It is therefore important not only to consider the acquisition height in predictions of detectability and accuracy, but also in situations where data acquired from different heights and with different accuracy (e.g. land data and airborne data) is combined in an attempt to develop a continuous interpreted geological model.

A.4.4 Acquisitions and Processing

Typically the signals sought are very small compared with variations associated with diurnal variations (orbits and tides), latitude, height, topography and the motion of the instrument itself. It is possible to acquire data from mobile airborne or marine platforms, however the relative instability of the instrument compared with a stationary instrument on land limits the resolution. Data is acquired either over a grid of observation points, or along continuous tracks. The accuracy of position and height data must be sufficient to enable their effects to be adequately removed from the data.

Terrain data (including water depth where necessary) will also be required, and may have to be acquired specifically for the gravity survey if sufficiently accurate data are not available. It is possible to obtain this simultaneously with the gravity observations using lidar or bathymetric measurements made from the same platform. Additional data may also be required from outside the immediate acquisition area to encompass significant features that may affect the observed gravity. High resolution land surveys may also require measurements to be taken of large buildings and structures in order to calculate and remove their effects from the observations.

Before a survey is commissioned it is good practice to undertake a feasibility study to calculate the gravitational expression on the expected features of interest to the survey. The amplitude and wavelength of predicted anomalies can then be compared with the accuracy reasonably expected from a particular instrument given a particular survey design. Given a particular acquisition platform it remains important at the planning stage to understand the measurement accuracy typically obtained, and note that this may be different to that possible in ideal circumstances. This will inform both the acquisition planning and execution, and the subsequent interpretation of the data.

Once an anomaly map is obtained a number of approaches can be used to obtain a robust interpretation. An experienced geophysicist will be able to provide a qualitative interpretation of the geology based on the anomaly map alone. A more quantitative overview can be obtained by isolating anomalies with particular wavelengths that will relate to features at specific depths. The most robust interpretations are obtained by iterative forward modelling in which a ground model is refined until the predicted gravity anomalies provide a close match to the recorded data. This process can also be used to test the sensitivity of the predicted gravity to changes in the ground model, and therefore provide a quantitative estimate of the uncertainty in the best fit model produced.

A.4.5 Recent and future advances

In recent years instrumentation has improved considerably, increasing data acquisition productivity, and also accuracy. The greatest advances have been in the development of increasingly stable airborne and marine instruments, and in the development of vertical gradiometers and tensor (vertical and two horizontal component) gradiometers (O'Brian *et al*., 2005).

As with most areas of geophysics the increasing affordability of computer processing power has driven the development of more sophisticated and computationally intensive processing (Pajot *et al*., 2008; Hwang, 2006). As such complex or mountainous terrain, or the presence of large buildings or other infrastructure, can be more effectively removed improving the ability to resolve targets (Jia *et al*., 2009a). Joint inversion of gravity and magnetic data is increasingly commonplace (Somerton *et al*., 2009).

A.5 Magnetics

A.5.1 Overview

Local variations in the electromagnetic properties of the subsurface act to cause small perturbations in the magnetic field, which are measurable using appropriate instrumentation. The technique is used extensively in archaeological investigations to identify former structures, and associated variations in the shallow subsurface, but is equally applicable to determining large scale variations in geology.

Different geological units contain different concentrations of ferrous minerals, and therefore have a different effect on the measurable magnetic field. High concentrations of ferrous minerals associated with ore mineralisation, or igneous intrusions manifest prominently in the magnetic anomaly data.

A.5.2 Application

The principal use of the technique will be in obtaining regional information on the distribution of major geologic units, and the large scale structure of an area. Major geological structures such as faults, especially where they displace basement rocks, and the distribution of ore mineralisation or igneous intrusions can be identified.

A.5.3 Limitations

Man-made near-surface buildings and infrastructure can generate significant magnetic anomalies that may act to mask those from natural features. In addition to large areas of urbanisation, major infrastructure such as electricity supply cables (including pylons) and buried pipelines can affect the data.

Magnetic fields behave similarly to other potential fields such as gravity in that the distance to the causative body is important. The measurable field perturbations become much larger for closer objects. In addition, natural magnetic materials may have their own magnetic field which will be superimposed on the local perturbations of the earth's field. Processing these signals to produce quantitative interpretations can be correspondingly difficult, and the majority of magnetic data are interpreted qualitatively from maps of the total field measurements.

A.5.4 Acquisition and Processing

The measured magnetic field at any one location at or near to the Earth's surface will vary considerably through time because of the effect of the solar wind.

Typically this is compensated for by installing a stationary recording position in a magnetically quiet location at which theoretically only the temporal variation of the magnetic field will be recorded, allowing this signal to be removed from the data obtained over the survey area. Alternatively magnetic gradiometer data can be acquired that eliminates the effect of the temporal and regional magnetic field by measuring the field at two positions a fixed distance vertically or horizontally apart, and is sensitive only to local field variations from relatively close features.

Processing typically involves the correction for diurnal effects, removal of the Earth's background magnetic field and the levelling of all data to a common height. Once a map is produced it can be further analysed using image processing techniques to identify particularly localised changes in the measured field. Quantitative information on the location and geometry of causative bodies can be calculated by comparison of the measured field with predicted anomaly profiles from forward models. If certain simplifying assumptions can be made about the causative bodies (e.g. that they are cylindrical, spherical, planar, etc.) then the location and depth of causative bodies can be estimated by an automated analysis of the magnetic anomaly data using a technique called Euler decomposition.

A.5.5 Recent and future advances

The processing and interpretation of magnetic data shares some commonality with gravity data, and has benefited similarly from the development of more computationally intensive algorithms to process, filter and model the data (Stavrey *et al*., 2009). Euler decomposition and wavelet analysis for example have been shown to have equal application to both magnetic and gravitational data (Cooper, 2006). It is increasingly common to derive interpretations of structural geology and the depth to basement rocks by jointly inverting magnetic and gravity data (Somerton *et al*., 2009).

A new concept to emerge is that of a rotating magnetic tensor gradiometer which is based on superconductor technology (Tilbrook, 2009). Currently only at a theoretical stage, such an instrument may provide considerable improvements in the accuracy and stability of airborne magnetic data.

A.6 Electromagnetic: Time-Domain

A.6.1 Overview

The electromagnetic (EM) time domain methods (more commonly referred to as Time-Domain Electromagnetic (TDEM)) are based on the principle of using electromagnetic induction to generate measurable responses from sub-surface features. When a steady current in a cable loop is terminated a time-varying magnetic field is generated. As a result of this magnetic field, eddy currents are induced in underground conductive materials. The decay of the eddy currents in these materials is directly related to their conductive properties, and may be measured by a suitable receiver coil on the surface.

A.6.2 Applications

The technique is useful to identify major changes in electrical conductivity with depth associated with fluid content and chemistry, and major changes in lithology. In particular the distribution of ground water, and the location and extent of saline intrusions would be expected to manifest in the data as clear anomalies. Areas of ore mineralisation also represent electrically conductive targets for this technique.

A.6.3 Limitations

The technique measures subsurface resistivity and as such only geological or hydrological structures that cause spatial variations in resistivity are detected by this technique. If there is no resistivity contrast between the different geological materials or structures, if the resistivity contrast is too small to be detected by the instrument, or if the resistivity of the subsurface material is very high, the technique gives no useful information.

The inversion and interpretation of TDEM data share similar aspects to seismic surface wave profiling in that a profile of conductivity with depth is produced which is then interpreted in terms of a layered earth model with the principal parameters being layer thickness and later conductivity. It also suffers from the problem of non-uniqueness of solutions, and also in resolving thin layers of contrasting properties. Its principal use in the context of the deep disposal of geological waste may be in the mapping of significant bodies of fluid, major geological units, and mineralisation.

Lateral resolution of a TDEM central loop resistivity survey is determined by the spacing between measurement stations. TDEM measurements are not able to resolve small individual features that are spaced less than the spacing between stations. Vertical resolution is limited and is a complex function of the target, size, depth, relative position, and resistivities.

A.6.4 Acquisition and processing

During the course of designing and carrying out a survey, the sources of ambient, geologic and cultural noise must be considered and the time of occurrence and location noted. The form of the interference is not always predictable, as it not only depends upon the type of noise and the magnitude of the noise but upon the distance from the source of noise and possibly the time of day.

The transmitter may have power output ranging from a few watts to tens of kilowatts. Important parameters of the transmitter are that it transmits a clean square wave, and that the “turn-off” characteristics are well known and extremely stable, because they influence the initial shape of the transient response. The size of the transmitter power supply determines the depth of exploration, and can range from a few small batteries to a 10-kW, gasoline-driven generator.

The interpreted resistivity is the resistivity of a particular horizontal layer at a given depth in the earth, and is determined by doing a data inversion procedure based on a horizontally layered earth model. Model interpretations are not unique and several different models will produce equivalent matches (to within the signal-to-noise ratio) of the survey data.

A.6.5 Recent and future advances

Recent advances have seen improvement in the equipment, specifically in the electronics that drive the transmitter and receiver coils. Critical to the acquisition of high quality data is the sharp and noiseless termination of the transmission signal, and the sensitive and stable reception of the ground signal. Other developments have centred on airborne deployment of the technique (Fountain *et al*., 2005; Steuer and Meyer, 2006).

Traditionally (since the 1970s), fixed wing airborne EM systems have been primarily time-domain, whilst helicopter systems remained primarily frequency domain. These distinctions were in part forced by the physical constraints and requirements of the transmitter and receiver coils, but also by the limitations of the controlling electronics. In the last few years there has been significant development of helicopter time-domain systems. Helicopter systems provide improved lateral resolution for shallow targets, and better data consistency through the platform's ability to best follow undulations in rough terrain.

The acquisition of multiple components of the electric and magnetic field, at multiple stations coupled with improved modelling and inversion software have improved signal to noise of measurements, and better constrain the models used to interpret the data [Jia *et al*. 2009b].

A.7 Electromagnetic Frequency Domain

A.7.1 Overview

The EM frequency domain technique uses two electrical coils to send and detect an electrical signal that is modified according to the electrical properties of the subsurface. The amplitude of the signal in the secondary coils is directly related to the bulk electrical conductivity of the ground. The phase of the signal in the secondary coil is an indicator of the presence or otherwise of highly conductive material including metals. The depth penetration is determined by the electrical properties of the ground and the separation of the coils, and is limited by the ability to generate a sufficiently powerful secondary field at depth to be detectable at the surface.

A variant of this technique is VLF (Very Low Frequency) EM. VLF techniques measure the perturbations in a planewave radio signal (15-30 kHz) emanating from one of several world-wide radio transmitters used for submarine communications. VLF instruments measure two components of the magnetic field or equivalently the "tilt angle" and ellipticity of the field. Some instruments also measure the third magnetic component and/or the electric field.

These frequency domain EM methods are used primarily as a reconnaissance tools to identify anomalous areas for further investigation.

A.7.2 Applications

This technique is typically limited to the upper few 10s of meters. Its usefulness in the context of characterisation of a GDF site would be to provide information on the shallow geology, for example the distribution of drift deposits, solid geology concealed beneath thin drift deposits, or the determination of the possible presence and location of made ground including landfill or shallow buried obstructions or contamination associated with brownfield sites.

A.7.3 Limitations

The principal limitation of this technique is its depth penetration. Its advantage is its ability to cover significant areas relatively rapidly. It can be deployed from an airborne platform, but is constrained in this context by a requirement to remain as close to the ground as possible.

EM measurements are sensitive to 'cultural interference' from pipelines, utilities, fences, and other linear, conductive objects. Interpretation is generally qualitative in nature and quantitative modelling requires a high data density and a well constrained model. Topographic effects in airborne data can be difficult to remove. VLF transmitters are subject to outages for scheduled or unscheduled maintenance.

The technique provides no depth constraints on the anomalies identified other than that they lie within the depth of ground sampled by the instrument. Limited indications of depth can be determined by collecting a number of data sets with different coil separations. Where a feature appears in the larger coils separation data, but not in closer coil separation data it can be interpreted to lie at a depth beyond the penetration of the closer coil separation survey.

A.7.4 Acquisition and Processing

Acquisition and processing are relatively straightforward for this technique. Following basic noise removal from the data set, and the referencing of the data to the correct geographic grid, the conductivity map produced can be interpreted in terms of lithological or fluid composition changes.

As with magnetic data maps it is possible to apply image processing routines to enhance certain details within the data.

A.7.5 Recent advances

The technology allowing the more routine and effective deployment of airborne systems has pushed forward research into improved calibration and levelling techniques, and improved interpretation of the data (Steuer and Meyer, 2006). Future advances are expected to address the more effective isolation and removal of cultural interference.

A.8 Electromagnetic: Magneto-Tellurics

A.8.1 Overview

The decay of EM fields in a medium is governed by both the resistivity of the medium and the frequency of the signal.

Time variant magnetic fields of either natural or artificial origin cause eddy currents within the conductive sediment layers. As these eddy currents are time variant as well they cause a secondary EM-field that can be sensed with magnetic or electric sensors placed at the surface. The ratio of the electric field to magnetic field can give simple information about the subsurface conductivity. The ratio at higher frequency ranges gives information on the shallow ground, whereas deeper information is provided by the low-frequency range. The ratio is usually represented as magneto-telluric (MT) apparent resistivity and phase as a function of frequency.

In the MT method natural fields are used as source and therefore only a receiver measuring horizontal electric and magnetic fields is needed to do the measurements. Other implementations use artificial fields with a vertical current path combined with the MT receivers. This vertical current flow causes charge build up that allows the detection of resistive layers. This method is known as controlled source MT (CSMT). A different interpretation approach for the same data sets using the individual transmitter receiver configuration of the electrical field components is controlled source EM (CSEM). A wide distribution of frequencies is used to record data from a wider range of depths at each transmitter receiver offset. The 'A' in AMT and CSAMT implementations refer to the acoustic frequency range used in these particular surveys (typically between 1 Hz and 10 kHz).

In magnetotellurics, the Earth's naturally varying electric and magnetic fields are measured over a wide range of frequencies (1/10,000 to 10,000 Hz). These fields are due to electric currents (telluric currents) that flow in the Earth and the magnetic fields that induce these currents. The magnetic fields are produced mainly by the interaction between the solar wind and the magnetosphere. In addition, worldwide thunderstorm activity causes magnetic fields at frequencies above 1 Hz. These natural phenomena create strong MT source signals over the entire frequency spectrum.

The ratio of the electric field to magnetic field can give simple information about the subsurface conductivity. Due to the skin effect phenomenon that affects electromagnetic fields, the ratio at higher frequency ranges gives information on the shallow Earth, whereas deeper information is provided by the low-frequency range. The ratio is usually represented as MT-apparent resistivity and phase as a function of frequency.

A.8.2 Applications

This technique provides a method by which electrical resistivity data can be obtained at large depths. It may be useful for the determination of major geological units, especially resistive layers, and for the identification of pore fluids of differing compositions (e.g. saline intrusions). Geological structures may also be discerned where they offset contrasting rock types, or where they provide a conduit or barrier to fluid migration.

A.8.3 Limitations

EM and MT sounding methods often have advantages over galvanic resistivity methods, with the choice of the best approach determined by a number of site specific factors. Resolution is a significant advantage over direct current electrical techniques, particularly for deeper (greater than 100m) surveys. The lateral resolution of CSAMT, AMT and MT is a function of frequency and dipole size. Differences in vertical resolution between EM and DC methods are generally minor.

At present CSAMT data are limited in depth penetration to the upper 3km. EM and MT data are capable of obtaining information at greater depths. For natural source rather than controlled source EM techniques in a layered subsurface only horizontally flowing eddy currents are induced. Such current systems are good to detect conductive layers but are insensitive to an electrically resistive feature.

A.8.4 Acquisition and processing

Acquisition depends on the specific technique deployed, and the configuration of the transmitter (if used) and receivers will be determined by the requirements of the survey.

Processing is typically done in two stages. Pre-processing involves an examination and, where required, editing of the data for errors and noise. Once the data are in an acceptable condition they can be inverted by automated curve fitting or by more sophisticated numerical modelling of expected signals for comparison.

A.8.5 Recent and future advances

Whilst land based measurements have become more straightforward and stable in recent years, equipment advances have allowed these EM techniques to emerge as a practical tool in marine environments. Much of this work has been driven by the hydrocarbon industry where the techniques have proved useful in locating relatively electrically resistive productive reservoir rocks (Schumacher, 2008).

Recent work has been principally concerned with the improvement of interpretation algorithms to provide better or more automated fit to data (Miller *et al*., 2005). Current research is also addressing the near-field effect experienced in controlled source surveys (Xu and Yue, 2006). At a position close to the transmitter the assumption of plane wave propagation of the signal becomes invalid. The precise location of the near-field effect, and the manner in which it manifests in the recorded data is complex and depends on the specific transmitter and receiver geometry, and on the details of the geological conditions, but can be accurately modelled to obtain useful information.

A.9 Direct Current Electrical Resistivity

A.9.1 Overview

The electrical resistivity method employs a number of electrodes that are deployed along a survey line (to produce a cross section) or in a grid (to obtain a 3D image), and between which ground resistivity measurements are taken. By making measurements between different combinations of electrodes the resistivity at different locations and depths is recorded to build up the data set.

Different geological strata have different electrical properties, and as such variations in the subsurface resistivity can be correlated with geological boundaries. In addition, the presence of pore fluids and their electrical properties can significantly modify the measured electrical properties of the ground.

A.9.2 Application

The technique will provide an image of the electrical resistivity of the subsurface. It is able to distinguish geological units by their contrast in electrical properties as well as the presence of pore fluid. It may be of particular use in mapping the water table and the possible presence of saline waters.

A.9.3 Limitations

The depth penetration is limited by the current that it is possible to drive through the subsurface at depth. Typically a practical limit is within the upper 100m below surface. Resolution decreases with depth so that deeper features have to be increasingly large in volume to be visible to the technique.

Surface electrical noise from man-made sources can interfere with the data collected, and can be difficult to remove the effects of such interference. This may limit the utility of the technique, particularly at the expected limits of depth penetration where the signal to noise ratio is expected to be low.

A.9.4 Acquisition and Processing

A known current is forced between two electrodes, and the potential difference is measured across the other two electrodes. A number of such measurements are required with increasing electrode spacing required to obtain information from greater depths. Once these measurements are obtained the data can be inverted using standard tools to determine the image of resistivity that best matches the observations and any other prescribed constraints.

The inversion process is more robust, and the practical noise levels minimised, where the maximum density of data are acquired for the particular array deployed. An amount of 'over sampling' can allow the noise and repeatability in the data to be estimated, which in turn informs the interpreted accuracy of the resultant ground model.

A.9.5 Recent and future advances

Recent developments in computer technology as well as inversion algorithms have led to faster tomography processing. Data acquisition systems have also become considerably faster with the development of multi-channel systems that can acquire data more quickly, and with a greater number of electrodes in the array. This has allowed the deployment of larger, deeper looking, arrays, and also of three-dimensional arrays.

Current and future research topics include the assessment of the influence of noise in the data and in the resultant inversions, an analysis of the pros and cons of specific array geometries in obtaining the most reliable lateral and vertical resolution for particular targets (Daily *et al*., 2004).

A.10 Ground Penetrating Radar

The Ground Penetrating Radar (GPR) technique operates by transmitting a pulse of high frequency (radar band) EM radiation into the ground which is reflected back to the instrument at boundaries between materials with contrasting electrical properties. The technique is used in the UK in environmental and shallow engineering surveys where data are required from the upper 5m. The penetration depth of GPR increases with decreasing frequency, with the lowest frequencies of 25MHz or 50MHz typically deployed for geological applications where depth penetration in favourable conditions can be 40-80m. The main limitation of the technique is that the signal is rapidly attenuated in conductive ground conditions. The majority of soils and quaternary deposits in the UK are clay rich and electrically conductive. As such it is of limited use for geological studies within the UK unless bedrock is exposed at the surface since depth penetration is limited to less than 5 to 10m. For this reason GPR has not been considered in detail in this report.

Of principal interest to the characterisation of a GDF in the UK is likely to be the deployment of GPR within boreholes. Down-hole imaging and cross-hole tomography can provide useful information on the presence of fractures and fault surfaces, and can also map changes in lithology or pore fluids.

Appendix B. Geophysical investigation of different geological environments

A site to host a GDF has not been proposed or selected at the time of publication of this report, hence the geological setting of a GDF is unknown. Therefore, this review considers geological environments representing the range of plausible host environments in England and Wales to highlight the technical issues relevant to geophysical surveying. These geological environments are derived from a recent Environment Agency report (Metcalfe and Watson, 2009).

B.1 Description of geological environments

We use the term 'geological environment' in this report for simplicity. Each of the 9 representative geological environments is defined in terms of its geological, hydrogeological and geochemical characteristics, distinguished principally by:

- the spatial distributions of host and cover rocks
- physical and chemical properties of the host and cover rocks
- chemical compositions of groundwater
- processes driving groundwater and solute transport

For each of these environments there are a number of key implications for and technical challenges on the safety case. The descriptions developed for each of the geological environments include the most relevant features that would affect a deep GDF, but not in sufficient detail to suggest specific rock formations or sites. The geological environments identified are discussed in detail in the project report (Metcalfe and Watson, 2009) and are summarised below in Table B1.

B.2 Geoscience indicators

The recent Environment Agency science project (Metcalfe and Watson, 2009) also defines a number of “Geoscience Indicators”. Geoscience indicators were qualitative or semi-quantitative characteristics that were used to describe different geological environments. They were designed to illustrate the similarities and differences between the different environments.

The geoscience indicators have been divided into 6 groups: geological, geotechnical, geochemical, hydrogeological, gas migration and resources. Table B2 gives examples of the types of indicators that might fall into each category, and comments on how geophysical surveys may be used to characterise these effects.

Table B1. Summary of representative geological environments

Environment 1 Hard fractured rock to surface	In this environment the GDF would be developed in a hard fractured host rock. This rock is likely to be fractured on a range of scales, from fault and fracture zones at the regional scale (traceable over some kilometres) to small-scale fractures (on a scale of a metre or less). Rock within the near-surface zone will be weathered and there is likely to be a surface layer of (recent) Quaternary deposits, which may be up to a few tens of metres thick.
Environment 2 Hard fractured rock overlain by relatively high-permeability sedimentary	In this environment the GDF host rock would be a hard fractured rock, similar to that in Environment 1. However, in contrast to the host rock in Environment 1, the host rock in Environment 2 is unconformably overlain by a sedimentary rock sequence between 200 m and 800 m thick. Faults in the sedimentary rocks are likely to be transmissive and thus would not provide barriers to flow and solute transport. Advection will be the dominant solute transport mechanism in the cover sequence.
Environment 3 Hard fractured rock overlain by a sedimentary rock sequence containing at least one significant low-permeability formation	The main difference from Environment 2 is that the sedimentary rock sequence contains at least one formation with significantly low-permeability in which the dominant solute transport mechanism will be diffusion. Faults within the low-permeability formation are expected to have low transmissivities (at least over significant parts of their areas). Therefore, groundwater flow and solute transport will be restricted.
Environment 4 Evaporite host rock	In this environment the GDF host rock is an evaporite formation. It is most likely to be halite (rock salt), but could also be anhydrite, gypsum or another type of evaporite. In the onshore areas of England and Wales, this host rock will be a bedded formation rather than a salt dome. Significantly thick low-permeability rocks (most likely mudstones and siltstones) must occur in the vicinity of the evaporite host rock to prevent ingress of flowing water and dissolution of the host rock. The evaporite host rock formation is likely to be bounded by such low-permeability rock formations. However, these rocks do not necessarily need to occur immediately adjacent to the evaporite formation. Faults are likely to have low transmissivities, at least over significant parts of their areas, and thus restrict or provide barriers to groundwater flow and solute transport.

Environment 5 Siliceous host rock	In this environment the GDF host rock is a strong, dominantly siliceous rock, although there may be a carbonate cement. The host rock is part of a sedimentary rock sequence that is likely to contain high- and low-permeability sedimentary rocks. This environment can be divided into two sub-environments on the basis of the character and tectonic history of the host rock: • Environment 5a, in which the sequence overlying the host rock does not contain any significant low-permeability formations. • Environment 5b, in which the sequence that overlies the host rock contains at least one significant low-permeability unit.
Environment 6 Indurated mudrock host rock	The host rock in this environment is an indurated mudrock. The host rock has a low permeability and is not significantly fractured. The dominant solute transport mechanism within the host rock is likely to be diffusion. This environment can be divided into two sub-environments on the basis of the character and tectonic history of the host rock: • Environment 6a, in which the host rock is a dominantly flat-lying and undeformed, although indurated mudstone. • Environment 6b, in which the host rock has been tectonised and may have a well-developed fabric/cleavage (such as tectonised mudstone). This fabric/cleavage may be important in determining its engineering properties. The main difference between Environments 6a and 6b are the physical properties of the host rock.
Environment 7 Plastic clay host rock	In this environment, the GDF host rock is a plastic (non-indurated) clay within which water and solutes would be transported only by diffusion. The plastic characteristics of the rock would lead to the self-sealing of any faults or fractures, which would therefore be non-transmissive.

Environment 8 Carbonate host rock	In this environment the host rock is a carbonate (limestone). This environment can be divided into three sub-environments: • Environment 8a, with a low-permeability carbonate host rock within which water and solutes are transported dominantly by diffusion. • Environment 8b, with a highly permeable carbonate host rock within which significant water and solute transport occurs dominantly by advection through fractures and/or solution (karst) features. • Environment 8c, in which the host rock is a relatively massive limestone formation within which the majority of the rock mass supports water and solute transport only by diffusion, but which contains fractures through which water and solutes are transported dominantly by advection, leading to moderate to high overall permeability.
Environment 9 Non-evaporitic host rock with hypersaline groundwater	This environment could be considered a variant of any of the other environments apart from Environment 4 (by definition). However, there may be particular issues associated with the presence of hypersaline groundwater at a GDF location. The high groundwater salinity is most likely to originate in an evaporite rock formation and therefore evaporite deposits of some form are likely to occur relatively close to the host rock.

Table B2 Geoscience indicators and how geophysical surveys may be used to characterise them

Group of Indicators[1]	Specific Indicators	Possible contribution of geophysics
Geological	• Complexity of stratigraphic sequence that will require characterisation • Topographic relief • Likely horizontal extent and thickness of host rock formation • Likely homogeneity of host rock and overlying rocks • Likely frequency and magnitude of faulting and fracturing • Long-term stability of environment – susceptibility to significant erosion, significant alteration by future glaciation etc…	A number of techniques are applicable to informing the stratigraphic sequence and general arrangement of the geological strata or units, and to determining the more detailed dimensions or homogeneity of individual units (for example the target host rock). Large scale geological structures such as major faults and fold structures will be directly visible to certain geophysical techniques. Smaller scale structures such as minor faults and fractures may not be directly imaged, but their presence and distribution may be inferred by their effect on certain geophysical signals.
Geotechnical	• Rock strength • Likely stress state • Potential stability of underground excavations in host rock and in any cover rocks – implications for spans and geometries of vaults and construction of access shafts/drifts	Rock strength cannot be directly measured by geophysical means, but the behaviour of the rock mass in transmitting geophysical signals can indicate the “quality” or mechanical continuity of the rock mass. An understanding of the stratigraphic arrangement of the constitutive rock units as described above will inform the design of any excavation.

Group of Indicators[1]	Specific Indicators	Possible contribution of geophysics
Geochemical	• Composition (not just 'salinity') of host rock porewater • Composition (not just 'salinity') of groundwater along likely path of groundwater plume • Fracture and rock matrix materials that will interact with radionuclides along likely path of groundwater plume • Redox state and buffering of host rock groundwater • Any unusual geochemical conditions – high sulphate, unusual pH etc… • Expected geochemical heterogeneity • Likely stability of geochemical conditions	The location of ground water, for example the position of the water table, or the intrusion of saline water in a coastal area, may be detected by geophysical techniques. In particular the presence and chemistry of pore fluids can manifest as marked variations in the electrical properties of the ground. A number of geophysical techniques can detect these contrasts.
Hydrogeological	• Host rock permeability and mode of groundwater flow (porous- or fracture-controlled) • Cover sequence permeability and mode of groundwater flow (porous- or fractured-controlled) • Likely hydraulic gradients in host rock and cover rocks • Expected dominant solute transport process (advection or diffusion) in host rock • Expected dominant solute transport process (advection or diffusion) in cover rocks • Expected length of groundwater discharge pathway and estimate of groundwater return time • Stability of hydrogeological regime to climate change etc… • Potential for fast pathways • Expected discharge location and extent for natural discharge pathway	The detailed hydrogeological flow regime will not be directly imaged by geophysical techniques, however a number of relevant indicators described above contribute to the hydrogeological conditions. Notably, the stratigraphic arrangement of the geological units, major geological structures such as folds and faults, the presence and orientation of minor faults and fractures and the location of ground water including any saline water bodies are of direct relevance to the description of the hydrogeological regime.

Group of Indicators[1]	Specific Indicators	Possible contribution of geophysics
Gas migration	• Ease with which gas can migrate through the host rock • Ease with which gas can migrate through cover sequence • Potential for trapping or dissolution of gas within cover sequence	In a similar way to the hydrogeological indicators described above, it is not likely that gas migration will be directly imaged, however, the significant contribution of geophysics to characterising this indicator is in constructing a detailed ground model describing the stratigraphic arrangement of the geological units, major geological structures such as folds and faults, and the presence and orientation of minor faults and fractures
Resources	• Potential for presence of coal or hydrocarbons • Potential for other exploitable resources • Potential for exploitable aquifers in cover sequence	We note that the presence or otherwise of natural resources is part of the screening criteria at MRWS Stage 2. Any site with economically significant natural resources will have been removed from consideration before a site is selected for characterisation. Where natural resources are present, but at a level sufficiently low to pass screening, their characterisation becomes part of the development of the geological model. A number of geophysical techniques have been developed to detect natural resources.

[1]Seismicity is not included in the potential attributes in the geoscience indicators because it is considered to be uniformly low throughout England and Wales.

B.3 Geophysical investigation of different geological environments

A generic strategic approach to the application of geophysics may, at a high level, remain much the same for different geological environments. However, elements defined previously that make each environment distinct may present specific difficulties or opportunities for using a particular geophysical technique.

Table B3 presents a matrix of geological environments against the geophysical surveying techniques. We have considered Environments 2 and 3 together since they present near identical geophysical challenges. We have assigned an indicative score for each cell, to indicate a relative measure of the value or “fitness for purpose” of the technique. A score of 1 indicates we expect the technique will provide useful information. A score of 2 indicates the technique may provide useful information in certain circumstances. A score of 3 suggests that we consider the technique is unlikely to provide useful information. The scoring system used here and the broader text of this report provide a qualitative indication of the relative efficacy of a particular technique in a generic geological environment, but a decision to apply a specific survey in a specific circumstance will rely on the expertise of an appropriately qualified geophysicist.

Techniques and applications are not uniquely matched. A particular technique may be used in a number of different situations and single techniques rarely provide an optimal investigative solution in isolation. A combination of two or more geophysical data sets often allows a more detailed and robust interpretation.

Certain geological environments or targets of interest present onerous challenges for geophysical techniques, whilst others may prove relatively straightforward. Table B3 enables a first-pass assessment of suitable techniques by application. Further discussion on the potential application of geophysical techniques to the geological environments is provided in the sections below. For each of the geological environments a description of the potential application of geophysical surveying techniques is provided which includes an indication of detectable sub-surface features as well as the challenges. It should be noted that this is not intended to be used as a guide for designing geophysical surveys as part of a characterisation programme. Appropriate experts will need to assess the specific technical application of geophysical techniques at the survey design stage for a specific site. Table B3 does, however, indicate whether a particular technique has the potential to provide useful information about a particular Geoscience Indicator.

In the discussion which follows Table B3 additional material has also been drawn from a review (British Geological Survey, 2001) of the use of geophysical surveying techniques other national programmes has been included. Where appropriate the relevant material from the review has been included in the discussion on the corresponding geological environment in this report. For example, within Belgium investigations have been carried out within a geologic strata known as the Boom Clay, which is an example of a Plastic clay host rock.

Table B3. Review of potential applicability of geophysical surveying techniques to geological environments

	1. Hard fractured rock to surface						2&3. Hard fractured rock overlain by sedimentary rocks						4. Bedded evaporite host rock						5. Siliceous sedimentary host rock					
	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources
Seismic reflection	1	1	3	2	2	1	1	1	3	2	2	1	1	1	3	2	2	1	1	1	3	2	2	1
Seismic refraction	1	1	3	3	3	2	2	2	3	3	3	2	2	2	3	3	3	2	2	2	3	3	3	2
Surface wave profiling	2	1	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3
Micro-gravity	2	2	3	3	3	1	2	2	3	3	3	1	2	2	3	3	3	1	2	2	3	3	3	1
Magnetics	2	3	3	3	3	1	2	3	3	3	3	1	3	3	3	3	3	2	3	3	2	3	3	1
EM: Time Domain	2	3	1	2	3	1	2	3	2	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1
EM: Frequency Domain	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2
EM: CSAMT/MT/AMT *	1	3	1	2	3	1	1	3	1	1	2	1	1	3	1	2	2	1	1	3	1	2	2	1
DC Electrical Resistivity	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2

* Controlled Source Acoustic-frequency Magneto Tellurics / Magneto Tellurics / Acoustic-frequency Magneto Tellurics

Score: 1 Expected to provide useful information; 2 May provide useful information in certain circumstances; 3 Unlikely to provide useful information

	6. Mudstone host rock						7. Plastic clay host rock						8. Carbonate host rock						9. Non-evaporitic host rock with hypersaline ground water					
	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources	Geological	Geotechnical	Geochemical	Hydrogeological	Gas migration	Resources
Seismic reflection	1	1	3	2	2	1	1	1	3	2	2	1	1	1	3	2	2	1	1	1	3	2	2	1
Seismic refraction	2	2	3	3	3	2	2	2	3	3	3	2	2	2	3	3	3	2	2	2	3	3	3	3
Surface wave profiling	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3
Micro-gravity	2	2	3	3	3	1	2	2	3	3	3	1	2	2	3	3	3	2	2	3	3	3	3	2
Magnetics	3	3	2	3	3	2	3	3	2	3	3	2	3	3	2	3	3	3	2	3	3	3	3	2
EM: Time-Domain	2	3	1	2	3	1	2	3	2	2	3	2	2	3	2	2	3	2	2	3	1	2	3	2
EM: Frequency Domain	2	3	3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	2	2	3	1	2	3	2
EM: CSAMT/MT/AMT *	1	3	1	2	2	1	1	3	2	2	3	1	1	3	2	2	3	2	2	3	2	2	3	2
DC Electrical Resistivity	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2	2	3	2

* Controlled Source Acoustic-frequency Magneto Tellurics / Magneto Tellurics / Acoustic-frequency Magneto Tellurics

Score: 1 Expected to provide useful information; 2 May provide useful information in certain circumstances; 3 Unlikely to provide useful information

B3.1 Environment 1 – Hard fractured rock to surface

The principal challenge to carrying out and interpreting geophysical surveys in this environment is the potentially complex tectonic history. The occurrence, distribution, orientations and connectivity of faults and fractures will be of particular interest. If these faults and fractures contain fluids or mineral deposits, or are associated with alteration to the composition of the rock mass, they may be detected using electrical techniques. Faults and fractures that are marked by significant density contrast may be identified by micro-gravity techniques. Seismic reflection is likely to provide the most detailed data on the structure of the rock mass, and in particular may help identify tectonic lenses or other geologic units that may be relevant to studies of rock stress or geomechanics. Seismic measurements taken from the surface, supported by those taken from seismic methods in boreholes, may help to measure fracture density and determine orientations of fractures, by analysing seismic attributes and velocity anisotropy.

Geological structures may form impermeable barriers that act to compartmentalise the distribution or flow of fluids or gas. Groundwater distribution may be detected using electrical methods.

The presence of potentially economic deposits of minerals which had not previously been identified in early screening (i.e. MRWS Stage 2, see Section 2.1) may be detected using electrical and magnetic methods, and their distribution informed by seismic or gravitational techniques.

An example of this environment type is the site of the spent fuel disposal facility at the island of Olkiluoto in Finland. The geology comprises Archaean granitic gneiss containing fracture zones and some igneous intrusions and has little sedimentary or soil cover (e.g. Posiva, 2009).

A previous review of the use of geophysical techniques in characterising potential sites for radioactive waste disposal included consideration of the approach used at Olkiluoto (British Geological Survey, 2001). Site-specific data were reported to have been available from the national low-level high resolution airborne geophysical survey (magnetics, radiomatrics and electromagnetics) at the early stage of site characterisation. An initial regional survey used airborne and surface geophysics over four sites to inform a preliminary assessment of the geology. Magnetics and electromagnetics, including Very Low Frequency electromagnetics, were used to investigate specific geological structures and fracture zones.

At Olkiluoto some surface geophysical data was available that had been collected in support of the construction of the adjacent nuclear power plant. Further surface geophysical investigations were undertaken in the third phase (post borehole) to resolve remaining uncertainties. Ground magnetic and Very Low Frequency electromagnetics data contained signal noise from the existing power lines and other surface infrastructure. High frequency electromagnetic data were acquired to detect fractures in the bedrock and map contrasting soil types. Time-Domain Electromagnetic data were acquired to detect variations in resistivity which were considered representative of moisture content or pores and microfractures, and used to map saline groundwater present in the deeper bedrock. This data also identified possible massive sulphide deposits. Direct Current Electrical Resistivity soundings provided good data in the upper 50-100m, and complemented the electromagnetics and Time-Domain Electromagnetic data in constructing geo-electrical cross-sections (British Geological Survey, 2001).

The review also considered the use of geophysics to investigate the Äspö underground research laboratory in Sweden. The regional geology around the site is dominated by the Smaland granite which lies beneath a thin regolith which is never more than 10m thick (e.g. SKB, 1999).

A phased investigation programme started with regional surveys, which investigated an area of 20km^2 encompassing five closely spaced potential sites. This was followed by more detailed surveys over three of the potential sites during the 'siting programme'. The final 'prediction stage' concentrated on taking more measurements at the southern part of Äspö (British Geological Survey, 2001).

The regional surveys deployed airborne magnetics and electromagnetics (horizontal loop and Very Low Frequency) to map the geology and to identify major fracture zones. The site specific surveys included additional airborne magnetics and electromagnetics collected on a higher resolution grid. Ground techniques used included gravity, magnetics, electromagnetics, Direct Current Electrical Resistivity, Ground Penetrating Radar and seismic reflection and refraction (British Geological Survey, 2001).

Surface measurements confirmed and added detail to the airborne surveys. Gravity data informed regional scale lithological mapping, and provided information to model the shape of relatively high and low density intrusions. Electrical and magnetic techniques were very effective in identifying fracture zones. Seismic refraction was particularly useful where magnetic, resistivity and electrical techniques were adversely affected by signals associated with manmade infrastructure or activity or highly conductive sea water. Seismic reflection proved relatively ineffective in identifying fracture zones (British Geological Survey, 2001).

B3.2 Environment 2 and 3 – Hard fractured rock overlain by sedimentary rocks

The hard fractured rock would be surveyed in a similar way to Environment 1. There may be additional challenges in obtaining high quality seismic data through the sedimentary cover and in to the hard rock beneath, depending on the thickness and nature of the sedimentary cover. Seismic reflection can identify structural features that extend through the entire sequence. These features may also be characterised by airborne gravity and/or magnetic surveys on a regional scale. Seismic reflection can also map the thickness and lateral persistence of units within the sedimentary sequence.

Near-surface units that may act as minor aquifers containing potable water may be identified and mapped using seismic and electrical techniques. Coal and hydrocarbons may be present, depending on the history and age of the basin. If not previously identified these resources can be mapped by seismic reflection. Hydrocarbons can also be mapped by electrical methods.

Previous investigations by Nirex used a large number of different techniques to characterise the geology and hydrogeology of the site around Sellafield (e.g. Chaplow, 1996). The geology at the site considered was hard rock with sedimentary cover. Geophysical results were reported in separate studies and used by joint interpretation teams to arrive at broader compilations and assessments of the structure and properties of the rock/fluid mass. Specific targeted surveys and a number of geophysical techniques were used to test their suitability to produce useful information in the context of characterising the specific site (British Geological Survey, 2001).

Airborne gravity and magnetic surveys were undertaken to inform regional structural models, and test models of depth to basement beneath the sedimentary cover. Trial surveys were done using electromagnetic methods including Magneto-Tellurics, Time-Domain Electromagnetic and Controlled Source Acoustic Magento-Tellurics. Ground Penetrating Radar, Electromagnetics and seismic refraction methods were used to identify faults at the detailed scale. Direct Current Electrical Resistivity was used in addition to the other techniques to investigate the quaternary sediments (British Geological Survey, 2001).

B3.3 Environment 4 – Evaporite host rock

A relatively simple layered stratigraphy may be complicated by faulting associated with a basin environment. Seismic reflection would be expected to provide the most detailed information on such structures, perhaps supplemented by gravity and magnetic data, at a regional scale.

The host rock itself may be only 50-100m thick. Variation in thickness is best mapped by seismic reflection, supported by borehole data from a number of locations. The resolution of electrical methods reduces with depth, and where the host rock lies beneath a thick cover of sediments electrical methods may not be able to provide a useful resolution. Groundwater flow in evaporites is likely to be negligible but where is does occur it will be along thin interbedded marl layers. These layers will probably be too small to identify using surface geophysical techniques. They will be identified and characterised by drilling, using borehole logs and down-hole geophysical tools.

The distribution of brine and groundwater could be identified as clear and detectable contrasts in electrical properties from the host rock.

Coal or hydrocarbon resources that have not previously been identified could be mapped using seismic reflection. Hydrocarbons could also be mapped using electrical methods.

B3.4 Environment 5 – Siliceous host rock

This environment is likely to be a relatively complex basin setting where strata are cut by faults. Suitable thickness and lateral extent of potential host rock may be limited. Characterising the stratigraphy and structural geology of this environment to host a GDF may follow approaches used to explore sedimentary basin structures for hydrocarbons or coal. In these cases, the regional structure is investigated by geological mapping, airborne surveys and perhaps 2D seismic data. Within the limits of the economic potential of the area, 3D seismic coverage will be as thorough as is practical, and will be constrained by a number of boreholes with detailed geological logs and down-hole geophysical measurements. Seismic anisotropy and seismic attribute maps may provide additional information on the distribution and orientation of fractures.

Groundwater distribution and transmissive fault zones that are presently acting as flow conduits may be mapped by electrical techniques. Coal or hydrocarbon resources that have not previously been identified could be mapped by seismic reflection data. Hydrocarbons could also be mapped by electrical methods. Significant ore deposits (e.g. iron ore) may be detected by electrical and magnetic methods, and their distribution informed by seismic and gravitational techniques.

B3.5 Environment 6 – Indurated mudrock host rock

This may be in the form of a relatively simple layered stratigraphy (Environment 6a) or it may be complicated by faulting associated with a basin environment (Environment 6b). Seismic reflection would be expected to provide the most detailed information on such structures, perhaps supplemented by gravity and magnetic data at the regional scale.

The host rock itself may be only 50m thick. Variable thickness is best mapped by seismic reflection. Depths can be estimated by measurement and analysis of the seismic velocity in each geological material. Greater accuracy may be provided by constraining the layer boundaries with borehole data in a number of locations. Electrical methods may be unable to provide information at a useful resolution, if the host rock is too deep.

B3.6 Environment 7 – Plastic clay host rock

In this environment it is anticipated that suitable clay host rocks would occur at a relatively shallow depth in a fairly young basin. The host rock unit may have limited thickness (50-100m). Seismic reflection may be used to determine the vertical and lateral variations in a potential host rock horizon. Electrical methods may provide useful additional information if the potential host rock is less than 500m deep.

The Boom Clay in Belgium was investigated as a potential host rock using geophysical techniques. This work was reviewed by the BGS (British Geological Survey, 2001). Only 2D seismic surveys and borehole logging were undertaken in the initial characterisation programme. Higher resolution seismic reflection data, from the area of Mol-Dessel, were acquired subsequently, but the results were not available to the review.

The Boom Clay has been affected by tectonic faults related to the Roermond Graben. Some satellite faults are found in the Poppel, Mol and Lommel areas that have been reactivated during the Tertiary to Miocene and Quaternary periods.

These faults have been identified on the basis of seismic profiles where either a clear throw could be seen or deduced from a difference in a layer depth between two boreholes. Some evidence can be found for the Mol Rauw and Poppel faults in the geomorphology (Bernier *et al*., 2000).

The Boom Clay consists of relatively simple horizontal sedimentary sequences with very little faulting and is therefore amenable to characterisation using borehole investigations and from the subsequent construction of an underground rock laboratory.

B3.7 Environment 8 – Carbonate host rock

Environments 8a and 8b are expected to be a relatively simple layered rock sequence. The vertical extent of the host rock is controlled by the location of the top of the low-permeability limestone. Environment 8c is potentially a complex structural environment and is likely to be faulted. In all cases the host formation may be thin (50m or so). Geological structures (where they exist) can be mapped by seismic reflection, supplemented by gravity and magnetic surveys at a regional scale, as described for other environments.

The application of geophysical surveying techniques to identify and characterise the host rock in this environment may be limited because the contrast between the suitable low permeability carbonate rocks and the unsuitable more permeable horizons may not be so marked.

In Environment 8c fractures are expected to be important controls on groundwater flow. Seismic measurements from the surface may be useful to determine fracture density and orientation. These may be supported by drilling and down-hole borehole seismic methods at a later stage.

B3.8 Environment 9 – Non-evaporitic host rock with hypersaline groundwater

This environment could be any of the other environments except for 1, 4, 7 and 8a. However, in this environment the groundwater at the GDF location is highly saline. The main feature is that highly saline (dense) water should be relatively stable.

Geophysics would be used in this environment to map the extent and distribution of hypersaline groundwater. This would be best done using electrical methods. The contrast in bulk electrical properties (conductivity) presented by hypersaline ground water would be expected to be significant and readily detectable by surface electrical methods.

B3.9 Summary of potential application of geophysical surveying techniques to geological environments

Following the information and discussion presented in the previous sections it is likely, although not certain, that seismic reflection will be the dominant geophysical investigative tool at the site scale. Dependent upon the geological environment, and the specific geological and logistical challenges of the characterisation project a number of other geophysical techniques could yield valuable additional information both at the regional and the site scales. As the information requirements and detail required evolve with the iterative development of ground models the application and targeting of the suite of available geophysical tools will also change. In this evolving investigation the role of the geophysical experts is key to ensure geophysical techniques are used appropriately and efficiently, and to ensure they are effectively integrated with other sources of information.

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