

Digital Outcrop Modelling and its Application to Deep Geological Disposal of Nuclear Waste.

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List of Abbreviations

ANDRA - Agence Nationale pour la gestion des Déchets RAdioactifs

AR - Augmented Reality

BMWi - Bundesministerium für Wirtschaft und Energie

BGS - British Geological Survey

BUSC - Basement Under Sedimentary Cover

BVG - Borrowdale Volcanic Group

CPU - Central Processing Unit

DECC - Department for Energy and Climate Change

DECOVALEX - DEvelopment of COupled models and their VALidation against Experiments

DFN - Discrete Fracture Network

(D)GPS - (Differential) Global Positioning System

DOM - Digital Outcrop Modelling

DTM - Digital Terrain Model

FLOPS - FLoating Point Operations Per Second

GDF – Geological Disposal Facility

GPGPU - General-Purpose computing on Graphics Processing Units

GPU – Graphics Processing Unit

HAW- Higher Activity Waste

HLW - High Level Waste

HRL - Hard Rock Laboratory

ILW - Intermediate Level Waste

ISIS - Interactive Set Identification System

KORAD - Korea Radioactive Waste Agency

LAW- Lower Activity Waste

LDBF(Z) - Lake District Bounding Fault (Zone)

LLW - Low Level Waste

LLWR - Low Level Waste Repository

LSSR - Low Strength Sedimentary Rock

Ma - Millions of years ago

MIPS - Millions of Instructions Per Second

MRWS - Managing Radioactive Waste Safely

MVS - Multi-View Stereo

NDA - Nuclear Decommissioning Authority

NRC - Nuclear Regulatory Commission

NUMO - Nuclear Waste Management Organization of Japan

NWMO - Nuclear Waste Management Organization

ONDRAF/NIRAS - Organisme National des Déchets Radioactifs et des Matières
Fissiles Enrichies

OSGB – Ordnance Survey Great Britain

PRCS - Project Coordinate System

PRZ - Potential Repository Zone

RCF – Rock Characterisation Facility

RWM – Radioactive Waste Management

RWMD - Radioactive Waste Management Directorate

SFM - Structure From Motion

SFR - Storage For Reactor

SKB - Svensk Kärnbränslehantering

SOCS - Scanners Own Coordinate System

SOP - Sensor's Orientation and Position

TVO - Teollisuuden Voima Oy

VLJ - Voimalaitosjäte

VLLW – Very Low Level Waste

VR - Virtual Reality

VRGS - Virtual Reality Geologic Studio

WIPP - Waste Isolation Pilot Plant

Abstract

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Disposal of the UK's legacy nuclear waste is the biggest challenge facing the industry at present. There is currently no long term storage facility in the UK and the inventory is continually growing. This project investigates the role that digital geoscientific data collection, analysis and modelling techniques play in the search for, and development of, a Geological Disposal Facility (GDF), critically analyses classical techniques and new, digital methodologies to assess what their impact would be on any site investigation.

The Borrowdale Volcanic Group outcrop in Cumbria, NW England was chosen as it provides an analogue to a higher-strength crystalline basement setting for a GDF. Terrestrial lidar and photogrammetric surveys were conducted at four locations around the study area. These provided information on the fracture geostatistics which are the main fluid migration pathways in the subsurface in the BVG. The mechanics of deformation are identified by analysing the clustering of data points via digital stereonet analysis. The analysis shows the rocks sampled are highly fractured and their orientations and dips reflected the extensional tectonism experienced in the area. These are in the form of adjacent sets trending broadly NNE-SSW and NNW-SSE at very high angle dips ($\sim 70^\circ$).

A new workflow developed for this work demonstrates how a potential site's fracture statistics, and indeed the 3D geology, should be investigated as part of future GDF site investigations. Areas of complex geology such as the BVG present many difficulties in interpretation and analysis due to the poorly constrained polyphase nature of the deformation. These complexities make characterisation and modelling highly problematic, and as such, areas of simpler geology should be investigated first.

Assessments which were based on early geological studies using traditional field data collection techniques underestimated the impact of heterogeneity on fluid flow migration modelling within the subsurface. This suggests that, should a GDF should be developed in such a geological setting, huge difficulties may be encountered. These will be associated with the development of performance assessments and safety cases which are typically based on geological models that should use such complex data.

In addition to this, datasets collected using digital methods are a powerful visualisation tools for communication of complex geology, that can be utilised in stakeholder engagement activities that will form a key part of any GDF development process.

Declaration

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*“Although our intellect always longs for clarity
and certainty, our nature often finds
uncertainty fascinating.”*

Carl von Clausewitz, On War, 1832

Chapter 1: Introduction

Chapter 1

Introduction

Disposal of the UK's legacy nuclear waste is the biggest challenge facing the industry at present. There is currently no long term storage facility in the UK and the inventory is continually growing. In 1992, Nirex submitted plans to build a Rock Characterisation Facility (RCF) near Sellafield, West Cumbria. These plans were ultimately rejected in 1997 due to a range of scientific concerns (Knipe, 1996). The RCF was widely perceived as a precursor to the building of a Geological Disposal Facility (GDF) in which to store nuclear waste in the area, although this was denied by Nirex. One of the major concerns raised in the rejection of the planning application was the suitability of the host geology. In 2008 a second attempt was made to begin disposal investigations and the government announced that a GDF was the favoured method for containment and long term storage of the legacy waste (Defra et al., 2008). The Managing Radioactive Waste Safely (MRWS) West Cumbria process was abandoned in 2013 after a "no" vote from Cumbria County Council ended the investigations, even though Allerdale and Copeland borough councils were in favour of proceeding with investigations. If there is to be a GDF in the UK, the site selection process needs to evolve to address three main elements: issues raised in previous site selection attempts, adoption of new technologies that can be beneficial to the process, and

the dissemination of information to the public and relevant stakeholders.

Stakeholder engagement has, historically, been very poor in the nuclear industry (Whitton, 2010).

One major challenge is to predict the rock characteristics at the proposed depth range of the GDF, some 200 m - 1000 m at each repository site (DECC, 2014).

Subsurface geology and fluid flow characteristics are extensively modelled at these depths by the hydrocarbon industry to provide efficient production rates for oil and gas (e.g. He and Durlofsky, 2006). In the industry, surface outcrop analogues are used to predict subsurface reservoir properties where data at depth is limited or missing (e.g. scarcity of boreholes or only larger-scale information provided by seismic reflection surveys). One example of this is the Book Cliffs in Utah: outcrop analogues that were used as the basis for the development of sequence stratigraphy by Exxon Mobil (see Yoshida et al., 1998). Whilst characterisation techniques using outcrop analogues are well-established for clastic settings, less research has been conducted on outcrop analogues for crystalline basement settings, yet their properties can be used to populate small and large scale reservoir (or in this case hydrogeological) models.

The unit chosen to investigate in this project is the Borrowdale Volcanic Group (BVG). This is located in Cumbria in the North West of England. The unit was chosen as it matches the description for a higher strength crystalline basement rock setting (Norris 2012) as a possible host rock for a GDF. It was also the site of the previous Nirex studies and, as such, there is an existing dataset to work with. The BVG also has the advantage of being an exceptionally low porosity rock unit (Degnan et al., 2003) which means only the fracture network needs to be modelled,

rather than a dual porosity/permeability model which would increase the modelling complexity.

To collect outcrop data for this project, terrestrial lidar scanning was utilised. Subsequent references to "lidar" in this thesis refer to terrestrial lidar. The term 'lidar' is preferred to its variations (LiDAR or LIDAR) as discussed in Hodgetts (2013), as it is defined as such in the Oxford English Dictionary (OED, 2016). The technique allows fast collection of large datasets down to cm-scale resolution (Bellian, 2005; Wilson et al., 2009b; Hodgetts, 2013). It reduces sample bias and increases measurement accuracy (Seers and Hodgetts 2013). The large surface expression of the BVG requires a more efficient data collection method than the traditional scanline surveying method usually employed in fracture studies. This is a vital facet of the project; the BVG covers almost 500 mi², and without the acceleration of data collection via the lidar, this project would not be possible.

Lidar and the modelling datasets lend themselves well to visual presentation of data in a simple and easy to understand manner. This could be invaluable when presenting data as part of the stakeholder engagement that is a vital part of any site selection process. It is proposed that high resolution digital data could be utilised to create 3D models that can form part of the site selection process of any future GDF siting process.

1.1 Aims

Initially, it was conceived that model building of the BVG and subsequent fluid flow modelling would be an achievable goal, with the project concentrating on the behaviour of fluids in the subsurface. However, as the project progressed, it

became clear that the pre-existing data that could be used to condition the model was not readily available and the uncertainty in the subsurface was so great that only a highly simplified model could be generated, which would be unsuitable for fluid modelling. Therefore, the project was redesigned. Instead of being a definitive methodology for siting a GDF, the data collected can instead be used to investigate which aspects of a siting process can be digitised and which more ‘traditional’ techniques are required, including, but not limited to, manual fracture surveys and borehole analysis. Limiting invasive borehole studies is desirable as they only provide spatially limited data.

The aim of this project was to investigate best practice for site characterisation of a UK GDF. In particular, the project examined a possible workflow that utilises high-resolution digital data, obtained from outcrop analogues, as the basis for the production of a 3D/4D flow models of a geological setting that has the potential to host a geological disposal facility (GDF) in the UK, focusing, in particular, on the higher-strength geological setting, as defined in DECC (2014), and utilising a UK-based analogue for such a setting.

The secondary aim was to increase the 3D and 4D understanding of the structural geology and hydrogeology of a specific, UK-based analogue for the higher-strength geological setting, in this case the Borrowdale Volcanic Group of Cumbria.

A tertiary aim for the project is to investigate how any outputs from the project can be used as the basis for public engagement activities, to inform, discuss and explain the issues and science behind siting a GDF.

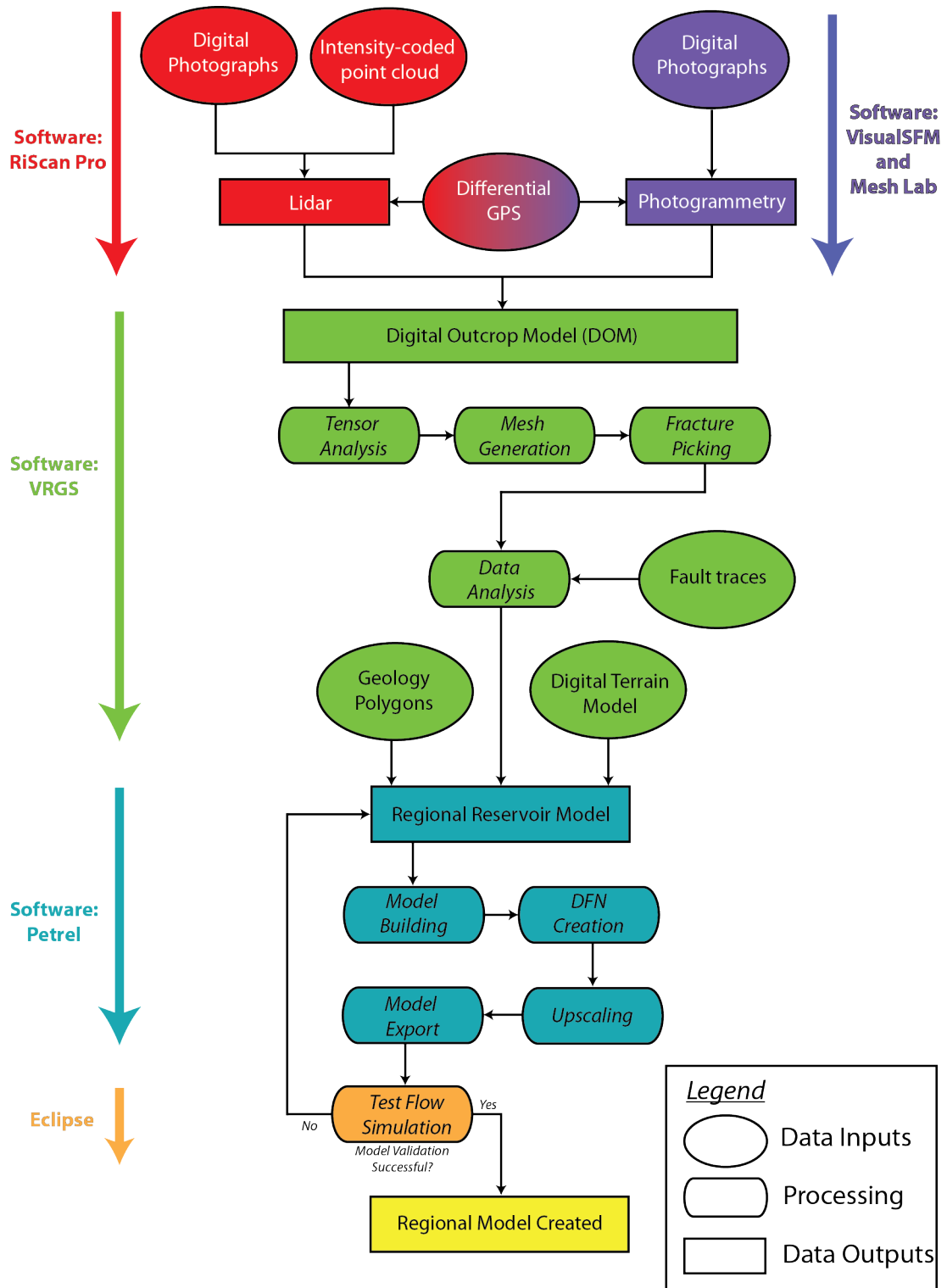


Figure 1.1: Project workflow, as envisaged at the beginning of the project.

Figure 1.1 shows the data acquisition and processing workflow, as envisaged at the beginning of the project. The workflow was built round the premise that existing

techniques (with some use of proprietary techniques developed in the research group) would be sufficient to characterise the region.

1.2 Objectives

1. Identification of a geological setting for a GDF which will be studied, including a specific onshore analogue and definition of the study area.
2. Collection of a low-resolution regional dataset from the Borrowdale Volcanic Group which is the chosen analogue for the higher strength geological setting for a GDF. This comprises published and unpublished existing data, including geophysical, borehole and field data (e.g. geological maps) and regional field data.
3. Application of high-resolution data from selected surface and subsurface field locations within the study area, using 3D lidar, high-resolution 3D digital photogrammetry and traditional field data collection techniques.
4. Creation of low resolution, regional 3D structural models of the BVG.
5. Creation of detailed 3D brittle deformation structure (fracture) models for each high-resolution field location using datasets collected.
6. Creation of 3D regional fracture network model for the BVG, integrating data collected and stochastic modelling.
7. Creation of a test fracture network at an outcrop scale.
8. Investigate how this data can be used as part of a wider effort to engage and inform relevant stakeholders.

Chapter 2: Background Literature

Chapter 2

Background Literature

2.1 Nuclear Waste

Nuclear waste falls into four distinct categories as defined by the Nuclear Decommissioning Authority (NDA) publication: “An Overview of NDA Higher Activity Waste” (NDA, 2012):

- High Level Waste (HLW) - waste in which the temperature may rise significantly as a result of its radioactivity, so this factor has to be taken into account in the design of storage or disposal facilities.
- Intermediate Level Waste (ILW) - waste exceeding the upper boundaries for Low Level Waste (LLW) that do not generate sufficient heat for this to be taken into account in the design of storage or disposal facilities.
- Low Level Waste (LLW) - waste having a radioactive content not exceeding 4 Gigabecquerels per tonne of alpha activity, or 12 Gigabecquerels per tonne of beta/gamma activity.

- Very Low Level Waste (VLLW) - a sub-category of LLW, comprising waste that can be safely disposed of with municipal, commercial or industrial waste, or can be disposed of in specified landfill sites subject to limits on radioactivity content.

Radioactive wastes can also be categorised as:

- Higher Activity Waste (HAW) - comprises HLW, ILW and a small fraction of LLW ($< 13,500 \text{ m}^3$ packaged volume) with a concentration of specific radionuclides that prohibits its disposal at existing and planned future disposal facilities for LLW.
- Lower Activity Waste (LAW) - comprises of LLW and VLLW.

The majority of UK nuclear stockpile of both HLW and ILW is currently stored above ground at Sellafield Nuclear Facility in a temporary storage facility (Figure 2.1).

The rest is distributed between 34 other sites (NDA, 2013a), but all spent fuel is held at the Sellafield site. The Sellafield site is not designed to hold waste for more than another 50 years and with a fleet of new reactors planned, it is essential that the UK continues to move towards a permanent solution to solve its legacy waste problem. The results of ignoring nuclear waste are shown at Pond B30 at Sellafield. This contains 50 years' worth of waste from the plant's MAGNOX reactors, a temporary measure which became permanent. It has been left untreated since and has begun to corrode and release radiation and radionuclides into the pond water, making the clean-up both difficult and dangerous; far more so than if it had been stored properly initially.

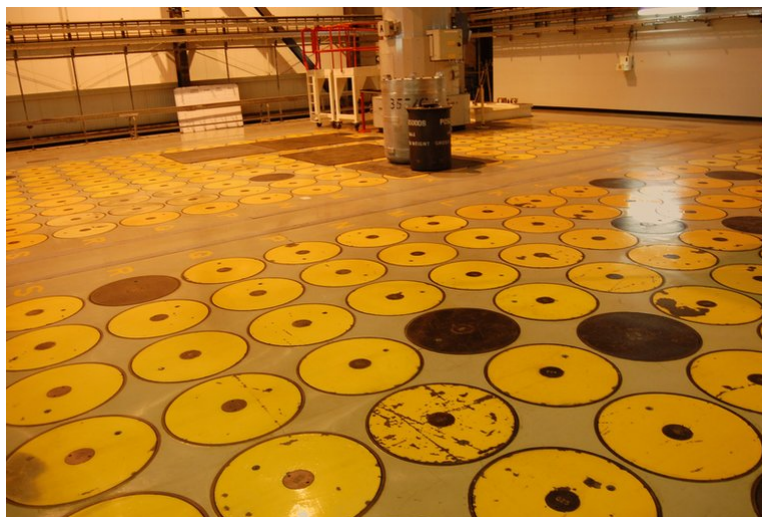


Figure 2.1: High Level Waste Storage facility at Sellafield (Source: BBC)

In 2008, the Government decided that all legacy and future waste was to be disposed of in a Geological Disposal Facility (GDF) (Defra et al., 2008). This would take the form of an underground repository (500 m - 1500 m depth depending on location) in which the UK's ILW and HLW waste would be disposed of until it had cooled and decayed to a safe level. This may take on the order of 100,000 years depending on the type of waste present. As the issue of nuclear waste disposal is understandably an emotive one, it was decided that communities would be required to volunteer to host the repository before any further steps could be taken. In return, these communities would receive not only the boost in jobs and income to local businesses that any such project would bring, but also financial incentives such as new public infrastructure and investment (IAEA, 2007). This was intended to mirror projects in countries such as Sweden and Finland with one major difference: there the whole country was screened to select a number of promising repository locations and then the relevant communities were approached. In the UK the government took the opposite approach; communities would volunteer and only then could site investigations begin. This poses a major problem to planners. Ideally, the geology and local environment

should be the defining factor in the search for a suitable site. However, if the search zones are limited to the communities who have volunteered, the geologic barrier to radionuclide migration could be less effective than in other areas. The multi-barrier concept (Defra et al., 2008) has been proposed as a way to counter this. Engineered barriers are placed between the waste and the surrounding environment to slow any release of radionuclides into the surrounding geosphere and, more specifically, the groundwater. However, engineering barriers that contain nuclear waste for in excess of 100,000 years is a major hurdle.

Three councils proceeded to the consultation stage of the application process: Allerdale Borough Council, Copeland Borough Council and Cumbria County Council (Ipsos MORI, 2012), all based in West Cumbria. However, on the 30th January 2013, although Allerdale and Copeland councils voted to proceed to the next stage of the process, Cumbria County Council voted not to proceed, and as a result, the consultation process has come to a close. This is due to Cumbria holding powers of veto over the smaller councils. This decision has left the UK at an impasse: the waste needs to be disposed of via a voluntary selection process, but nowhere is willing to host the repository.

2.1.1 Nirex: Lessons Learnt

The MRWS Cumbria project was not the first of its kind in the UK. In 1997, an attempt at building a nuclear waste storage facility in the North West of England was comprehensively defeated at the planning stages (Oldroyd, 2002). Examining the reasons for this provides a detailed geological perspective on the project and its shortcomings. Nirex Ltd. (previously the Nuclear Industry Radioactive Waste Executive) was tasked with disposing of the UK's nuclear waste. This involved

analysing the geology of sites around the UK and drawing up a shortlist. However, with a failed attempt to find a suitable disposal site in the late 1970's having already turned the UK public against the idea of geological disposal, Nirex faced a difficult task.

By the end of the 1980s public meetings, local offices at potential sites and newsletters had been implemented to try and restore the public's faith, but crucially, the site selection process remained shrouded in secrecy. When the deep site selection programme was started, the public still remained broadly opposed. To address this, in 1987, Nirex began a major public consultation exercise involving the distribution of around 50,000 copies of a discussion document entitled "The Way Forward" (Nirex, 1987) which asked the public to comment on a range of issues. As a public consultation, this initiative was considered a success, but there was little or no indication of how Nirex would take on board and act upon the views put forward by the public. The key public concerns that emerged in that consultation were:

- Repository safety was paramount, with safe waste transport coming second
- Monitoring and retrieval were considered important
- Negative impacts on local communities and industries

The analysis of the consultation process had only just been published when Nirex announced in 1989 that it intended to investigate two sites: Dounreay and Sellafield. The local communities near Dounreay and Sellafield supported investigations in their area, but there was no real evidence of the site selection process being influenced by views expressed in the earlier public consultation,

given the short time frame between the publication of the analysis and the announcement.

By 1991, Nirex had decided to focus its efforts on Sellafield, apparently without a great deal of scientific justification. They aimed to construct an underground Rock Characterisation Facility (RCF) in the area. Nirex's public communication activities became highly targeted, with local offices, mobile exhibitions and production of information materials. However, the local authority, fearful that approval of the RCF would lead automatically to a repository, given the geological conditions of the host rock, refused permission to build the RCF at the Longlands Farm site. The RCF was widely seen a precursor facility to a full-scale GDF: rock analyses and detailed site characterisation were to be performed to further test the geologic suitability of the area. Criticisms of the project were strong and wide-ranging. In a letter to the secretary of state rejecting the appeal against planning rejection (McDonald et al., 1996), the planning inspector overseeing the inquiry highlighted three main failings in the site selection process:

“The first was the late introduction of an alternative Sellafield site which was not particularly promising according to the original criteria, and so probably would have been eliminated earlier if it had been included at the start. The second was the inconsistency between the team and the Board, which resulted in this lately introduced site and the doubtful Dounreay being kept in play whilst others with better safety potential were discarded. The third was the subsequent dropping of the alternative Sellafield site when it was realised after all that it is not suitable, and its substitution by the appeal site which, although nearby, had not been through the process at all.”

All of which seemed to be a result (in his words) of:

“... a strong desire to locate the repository close to Sellafield.”

Another point raised, pertinent to this project, was that:

“(even though the) ... scientific and technical work since the appeal site was chosen has generally been very impressive... (However) All the work and cooperation have not led Nirex to a sufficient understanding yet of the “groundwater conditions in and around the appeal site.”

There seems to be two main failures in the project. The first was the perceived desire (real or otherwise) to place the RCF in a location suitable for Nirex, not the most geologically suitable site. The second was that Nirex did not, or could not, prove that they understood the geology or hydrogeology of the Potential Repository Zone (PRZ) to a satisfactory level. Figure 2.2 shows some of the data collected for the investigation. It shows the 2D depth map to the base of the Longlands formation on the left. On the right is the 3D geological block model which represents the geology of the PRZ. One thing to note in the 3D block model is the unit labelled “BVG” which suggests a large, relatively homogeneous unit. As we will see in Chapter 5 this is not a realistic representation of this area.

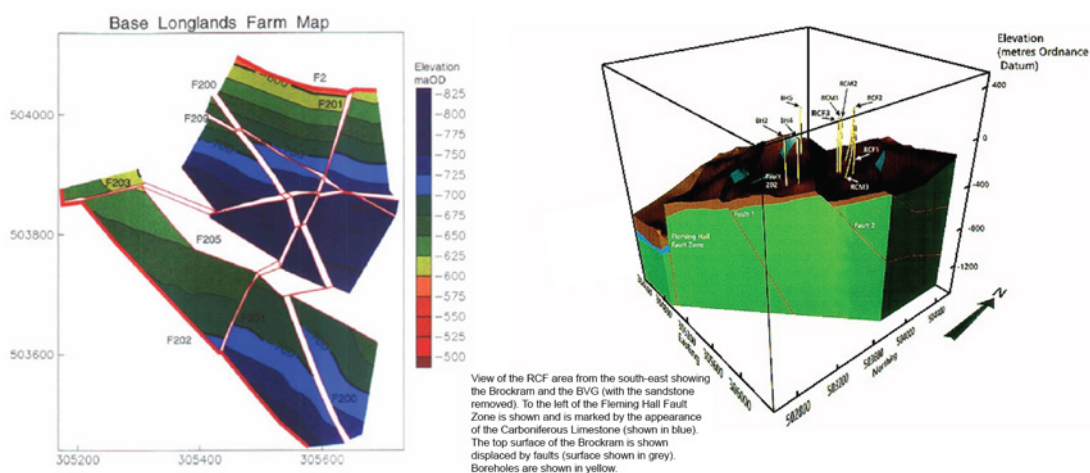


Figure 2.2: Previous data released by Nirex (Modified from Shaw et al., 2011). The models shown here are a reflection of the technology at the time, with low resolution and limited information (units are in OSGB Co-ordinates).

It is outside the scope of this project to examine the procedural or societal failings of the Nirex RCF venture in great detail, however suggested communication improvements are suggested in Chapter 6. It is possible to examine the failings, apparent or otherwise, in the site characterisation aspect. In the authors' view, the site characterisation is one of the most vital aspects of any future GDF project in the UK. If the scientists involved in the project are not confident in their findings, models or predictions, then the chances of the general public or the planning authority ratifying any proposal is almost non-existent. During any subsequent processes, it is unavoidable that concerns raised during the failed Nirex project will be revisited once again. It is important that evidence presented to the public and planning authorities is therefore robust, reliable, easy to understand and also address any criticisms raised in the 1997 report.

The groundwater and hydrogeological behaviour in the PRZ is important because of the long half-lives of the waste that will be buried. It is accepted that no GDF

can be constructed that will contain the waste until it has decayed to safe levels. It will escape into the surrounding geology. As part of any safety case, the planners must be able to prove they understand the local hydrogeological regime. The contaminants must either stagnate in the groundwater, or migrate so slowly that they will effectively become safe by the time they reach populated areas. In a porous sedimentary rock, flow is normally achieved through diffusion between pores. However in the PRZ, it was established that due to the impermeability of the rocks (welded ignimbrites, lavas and granites) that porosity is not an issue. Due to the high degree of fracturing the groundwater regime is fracture-driven in the BVG. This assumption has been applied across the whole study area as any porous regions due to lithology change will be virtually impossible to predict. It also simplifies the modelling process to concentrate on a single flow mechanism.

Borehole and seismic surveys were performed during the Nirex RCF project. The seismic surveys performed at the time were limited in scope, low quality and were therefore not included in the planning submission (Smythe, 1996). 3D seismic surveys can only detect features on the scale of $\sim 25\text{m}$ (British Geological Survey, 2006). Boreholes, whilst a useful tool to directly sample the subsurface, are invasive and therefore have to be limited. Restricting the number of boreholes limits the number of potential weaknesses, and therefore fluid migration pathways, created during their drilling. They also give only a narrow idea of the surrounding rocks and increase the uncertainty in any model created due to the increased statistical prediction needed. Limiting the number of boreholes is necessary, however, they will be required during the site selection process to provide some subsurface control data that will be used to condition the model. Full model population will need to include lithological characterisation, borehole geophysical

studies and also hydrological parameter determination (hydraulic head, ground water composition etc.)

2.1.2 Repositories Around the World

Interim Repositories	Country	Facility Name	Location	Status	Waste Management Organisation	Website and Reference
	Canada	Ontario Power Generation's Deep Geologic Repository	Ontario	licence application 2011	Nuclear Waste Management Organization (NWMO)	https://www.nwmo.ca/ (NWMO, 2016)
	Finland	Voimajätöasema (VL)	Okiluoto	In operation 1992	Posiva Oy	http://www.posiva.fi/en (Posiva, 2016)
		Lowisa	Okiluoto	In operation 1988		http://www.andra.fr/international/ (ANDRA, 2016a)
	France	Onkalo	Okiluoto	Under construction	Andra	
				Siting		
	Germany	Gorleben	Lower Saxony	Proposed, on hold	Bundesministerium für Wirtschaft und Energie (BMWi)	http://www.bmwi.de/EN/root.html (BMWi, 2016)
		Schacht Konrad		Under construction		
	Korea	Gyeongju	Gyeongju	Under construction	Korea Radioactive Waste Agency (KORAD)	http://www.korad.or.kr/kmc2011/eng/index.jsp (KORAD, 2016)
	Sweden	Storage for Reactor (SFR)	Forsmark	In operation 1988	Svensk Kärnbränslehantering AB (SKB)	http://www.skb.com/skb-swedish-nuclear-fuel-and-waste-management-company/ (SKB, 2016a)
	Switzerland	Permanent disposal		Licence application 2011		
				Siting	Nagra	http://www.nagra.ch/en (NAGRA, 2016)
	United Kingdom	Sellafield	Sellafield	In operation 1991	Radioactive Waste Management (RWM)	https://www.gov.uk/government/organisations/radioactive-waste-management (RWM, 2016)
	USA	Waste Isolation Pilot Plant (WIPP)	New Mexico	In operation 1999	Nuclear Regulatory Commission (NRC)	http://www.nrc.gov/waste.html (NRC, 2015)
Proposed/Abandoned	Country	Facility Name	Location	Status	Waste Management Organisation	Website Reference
	Argentina	Sierra del Medlio	Gastre	Under discussion	Comisión Nacional de Energía Atómica	http://www.cnea.gov.ar/ (CNEA, 216)
	Germany	Schacht Asse II	Lower Saxony	Closed 1995	Bundesministerium für Wirtschaft und Energie (BMWi)	http://www.bmwi.de/EN/ (BMWi, 2016)
		Morsleben	Saxony-Anhalt	Closed 1998		
	Japan			Under discussion	Nuclear Waste Management Organization of Japan (NUMO)	https://www.numo.or.jp/en/ (NUMO, 2016)
	United Kingdom			Under discussion	Radioactive Waste Management (RWM)	https://www.gov.uk/government/organisations/radioactive-waste-management (RWM, 2016)
	USA	Yucca Mountain Project	Nevada	Proposed, cancelled 2010	Nuclear Regulatory Commission (NRC)	http://www.nrc.gov/waste.html (NRC, 2016)
Underground Labs	Country	Facility Name	Location	Status	Waste Management Organisation	Website Reference
	Belgium	HADES Underground Research Facility	Mol	In operation 1982	Organisme National des Déchets Radioactifs et des Matières Fissiles Etanches (ONDRAF/NIRAS)	http://www.ondrat.be/ (ONDRAF/NIRAS, 2016)
	Canada	AECL Underground Research Laboratory	Pinawa	1990-2008	Nuclear Waste Management Organization (NWMO)	https://www.nwmo.ca/ (NWMO, 2016)
	Finland	Onkalo	Okiluoto	Under construction	Posiva Oy	http://www.posiva.fi/en/ (Posiva, 2016)
	France	Meuse/Haute Marne Underground Research Laboratory	Bure	In operation 1999	Andra	http://www.andra.fr/international/ (ANDRA, 2016a)
	Japan	Horonobe Underground Research Lab	Horonobe	Under construction	Nuclear Waste Management Organization of Japan (NUMO)	https://www.numo.or.jp/en/ (NUMO, 2016)
		Mizunami Underground Research Lab	Mizunami	Under construction		
	Korea	Korea Underground Research Tunnel		In operation 2006	Korean Radioactive Waste Management Company. (KRWM / KRMC)	http://www.korad.or.kr/kmc2011/eng/index.jsp (KORAD, 2016)
	Sweden	Äspö Hard Rock Laboratory	Oskarshamn	In operation 1995	Svensk Kärnbränslehantering AB (SKB)	http://www.skb.com/skb-swedish-nuclear-fuel-and-waste-management-company/ (SKB, 2016a)
	Switzerland	Grimmel Test Site	Grimmel Pass	In operation 1984	Nagra	http://www.nagra.ch/en (NAGRA, 2016)
		Mont Terri Rock Laboratory	Mont Terri	In operation 1996		
	USA	Yucca Mountain nuclear waste repository	Nevada	1997-2008	Nuclear Regulatory Commission (NRC)	http://www.nrc.gov/waste.html (NRC, 2016)

Table 2.1: A selection of current nuclear waste disposal projects around the world. None of

these projects are actively accepting waste as a method of permanent disposal.

As shown in Figure 2.3 there are numerous planned repository sites around Europe, but only three Worldwide which are currently receiving waste with a view to storing it longer-term: two in Finland and one in the USA. There are a number of underground laboratories (under a range of different names) spread around the world, similar to the RCF proposed by Nirex to provide supplementary information via experimental approaches. This means that 60 years of commercial nuclear waste is still accumulating with no permanent storage solution. With nuclear expansion planned not only in the UK, but abroad as well, this is a problem that needs to be addressed. An especially high profile repository failure was that of Yucca Mountain in the USA. After around 30 years of investigation and \$12 billion investment, the project to store America's nuclear waste in the facility was abandoned due to political pressure (Department of Energy, 2010). There are, however, some successful GDFs in operation that we can learn lessons from.

2.1.2.1 Olkiluoto, Finland (Posiva)

As one of the most advanced permanent disposal programmes in the world, Olkiluoto can provide insight into how the process can be successfully implemented. As we are considering the initial site selection process in this project, the detailed investigations and subsequent construction of an underground rock laboratory at Onkalo will not be considered for brevity.

The information in this section is modified from McEwen and Aikas (2000). In 1982 the Finnish government began a nationwide search for a repository location, beginning with a screening programme of site identification. This was an eight stage process that began with overall suitability screening of geology in Finland and progressed to increasingly detailed investigations. These began with regional

fault and fracture pattern identification using satellite photos and existing geological and geophysical data and progressed to smaller, more detailed surveys including field studies and fracture analysis. These investigations yielded five sites suitable for preliminary investigations.

The geology of Finland is less varied than that of the UK and is dominated by crystalline basement rocks, with very few sedimentary regions. It should also be noted that whilst the geology is less complex than the UK, Finland is a larger country than the UK. Whilst this will lead to a longer initial phase of investigation compared to the UK, it, theoretically, means there is an increased chance of finding a suitable host rock.

To begin with, large scale faults and fractures were identified as the major subsurface flowing features and were used as the first criterion for excluding an area from the study. They were classified as follows:

- Class 1: The width of the lineament is approximately 1 km and the corresponding length of the zone is dozens or hundreds of kilometres.
- Class II: The width of the lineament is hundreds of metres. The length of the zone varies from 5 km to dozens of kilometres. These zones often border a bedrock block chosen as a "target area" (size approximately 100-200 km²).
- Class III: Crushed (or Crush) lineaments inside the above-mentioned "target area", width from dozens of metres to a hundred metres. Commonly border an "investigation area", which is a block more intact than the surrounding area (size approximately 5-10 km²).

A constant theme of the report is that the rocks in Finland were all, broadly speaking, very similar in nature. Indeed this was highlighted during a review by

Teollisuuden Voima Oy (TVO, a Finnish nuclear power company owned by a consortium of power and industrial companies) in 1986 where it was suggested that more consideration be given to the differences between rock types, and McEwen and Aikas, (2000), also stated that they thought the two main drivers for site selection, once patently unsuitable sites had been excluded, were that the geology should be as simple as possible and that there should be minimal adverse disruption to local communities. The first point is most relevant here as they reason that a simple geology leads to a simple geological model, and therefore a simplified understanding presented as part of the safety case.

It is worth noting is that many of these investigations took place from 1980-87, 10 years before the rejection of the Nirex RCF planning permission.

This approach shows how an effective site investigation program can be implemented. Although partially mimicked by the UK, the main driver for the investigations was host rock suitability. The UK's approach also relies on community involvement as part of the selection process and as such can lead to areas being excluded even if they are well-suited to disposal. It could also be pointed out that the rocks in Finland were well-suited to nuclear waste disposal and that the site investigation process would, as a result, be much simpler there. However, this could also be said of the UK. The main focus of investigations has been on the BVG, an extremely complex geological setting, whereas simpler, sedimentary or evaporitic setting has not been identified as a possible repository setting.

The simplicity of the geology cannot be underestimated. Posiva could produce models that were accepted as part of a safety case almost 30 years ago and that, even with the revisions and further evidence obtained during the preceding

detailed site investigations, still stand up to scrutiny. This must be in part due to the geology in the regions targeted having a much lower element of uncertainty (McEwen and Aikas, 2000).

In November 2015 Posiva were granted a license to construct the final disposal facility. Posiva were able to demonstrate a high level of understanding in their safety case and show that whatever uncertainty there was in the model (e.g. faults and fractures discovered that were not predicted in the model) it would produce no alarming results that would lead to the site being rejected at a later stage. It removes the emphasis on proving to regulatory bodies that engineered barriers would be safe for the operational lifetime of the facility and rather that the modelling has predicted, with a high degree of certainty, that the groundwater conditions are favourable now and will remain so in the future.

2.1.2.2 Forsmark, Sweden (SKB)

The Swedish Nuclear Fuel and Waste Management Company (SKB) have also been investigating possible repository sites. Forsmark, whilst not as advanced in the process as the site in Finland, offers an updated view of a site selection process that has yielded a single site which is currently being reviewed as the final repository site (Svensk Kärnbränslehantering AB, 2011). It offers an insight into a more modern approach of site selection. The geological model of the target site was created using seismic reflection profiling and borehole analysis. Boreholes were used extensively to characterise the fracture network parameters in the modelling. The host geology is granitic (i.e. a Higher Strength Rock) and is bounded to the north east and south west by major deformation zones (SKB, 2007). Fracturing in the area was divided into deterministic “deformation zones” at both regional and

local scales (>10 and 1-10 km respectively) generated by faults in the model area. These are “seismic scale” features and would also be visible on the surface in many cases. For smaller scale features statistical prediction was required, and where possible deterministic analysis was used but this was not always possible (Svensk Kärnbränslehantering AB, 2011).

Analysis of the groundwater in the region, showed it to be over 1 million years old using geochemical analyses. This is a useful proxy indication that groundwater migration is very slow and thus any radionuclide contamination that manages to breach the containment measures, would not (rapidly) migrate and contaminate groundwater supplies or breach the surface. The techniques used here have informed SKB that Forsmark is a suitable location and they hope to commence with construction once the Swedish Government has issued a permit. At the moment SKB believes this could be some time early in the 2020’s.

The Hard Rock Laboratory (HRL) at Äspö by SKB, undertakes research pertaining to geological disposal of nuclear waste. Experiments are conducted 500 m underground, in preparation for a permanent facility near Forsmark (Svensk Kärnbränslehantering AB, 2011). The site, near Oskarshamn, has been active since 1986 and has provided data which is being used in the application process to site a permanent GDF in the area. The publication count for site characterisation studies alone is 2961 (as of 02/02/16) and the data collected will be invaluable to gaining planning permission for a GDF.

2.1.2.3 Zürich Nordost and Jura Ost, Switzerland (Nagra).

Nagra are leading underground investigations for nuclear waste disposal in Switzerland. As with the previous studies, Nagra undertook a survey of suitable

geologies within Switzerland and selected promising areas; the outcome of which was that claystone formations emerged as the most promising candidates. This was followed by a period of geologic site investigations of possible repository sites, which eventually led to local investigations in Canton Zürich. These investigations began in the late 1980's and continue today. This summary is limited by the fact a large proportion of the published literature is in German with only English abstracts.

The unit chosen is the Opalinus Clay, which falls into the classification of Low Strength Sedimentary Rock (LSSR). Clay is a ductile material, which provides an advantage over HSR settings, in that any fractures that appear within the rocks can anneal, retarding water migration. They also have exceptionally low permeability and can almost be considered an impermeable layer, as the clay and rocks below only allow transmission of water at very low speeds ($1-5 \times 10^{-13} \text{ ms}^{-1}$ for the Opalinus clay (Delage et al., 2010)).

A study in the Zürcher Weinland in Northern Switzerland was performed as part of the site selection process to test the suitability of the Opalinus clay as a host rock. This section is modified from (NAGRA, 2002). Experimental results and parameters obtained at the Mont Terri Rock Laboratory can be applied to the area as the clay unit is a large homogeneous claystone formation and the results can be applied to formations a sizeable distance away. This can be contrasted to any rock laboratory set in the BVG which would have to be located very near to any proposed repository site due to the levels of heterogeneity in the area.

The region is suitable for geological disposal due to a number of factors:

- Stability: the region is unaffected by any tectonic effects of the Alps and is largely seismically inactive. Uplift is minimal at around 0.1 mm/year.

- Host rock: thick, laterally continuous units of homogeneous Opalinus Clay. As mentioned, this rock type has low hydraulic conductivity, is geochemically stable and is geomechanically suitable to host a repository. Formations above and below the Opalinus clay are also low permeability, minimising hydraulic conductivity in the surrounding geosphere.
- Geometries: the topography and geometries of the subsurface geology means that it is a relatively simple region in which to perform site investigation studies, such as seismic reflection surveys and borehole investigations. A further benefit is that the seismic survey can be extrapolated to surrounding areas with a high degree of confidence. The shallow dip and continuity of the clay also allows a degree of flexibility in locating the facility as the location and also depth can be modified according to the investigations.

The suitability study comprised of:

- A 3D seismic campaign covering an area of approximately 50 km² (Nagra, 2000)
- An exploratory borehole (Benken) [NTB 00-01]
- Experiments in the Opalinus Clay as part of the international research programme in the Mont Terri Rock Laboratory (Canton Jura)
- Regional comparative studies of the Opalinus Clay, as well as comparisons with clay formations being investigated in other countries with a view to geological disposal.

The results of the study showed that the Opalinus clay in the region is suitable to host a disposal facility (Nagra, 2002). Quantitative analysis of the region has

demonstrated that the area far exceeds the safety requirements to host such a facility and that they are unlikely to change over the lifetime of the facility. All uncertainties that remain in the area are small enough that they will not adversely affect the safety of the site. The breadth of information for the region is large, and the subsurface geology is sufficiently well characterised as to back up the safety predictions made. The geometry and structure of the host rock and the surrounding strata are well characterised through high-resolution 3D seismic measurements and investigations in the Benken borehole. The presence of a large area of undisturbed host rock could be demonstrated. The future evolution of the site can also be predicted with a high level of confidence, due to the wide range of high quality data collected and the simplicity of the site.

As of 2015, Nagra have submitted plans to investigate two sites:

- Zürich Nordost
- Jura Ost

These are currently under review and both are in an Opalinus Clay geological setting.

2.2 Digital Outcrop Modelling (DOM)

The creation of Digital Outcrop Models (DOM's) is now considered to be a well-established technique in the geosciences. Around the time that planning permission was rejected for the Nirex RCF, Stafleu (1996) and in particular Bracco-Gartner (1997), were publishing some of the first digital geologic studies using stereophotogrammetric and laser transit techniques respectively.

Bracco-Gartner (1997) outlined a basic workflow to collect laser scan data and produce basic surface topographic outputs. The locality was an 80 m by 47 m outcrop and data was acquired at a range of 150 m. The scanner had a maximum range of 350 m and was accurate to 10 cm. These techniques were brand new at the time and did not have the computational or software support required to make data collection and processing widely available. This has changed in the succeeding 20 years and now lidar units ship with easy to use Graphical User Interface (GUI) control software, and alignment and processing tools are widely available.

These models can be supplemented by a range of data sources. A selection of techniques that were utilised in this project are listed below with appropriate examples.

- Geological maps and sections (Shaw et al., 2011)
- Seismic images (Evans et al., 1994; Nagra, 2000)
- Magnetic data (Kimbell, 1994)
- Digital terrain models (Moore et al., 1991)
- Gravity data (Bott, 1974; Lee, 1986)

There are also other data sources that were not used as part of this study:

- Aerial and satellite photos (Suárez et al., 2005; Zoheir and Emam, 2012)
- Data acquired with a ground penetrating radar (Busby et al., 2004)
- Hyperspectral imagery (van der Meer, 2006)
- Well log data (Shaw et al., 2011)

The main techniques utilised in this study are terrestrial laser scanning (TLS or lidar) and photogrammetry data.

2.2.1 Light Detection and Ranging (lidar)

Lidar as a tool in geoscience has been in use since the 1960's (Bellian, 2005). The technique has a wide variety of applications such as construction, hazard management and law enforcement. The premise of the unit is simple; a laser pulse is emitted from the unit towards the target. This is then reflected back and detected by the unit. The two-way travel time of the pulse is halved and multiplied by the laser speed (i.e. the speed of light in air) and this gives the total distance from the scanner to the target. From this a 3D point cloud representation can be generated. Depending on the size and specification of the unit, the accuracy of these scanners can be around millimetre scale, whereas longer range scanners have an accuracy of around a few centimetres. Reduction in the size of the units has allowed the development of portable lidar units which allows quick data capture in more remote areas.

Prior to this, the units were too large to transport easily and the preferred method of lidar surveying was via aeroplane (i.e. airborne lidar surveys, (Chen et al., 2006)). Now however, terrestrial lidar surveying is an expanding field.

The technique allows fast collection of large datasets down to cm-scale detail and several thousand data points can be collected per second (e.g. Bellian, 2005; Buckley et al., 2008; Pringle et al., 2006). As the units require line of sight to collect data, multiple scan positions must be used to prevent data shadows. Whilst an increase in point density is good in terms of the data quality collected, the data quantity poses a problem. Lidar surveys are limited by the processing power

available to the operator. Filtering of data is necessary as computers cannot handle the raw volume of data collected, especially during large regional-scale surveys. In this project, lidar has played a key role in collecting the large volume of data required to generate a viable model. Without the lidar, it would simply not be possible to manually collect the amount of data in the time available. Another advantage of the unit is that the highly visual nature of the datasets produced are ideal to demonstrate data collection and interpretation methods to the general public. Slob et al. (2005) and Bellian (2005) provide comprehensive reviews of lidar techniques as a whole and specifically with regards to generating DOM's, and (Buckley et al., 2008) details and assesses data collection specifically using a Riegl Z420i unit, the same model which has been used in this project. Hodgetts (2013) provides a comprehensive review of lidar usage in the context of location analysis for hydrocarbon exploration, for which the methods can be directly applied to nuclear waste disposal.

2.2.2 Photogrammetry

Photogrammetry is a technique that uses 2D photographs to extract 3D information. It is acquired over a range of scales, from airborne photography to capture large scale topography, to hand-held DSLR imagery of smaller features (e.g Smith et al., (2015)). As with lidar, the resolution decreases with the scale. It holds an advantage over lidar surveying in that it is a lot cheaper (relatively). A laser scanner will cost around £20,000 new, whereas the Sony NEX-5 that is used in this project costs £250. On smaller outcrops, photogrammetry provides higher resolution data using the Z420i and requires much less equipment in the field.

2.2.3 Differential Global Positioning System (DGPS)

DGPS units use signals received from multiple satellites to calculate a point location on the Earth's surface. The process differs from conventional GPS in that a separate receiver station is used to perform real time corrections (e.g. Real Time Kinematic (RTK) correction) to the signal in the field, increasing the accuracy of the measurement. DGPS is vital to the project as decimetre-scale positional accuracy is needed to correctly align and extract meaningful geostatistics from the models. The use of GPS is critical to the project as manual alignment of scans can introduce substantial positional errors, whereas DGPS can provide sub 20 cm positional accuracy and minimal orientation error (Pringle et al., 2006).

2.2.4 Geological Modelling

2.2.4.1 Modelling approach

Geological modelling is the process of building 3D representations of the subsurface by combining multiple raw data sources (seismic surveys, borehole/wells, outcrop, and petrophysical) to form a representative 3D model of the target area. Although it varies by software package, the models comprise of:

- Structural framework: representing major faults within the region
- Geology: comprising of relevant horizons and their geometries and relationships
- Petrophysical data: including porosity, permeability and any other relevant information
- Fracture networks: representations of flowing features in the model

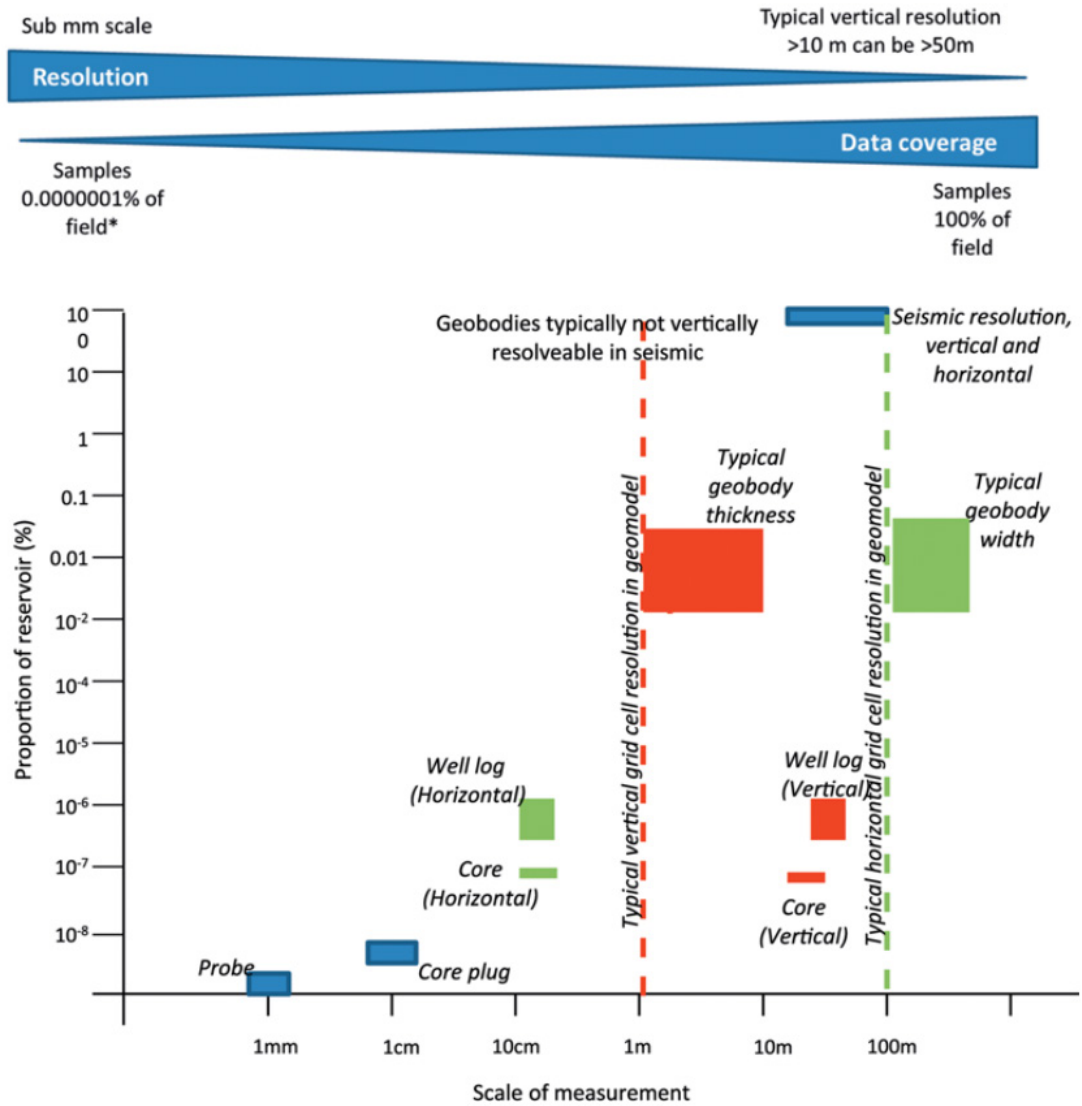


Figure 2.3: The varying scales of geological and geophysical datasets (after Howell, 2014). Broadly speaking as data coverage increases, the resolution decreases to allow effective manipulation and interpretation of data. Although this refers to a hydrocarbon reservoir, it is equally valid for a proposed GDF site.

- Upscaled dynamic model

Data in this project will mainly be derived from geological outcrop analogues. The use of outcrop analogues in geomodelling has been comprehensively reviewed in Howell et al, (2014), but will be briefly summarised here for completeness.

Outcrop analogues provide subsurface information to geological modellers that is between borehole scale (< 1 m) and seismic scale (> 25 m) and to understand rock geometries and connectivity (Figure 2.3). The data is collected and, if necessary, corrected for different conditions at depth (i.e. fracture aperture differences at depth).

This static geological model can then be upscaled into to form a dynamic model, from which fluid flow information can be extracted. The cells contain statistical information derived from the input data and modelled polygons. The reservoir modelling package Petrel (Schlumberger, 2013) will be used to build the geomodel for this project. The software is available within the University of Manchester under a free educational license. This is the main reason for using Petrel as opposed to the competition. Licensing is often very expensive so it would not be sensible to purchase other software when a viable option is already available.

Petrel is a well-established tool used in the hydrocarbon industry as part of their reservoir modelling process. Other software packages will be discussed in Chapter 5. The approaches employed by each package are similar and Petrel has no significant disadvantages compared to other software, although the software does struggle with complicated fault geometries and interactions. This is usually where faults cross or are antithetic and synthetic in nature. These relationships would lead to the pillar grid (the skeleton of the model) to become unstable.

Reservoir modelling is an umbrella term used in the hydrocarbon industry to describe management of subsurface hydrocarbon plays. This encapsulates exploration and production over the life of the field. It allows analysis and monitoring of the available resources, fluid flow prediction and depletion planning (Ringrose and Bentley, 2014).

These take the form of geocellular models, to which are assigned specific properties that are required for modelling (e.g. lithology, porosity, permeability (Pringle et al., 2006)). These models are a critical part of the hydrocarbon play managements and as such there has been significant investment into improving the techniques involved and their efficiency. The level of confidence shown by the hydrocarbon industry in this technique is proof that it should be considered as the basis for an approach to site selection by the UK nuclear industry.

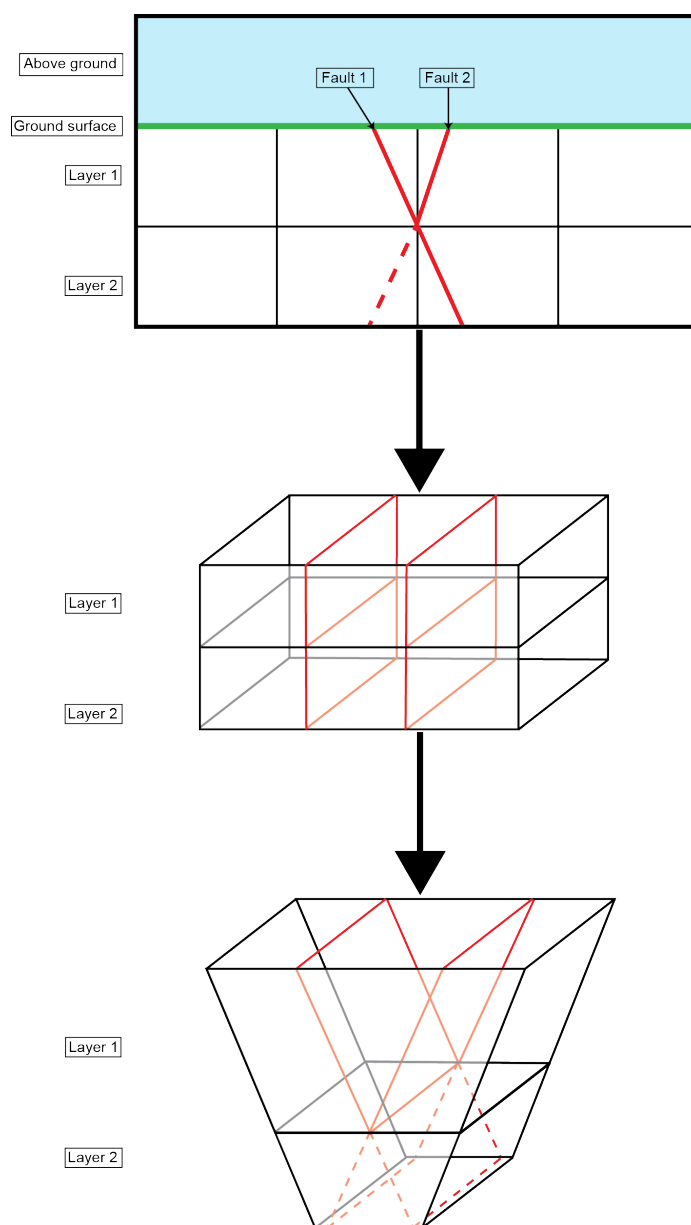


Figure 2.4: Schematic diagram to illustrate the negative cell volume problem in Petrel Software. The red lines indicate pillars within the modelling grid that would be forced to cross one another by the fault configuration in the top diagram. The pillars are required to align along the fault trace and are not permitted to bend. This grid would therefore not generate.

Petrel uses corner point grid gridding to generate models, which form hexahedral cells. Each corner is connected by straight lines to pillars within the model. These are assigned a value, which is used to determine the order of the cells. The cells have a set volume and this must always be 0 or greater in value. A negative cell

volume is not accepted by the modelling equations (see Figure 2.4). This is the reason it is not possible to model certain fault geometries.

One of the main advantages of the technique is that it is a proven method of modelling areas that will have a high level of heterogeneity within them. Whilst modelling areas such as this remains rooted in statistics and assumptions to allow successful creation of any model, these have been improved to the point where they provide an excellent understanding of what are highly complex geological areas. Statistical approaches such as semivariogram analysis (Gringarten and Deutsch, 1999) can be used to stochastically predict lithological trends within a modelling area.

Reservoir modelling is usually confined to sedimentary settings and is usually accompanied by good well control and seismic data (Falivene et al., 2006). Where possible, outcrop analogues are also widely utilised to provide further petrophysical and bedding or feature geometries that are sub-seismic scale, but are also too large to be seen or correlated using boreholes (Pringle et al, 2006, Wyatt, 2011, Hodgetts, 2013, Howell et al, 2014,).

2.2.4.2 Other Digital Approaches

For this project, the seismic reflection data from the Nirex study that are available are limited in their extent and also show very little useful information (See Figure 2.5). There have been substantial advances in technology in the subsequent 15 years. One such advance is in 2D- and 3-D seismic surveying techniques (see Bagaini et al., (2010) and Kaiser et al., (2011) for examples). This can be used to characterise large regional scale basins; ideal when examining a potential GDF location. The increase in computational power and advances in surveying

techniques mean that the limited seismic surveying techniques available to Nirex at the time are now outdated so are not particularly useful for this project.

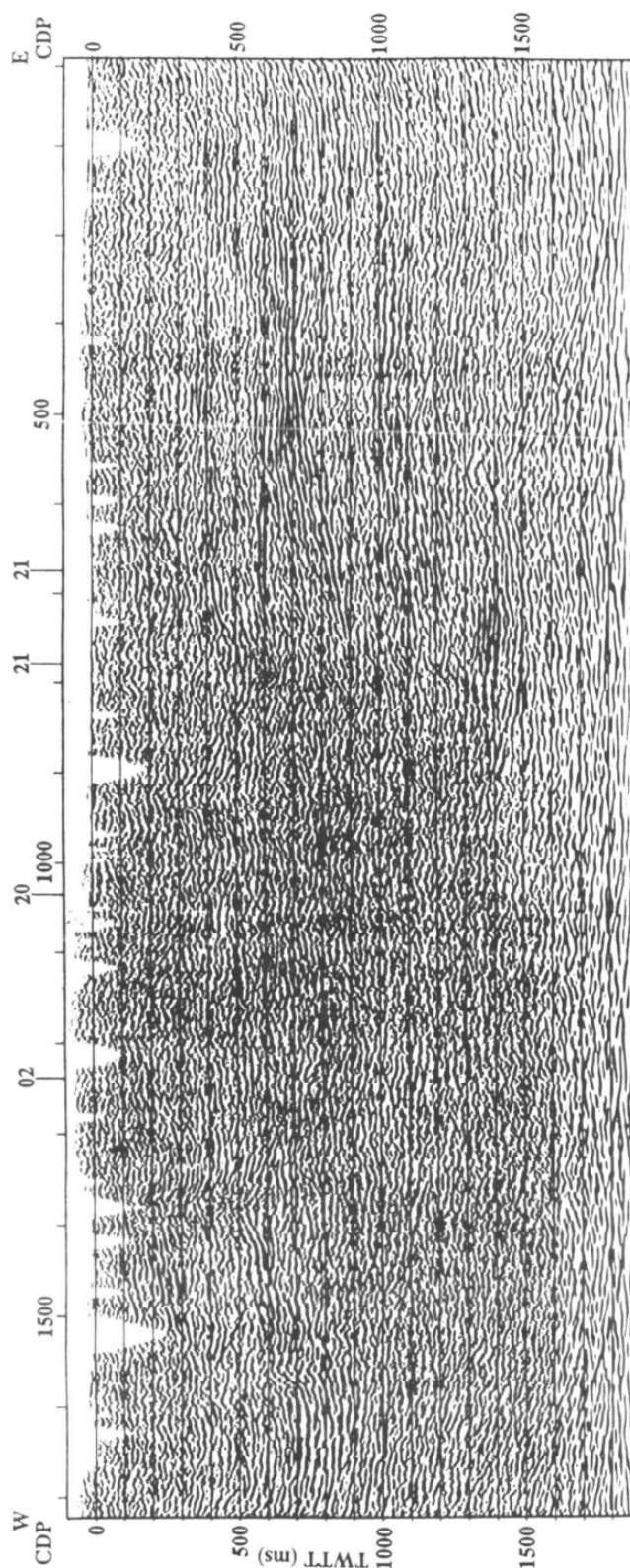


Figure 2.5: Seismic reflection data from Evans et al., (1994) that formed part of the Nirex investigation. It is of low quality and reflectors are hard to distinguish. This is understandable as this was the first onshore 3D seismic reflection survey at the time of data acquisition.

Computational modelling has also improved; both in terms of the accuracy of existing models and also in the ability to model complex process. To try and illustrate this, we can consider the extreme ends of computing power spectrum. In 1996 (the year when the data for the PRZ submission would have been processed) the world's fastest supercomputer was the HITACHI SR2201 with a peak speed of 600 gigaflops. The fastest computer at the time of writing is the Tianhe-2 which runs at 33.86 petaflops (Prometeus GmbH, 2015). This is a four orders of magnitude increase in computing power in 19 years, highlighting the progress in the field. As discussed in detail in Chapter 7 this is not the whole story and computer programming architecture and other factors have to be considered. This means larger datasets and more complex models can be processed in a much shorter time. It should be noted, however, that the topography and logistical issues would hamper any large scale surveys in built up areas, or areas of extreme topography. 3D seismic reflection surveys have the advantage of being able to acquire large volumes of data in a uniform manner and require little correction for the geophone height (if any). Onshore, the high relief, especially in the central fells and also the fact that there are numerous urban areas, precludes any surveys on the scale of the offshore kind. A smaller scale, more localised survey could be utilised once a potential area has been identified.

Whilst some data that has been included in this project involves borehole interpretations (such as the BGS cross sections as part of a wider range of data sources) there was no direct interpretation of borehole data by the author.

2.3 Fracture Networks

Fracture modelling is an integral part of the modelling process. In this study area, for a low resolution model such as this, the porosity can be assumed to be negligible (Degnan et al., 2003). Higher porosity rocks may be present but in terms of the volume of the overall rock mass, they can be ignored. There are specific parameters which are required to model fracture networks:

- Fracture orientation: Dip angle and dip direction or strike to provide directional control
- Fracture aperture: average mechanical aperture of a fracture that will provide a fluid flow pathway
- Fracture trace length: the apparent length of the fracture at its intersection with the 2D sampling plane
- Fracture density:
 - P10: Number of fractures / length of scan line or borehole
 - P20: Number of fractures / area of exposure
 - P30: Number of fractures / volume of rock mass
- Fracture Intensity:
 - P11: Length of fractures / length of scan line
 - P21: Length of fractures / area of exposure
 - P32: Area of fractures / volume of rock mass
- Fracture Porosity:

- P11: Length of fractures / length of scan line
- P22: area of fractures / area of exposure
- P33: volume of fractures / volume of rock mass

This is summarised in Figure 2.6. These parameters can be difficult to extract from outcrop data for a variety of reasons:

- Censoring: this occurs due to the fact that not all of the outcrop will be sampled in a fracture survey. Some fractures will be truncated and therefore an incorrect value for a parameters such as length will be obtained. This effect is reduced when analysing lidar data as more (or even all) of the outcrop is analysed.
- Scaling: Data collected may vary depending on the scale of the survey performed. As a result, a correction must be applied depending on the relationship observed between the data. This could be an inverse power law, a normal distribution or a log normal distribution, depending on the data type (Bonnet et al., 2001; Odling, 2001; Odling et al., 2004).
- Aperture data from outcrops will not be completely reliable as the rocks undergo uplift and decompression. Therefore, the apertures will not be representative of the fractures at depth that will be under increased stress. The stress orientation below the surface will also lead to the certain faults in certain orientations becoming open and others being closed. These stresses can vary over time and this can alter which faults are open or closed at a given time.

		Measurement Dimensions			
		0	1	2	3
Sample Dimensions	1	P₁₀ : Number of fractures per length of scan line	P₁₁ : Length of fractures per length of scan line		
	2	P₂₀ : Number of fractures per area of exposure	P₂₁ : Length of fractures per area of exposure	P₂₂ : Area of fractures per area of exposure	
	3	P₃₀ : Number of fractures per volume of rock mass		P₃₂ : Area of fractures per volume of rock mass	P₃₃ : Volume of fractures per volume of rock mass
		Fracture Density		Fracture Intensity	Fracture Porosity

Figure 2.6: Diagram showing increasing detail of fracture characterisation.

2.3.1 Discrete Fracture Networks (DFNs)

Modelling Discrete Fracture Networks (DFNs) in Petrel is achieved using a stochastic (statistical) approach to modelling the relevant parameters. Petrel utilises algorithms produced by Golder Associates to generate stochastic fracture networks (Golder Associates Inc., 2004). The algorithm produces a fracture network for each realisation of the model. Producing different realisations of the models allows us to quantify the uncertainty in each model. The models produced will not be a definitive version, so a range of models with varying parameters gives a good idea of how the variation affects the modelling process.

The alternative approach to this is building a deterministic fracture network where each fracture is modelled individually, as it is in the rock unit. This approach could potentially be useful later in the waste disposal process, when a site needs to be monitored after the rock volume has been mined. However, it is unlikely that you will be able to deterministically model all fractures in a system: a shortcoming of deterministic approaches. It is more common that fracture characteristics are extracted from smaller datasets that then need to be upscaled or extrapolated to provide coverage for the entire model (Chesnaux et al., 2009). For a regional scale

model such as this, it would be impossible to discretely model all fractures in the area. Instead it was decided to select the modelling resolution based on the computational ability available (Ringrose and Bentley, 2014).

Chapter 3: Study Area

Chapter 3

Study Area

The Borrowdale Volcanic Group (BVG) was chosen due to the presence of numerous potential surface and sub-surface outcrops (e.g. mining facilities) of higher-strength rock types. There is a large variation in rock-types present in the study area and, due to the previous Nirex and NDA investigations in the area, it was presumed a large amount of sub-surface data was available. There are other basement settings, for example rocks that are contemporaneous to the BVG around Snowdon in North Wales, however it was decided that the previous studies would mean there was an increased understanding of the rocks in the area and could also provide validation to any results collected in the project. It also allows for the direct comparison of findings, to assess the suitability of new approaches compared to more classical ones.



Figure 3.1: Study area. Council Boroughs (and their borders) are labelled in dark grey, with notable places labelled in black. (modified from Wikipedia.org)

3.1 Geographical Setting and Relevance to GDF

Studies in the UK

Figure 3.1 shows the study area. Cumbria County is located in the North West of England. It has a long history of nuclear industry stretching back to the construction of the Windscale Piles at Sellafield in July 1950 which produced plutonium for the UK's Nuclear Weapons program (Sellafield Ltd., 2015).

Sellafield was also home to the world's first commercial nuclear power plant:

Calder Hall which was built in October 1956 (Sellafield Ltd., 2015). As mentioned

in Chapter 2.1.1, the area was also the focus of the failed Nirex RCF project in the 1990's and the stalled MRWS Cumbria project in 2013. There is a large amount of data regarding the area around the Potential Repository Zone (PRZ) in the Nirex enquiry, however data for the rest of the Lake District is either outdated, inadequate or absent. At a fundamental level, this project will enhance the data available on the geology of the study area. This BVG will serve as a good example of a high-strength crystalline basement setting for any potential GDF, even though it may not be the final site. Any data collected for this project can also be compared to existing Nirex datasets.

3.1.1 Tectonic Setting

The volcanism in the area was driven by plate tectonic activity in the area, namely the subduction of Laurentian plate beneath Avalonian plate. This formed part of the Caledonian orogeny: a loosely constrained sequence of mountain building and plate tectonic events that occurred between 490 – 390 Ma and included the closure of the Iapetus Ocean (McKerrow et al., 2000).

3.1.2 Borrowdale Volcanic Group (BVG) Lithologies

The BVG is the dominant basement rock in the West of Cumbria (Figure 3.2). It is up to 6 km thick in some areas. The unit was emplaced during the Caradoc period, in the Ordovician around 440 Ma - 460 Ma. At this time the UK was in a volcanic island arc setting as a result of the closure of the Iapetus Ocean and the joining of Laurentia, Baltica and Avalonia (Stone et al., 2010). As a result, the region comprises over 100 different rock units, varying from volcanoclastic sandstones to ignimbrites, lavas, sills and dykes (Millward, 2004b). Many of these rock units are

laterally discontinuous, making correlation difficult across the region. Caldera collapse during eruptions and later the Caledonian orogeny (part of the Acadian orogeny) further complicate the stratigraphic picture with large scale, highly variable faulting and fracturing present in the region (Branney and Suthern, 1988).

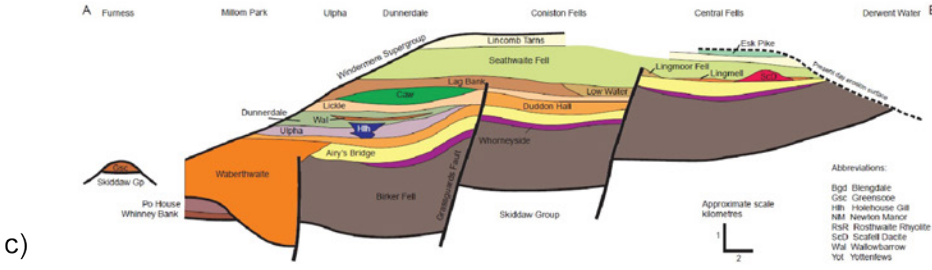
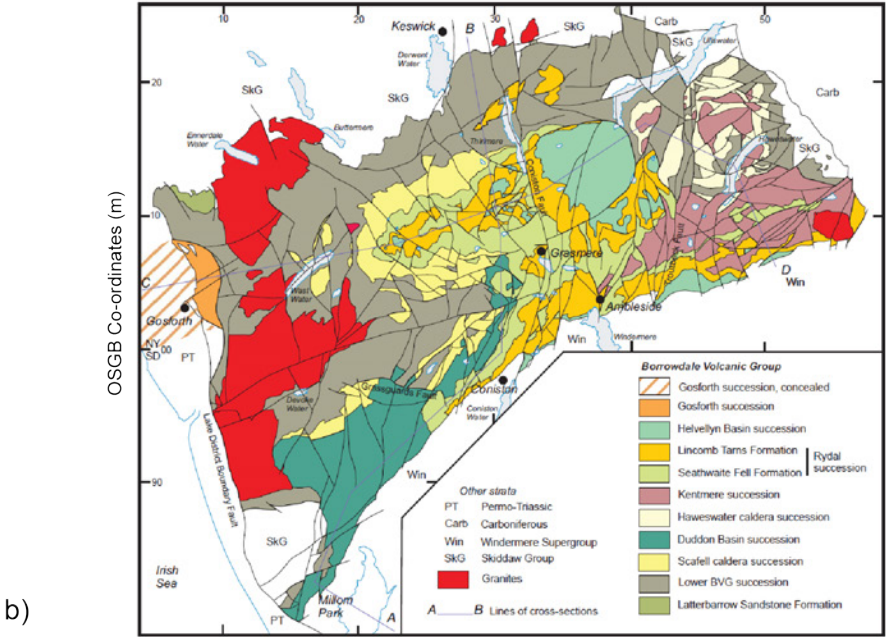
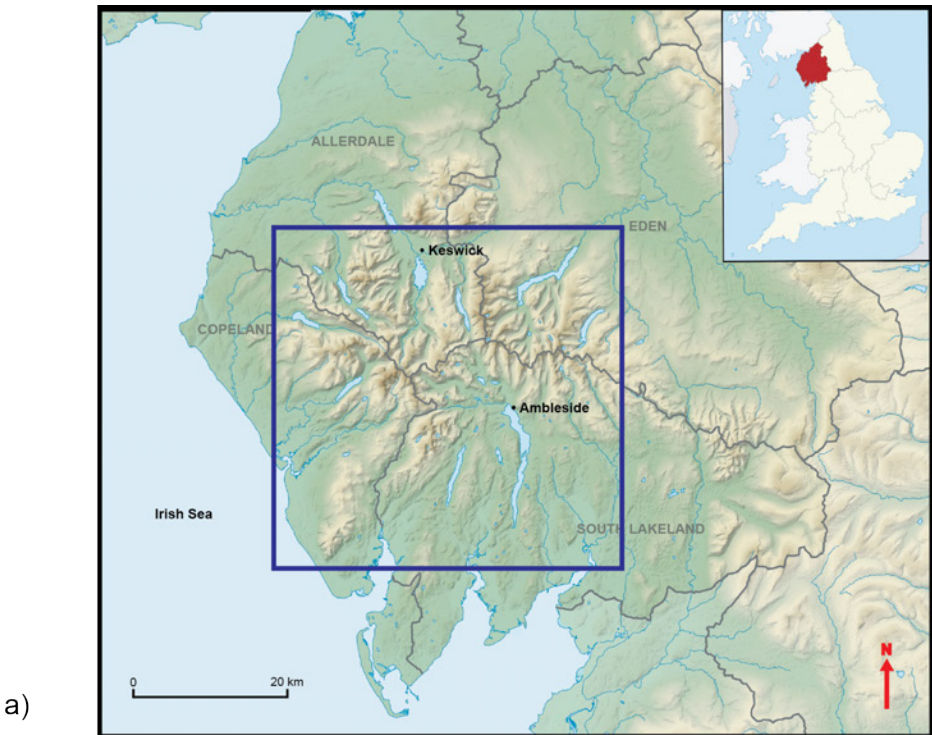


Figure 3.2: Schematic summary of the geology in the study area. The blue box in a) shows the approximate extent of the geological map below. b) shows a schematic outline of the geologies present in the study area, broadly grouped by the age of the deposit. The BVG has 107 individual units, so this simplification belies the level of complexity within the group. c) shows a schematic cross section (marked A and B on b)) outlining the approximate relationships between the units. This is not to scale and should only be viewed as a guide. (Modified from Millward 2004).

Taking this into account, modelling the BVG to a unit-scale resolution would not be possible within the confines of a PhD project. Whilst it is true that it is not only financially and computationally too expensive, the time taken to create a model that would be suitable on this sort of scale would be immense. Instead, this project aimed to produce a low-resolution model and show a possible workflow that could be used when the UK GDF moves into a siting phase. A decision was made to group the units into broadly contemporaneous groups. The logic behind this is explained in Chapter 5. Grouping the units into a much more simplified version of the geology and structure enables the production of a model that is not only creatable within the constraints mentioned, but will also be geologically valid. With the data collected, it would not be possible to state with any certainty that we could model the region in any higher resolution.

The BVG forms the heart of the central fells of the Lake District. Informally the unit can be divided into two parts: the “upper” and the “lower” units. These represent two different styles of eruptive activity.

3.1.2.1 Lower BVG

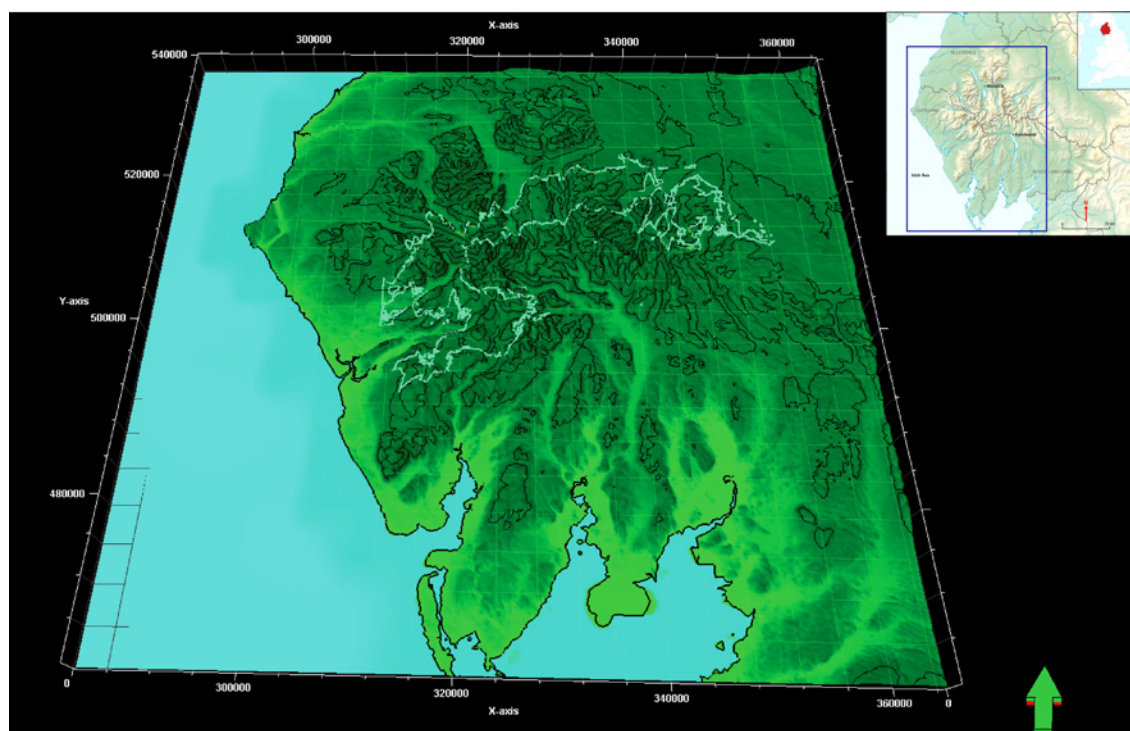


Figure 3.3: 3D visualisation from Petrel showing the surface expression of the Lower BVG in the study area (green outline). The blue box in the location map shows the approximate extent of the image. The outline was created using the geology polygons imported into Petrel (units for grid are OSGB coordinates in metres).

The lower unit represents an early stage of magmatism that was characterised by andesitic lava flows and low-profile volcanoes (Millward, 2004a). There are also some small effusive and pyroclastic deposits in the unit. The majority of the Lower BVG units are found near the outer edges of the study area at what would have been the distal sections of the volcanic centre. There is limited outcrop of the lower BVG in the south of the study area as it is concealed below the upper BVG (British Geological Survey, 1996). It is postulated that the andesitic lava beds are still present in the subsurface in the central fells, but at much greater depths after the collapse of the caldera. This is based on indirect sampling methods such as aeromagnetic analysis and interpretation of subsurface relationships on cross

sections (British Geological Survey, 1999). As the area was glaciated at the time of the eruption, there are also ephemeral lakes that formed reworked ash fall and turbidity deposits (Beddoe-Stephens, 2007). The surface expression of the Lower BVG units is shown in Figure 3.3

3.1.2.2 Upper BVG

The Upper BVG unit is dominated by explosive volcanic episodes with silicic pyroclastic density currents and ancient caldera depocentres, such as Scafell and Haweswater. The depression created by Scafell filled with water, again resulting in the formation of the fluvial and lacustrine sedimentary units observed (Millward et al., 2000). The tectonic activity associated with caldera-forming eruptions led to fault-controlled depocentres parallel and south of Haweswater and Scafell (Millward, 2004). The Lincomb Tarns Tuff formation is the most voluminous of all of the ignimbrites preserved within the BVG.

3.1.2.3 Intrusive Rocks

The BVG also contains numerous contemporaneous sills and dykes and some younger granitic bodies such as the Shap, Eskdale, Ennerdale and Threlkeld granites (Millward, 2004b). These are important as they would form a substantial part of the lithology within the study area and leave holes within the model if not included.

3.1.2.4 Sills and Dykes

The sills and dykes in the study area are basaltic, andesitic, dacitic and rhyolitic in composition and can be up to 250 m thick (Stone et al., 2010). Most of these reside in the Duddon, Kentmere, Ambleside and Helvellyn successions (See Figure

3.2). There are fewer observed in the Birker Fell Formation, with the exception of the Eagle Crag Formation. The sills have peperitic margins and are strongly vesicular, suggesting emplacement into water saturated sediments (Branney and Suthern, 1988). Some sills have broken up and formed mass-flow deposits with the overburden. However, sills in the Helvellyn basin succession show a different emplacement environment. Thin chilled margins indicate intrusion into consolidated rock, potentially in the latter stages of the volcanism.

3.1.2.5 Granitic Intrusions

The Eycott Volcanic Group includes two granitic bodies which intrude to the surface through the BVG. The first is the Eskdale Granite, emplaced 450 ± 3 Ma. It is around 53 km^2 of outcrop and consists of a medium-grained muscovite granite, a coarsely crystalline to very coarsely crystalline granite and an aphyric and megacrystic microgranite, common in the northern section (Stone et al, 2010). The second granitic unit is the Threlkeld Microgranite intrusion, emplaced 451 ± 1.1 Ma. This is a partially exposed intrusion thought to be 12 km^2 in area and roughly 500 m - 1000 m thick (Stone et al, 2010). The Shap Granite pluton (emplaced in the Early Devonian 404 ± 0.5 Ma) cuts both the BVG and the Windermere Supergroup (Stone et al, 2010). It is around 8 km^2 in outcrop but is thought to be much more extensive in the subsurface.

Seismic reflection analysis of Eskdale and Ennerdale granites (Evans et al., 1993) suggests that the two units are a series of laccolith intrusions. This is evidenced by the zones of high and low reflectivity within the granite. They appear to be fault controlled as the granites dip steeply to the west. Whilst broad geometric interpretations can be inferred from these seismic interpretations, care has to be

taken. Existing datasets show quite poor lateral continuity in the reflectors which means more detailed interpretations are not possible, and also raises the level of uncertainty in the interpretations made.

3.1.3 Structural History

3.1.3.1 Volcaniclastic Deformation

Caldera-forming eruptions expel a large amount of material from the subsurface over a relatively short period of time. This leads to subsidence of the caldera floor. Branney and Kokelaar (1994) examined the piecemeal subsidence in the Scafell Caldera. Deformation of the softer deposits such as the ash fall and the hot ignimbrite is common. The rocks deform in a ductile manner when stressed, prior to cooling and solidifying. Large explosive eruptions can also cause substantial landslides, leading to the formation of Mesobreccias, as seen in the Crinkle Tuffs or Long Top Tuffs. This extensive piecemeal collapse of the caldera during eruption resulted in most (but not all) of the extensive fracturing and faulting that has deformed the BVG (Stone et al. 2010).

3.1.3.2 Deformation of BVG Subsequent to Formation

The Acadian Orogeny led to a distinct South-facing monocline in the BVG, most notably the Westmorland Monocline, which affected the southern margin of the BVG. These are characterised by strongly developed cleavages near the hinge zone (Tilberthwaite) and also the Honister Slate belt (Stone et al. 2010). The Acadian Orogeny superimposed a tectonic footprint over the existing volcano-tectonic deformation already present in the BVG. Main basins were constricted, beds were folded and old faults reactivated. A local cleavage in the rocks was also

superimposed. These deformations seem to align superficially with the existing deformation patterns (Stone et al. 2010). There are three main features to note in the BVG: the Haweswater Syncline that is heavily faulted and difficult to discern; the Scafell syncline a north-east trending fold, several km wide, which dominates the central fells and the Ulpha Syncline, a large but poorly-defined eastward plunging fold. It is worth noting that the main regional features in the BVG are all synclinal. This suggests that these are reactivated and constricted volcanic basins and reinforces the idea of the region's rigid response to the stress (Stone et al. 2010).

Younger deformation is related to the buoyant Lake District Massif's response to the basin-forming extensional tectonics occurring to the South during the formation of the Cheshire Basin and the Irish Sea Basin in the early Devonian (Cooper et al., 2003). Around 65 Ma (Lewis et al., 1992), the Lake District block was uplifted around 1750 m (Chadwick et al., 1994). The timing of these events is exceptionally difficult to place due to the lack of correlation across stratigraphy.

3.1.4 Implications for Structural Analysis for a GDF

The presence of numerous fractures and faults in a geological setting for a GDF is ideal. Typically a GDF's geology ought to be as homogeneous and un-deformed as possible, thus resulting in it being as easy to interpret as possible, and thus as easy to understand as possible. The more complex the geology, the more difficult it becomes to interpret and to understand, and therefore the more difficult it becomes to translate into suitable input into GDF performance assessments and safety cases. Knowledge of the UK's tectonic evolution, suggest that other likely GDF locations in the UK may well also be penetrated by numerous deformation

structures. This highlights the importance of a project such as this, where technological developments are used to extract more information on those structures than was available to previous studies.

The complex deformation seen in surface outcrops of the BVG suggests that subsurface correlation in the region will be extremely difficult. This is highlighted in previous work that showed it was exceptionally difficult to estimate fault throws. Barnes et al. (2002) looked at the deformation around the Lake District Bounding Fault Zone (LDBFZ) region. Fault throws of over 4 km were observed and it was suggested that much of the strata were emplaced during volcanic activity. This means it can often be difficult to identify the order of the succession and thus the correlations across the faults. Exposure across the Lake District in general can be inconsistent and difficult to correlate and often there are large areas which are concealed beneath younger cover. This is an issue as there is significant lateral variability over short distances.

3.1.5 Recent Study

The nuclear industry in West Cumbria has provided the impetus for most of the recent work on the geology of that section of the study area. During the Nirex RCF investigations, a large amount of data was collected, however this was confined to a limited area around the proposed RCF.

Site investigations of the RCF, coupled with site investigations and on-going groundwater monitoring in and around the nuclear sites of the Sellafield Ltd. and the Low Level Waste Repository (LLWR) have resulted in the drilling of thousands of shallow boreholes and a number of key deep boreholes. Whilst the Nirex boreholes contributed to the Nirex studies, and indeed have provided the basis of a

number of key papers on the structure and groundwater features of the BVG (Black and Brightman, 1996; Degnan et al., 2003; Michie, 1996), those at Sellafield and LLWR nuclear sites typically did not. In the context of the operation of those nuclear sites at the time (1980's) this is understandable, but even if they had been integrated into the dataset, many of them were not deep enough to contribute to the geological understanding. Indeed for the study described in this thesis, it is likely that even the information on record from the RCF investigation would not have adequately represented overall heterogeneity in a regional geological model as these can only be considered as 1D representations of the geology.

However, one significant conclusion from the Nirex RCF work, especially the hydrogeological studies utilising structural and lithological information from boreholes and geophysical data, is that the flow in the areas studied is purely confined to the fractures within the rocks (Michie, 1996). This is significant as if this is applied to the model as a whole, then only a single, fracture-driven mechanism of flow needs to be considered. Porous flow would be non-existent and can thus be ignored. Even porous rocks such as ignimbrites (or pumices) that were formed by the explosive eruptions, have either been deformed when cooling to form welded ignimbrites (such as the intracaldera succession that is part of the Scafell caldera units (Millward, 2004a) or are inherently highly porous, but have exceptionally low permeability due to the pores not being connected. Acadian deformation introduced a cleavage, realigning clay minerals and further decreasing porosity and permeability (for example Fisher and Knipe (1998) discuss porosity reduction in fault zones).

The latest update to the area's geology has come as part of renewed efforts to site a UK GDF. A major revision was the GB3D Model which has been produced by the

British Geological Survey (BGS) (Mathers et al., 2014). This is a nationwide study to produce representative scale models of the UK Geology. The model and cross sections have been produced from a range of data sources and projects that the BGS have been a part of from 2009-12. The model is designed to be compatible with the existing 1:625,000 scale geological maps. The data sources used are geological maps at 1:1,000,000, however some cross sections have been simplified to allow model creation. Where faults are present, they are simply shown as terminations in bedding or units and are not modelling as discrete objects.

Chapter 4: GDF Potential Host Rock Characterisation

Chapter 4

GDF Potential Host Rock

Characterisation

4.1 Rationale for Modelling

A critical part of GDF site selection is the creation of a geological model that is a realisation of the geology of the proposed host rock. Characterisation outputs are typically based on whatever existing data are available, including borehole logs. However GDF siting activities involve looking for locations where subsurface penetration is kept to a minimum, meaning boreholes are less likely to be present. Most of the UK's geology is only understood to the level of detail that reflects the importance of the area's geology. Regions that have some significance, usually economic, often have a substantial amount of existing subsurface data. For example, nuclear waste disposal studies have led to an improved understanding of the BVG in West Cumbria and coal mining has led to improved knowledge of Carboniferous geology in areas such as the North East of England and South Wales. Conversely, regions that have no economically important geology or

excavations, are often only characterised to a low resolution. This means a robust approach is required to adequately characterise the geology of any potential GDF repository site, as it could be located in an area where the geology is poorly understood.

As previously mentioned obtaining a detailed understanding of the subsurface geology and environment of nuclear sites (particularly deep geological disposal facilities) is characterised by the need to obtain as much subsurface information as possible whilst keeping intrusion to a minimum. Yet at pre-site investigation stages in GDF developments there is likely to be a dearth of subsurface information. A comparison can be drawn with the hydrocarbon industry where scientists are faced with the challenge of predicting hydrocarbon fluid flow in areas where rocks are penetrated by few boreholes, and are typically not visible, especially in offshore areas. Whilst it is known what types of rock create, store and trap the hydrocarbons, the petrophysical and geometrical aspects of potential reservoirs are often uncertain. The oil industry uses rocks that outcrop onshore as analogues for rock units that may be buried under several kilometres of overburden, or are inaccessible as they are underwater. A good example of this is the development of sequence stratigraphy by Exxon Mobil (Yoshida et al., 1998). Here, the Book Cliffs in Utah, USA, were used to determine the depositional environments at the time of emplacement and these could be used to predict the depositional environment of potential hydrocarbon reservoirs, to great success. Outcrop analogues were utilised during the Nirex studies, but techniques available at the time were limited to traditional field techniques, resulting in low-resolution datasets.

4.2 Digital Outcrop Modelling

Data collection needs to evolve past the classical manual surveys utilised during the Nirex investigations and, that are to some extent, still in use today. Digital outcrop modelling and the creation of Digital Outcrop Models (DOMs) allows quick and accurate data collection and visualisation (Seers and Hodgetts, 2013). This project will mainly utilise digital data to analyse discontinuities in the geology (e.g. fractures and faults) and also the geometries of major rock units in the study area.

Geologists often have a nostalgic approach to collecting geologic data. Partially this is a reflection of teaching methods, whether it be stereonet generation using tracing paper and pin tacks, seismic reflection interpretation using long black and white printouts or field mapping projects which require hand drawn maps to be digitised at a later date. Digital methods are often viewed with some suspicion, rather than critically evaluated as they should be. There is a difference between not trusting the data and assessing the data objectively.

This project utilises Terrestrial Laser Scanning (TLS or “lidar”) and photogrammetric data. It is envisaged that these data sources will feed into a much larger digital methodology that can be utilised in site characterisation. This broader approach will be discussed in detail in Chapter 6.

4.3 Methodology

4.3.1 Light Detection and Ranging (Lidar) Acquisition

4.3.1.1 Description of Techniques Used in this Study

The lidar instrument (Figure 4.1) that was used for data acquisition in this project was a RIEGL LMS-Z420i coupled with a Nikon D300 12.5 megapixel camera, used as described in (Bellian, 2005). The D300 can be fitted with different prime lenses depending on the range of the scan. The laser is near infrared and has a minimum range of 2 m and a maximum effective range of 600 m, dependant on atmospheric conditions. Data were acquired at a rate of 8000 points/sec and it is accurate to approx. 1 cm. The beam divergence in our instrument is 0.25 mrad which corresponds to a 25 mm increase in bandwidth per 10 0m range. The lidar unit was controlled by a Trimble YUMA ruggedised field computer which was suitable for data acquisition. However, for processing and visualisation, data were transferred to a higher-specification computer. As the unit require line of sight to collect data, multiple scan positions must be used to prevent data shadowing (see Buckley et al, 2008).

Whilst an increase in point density is good in terms of the data quality collected, the data quantity poses a problem. Lidar surveys are limited by the processing power available to the operator. Filtering of data is necessary as computers cannot handle the raw volume of data collected, especially during large regional-scale surveys. Lidar scanning provided the majority of the data collected in the project. RiSCAN Pro is the software developed by RIEGL Ltd. for use with their laser scanners. It allows set-up of scans and control over modifying the beam

characteristics, scan region, sampling density and photo acquisition. The data can be merged with the photographs acquired during scanning using the software.

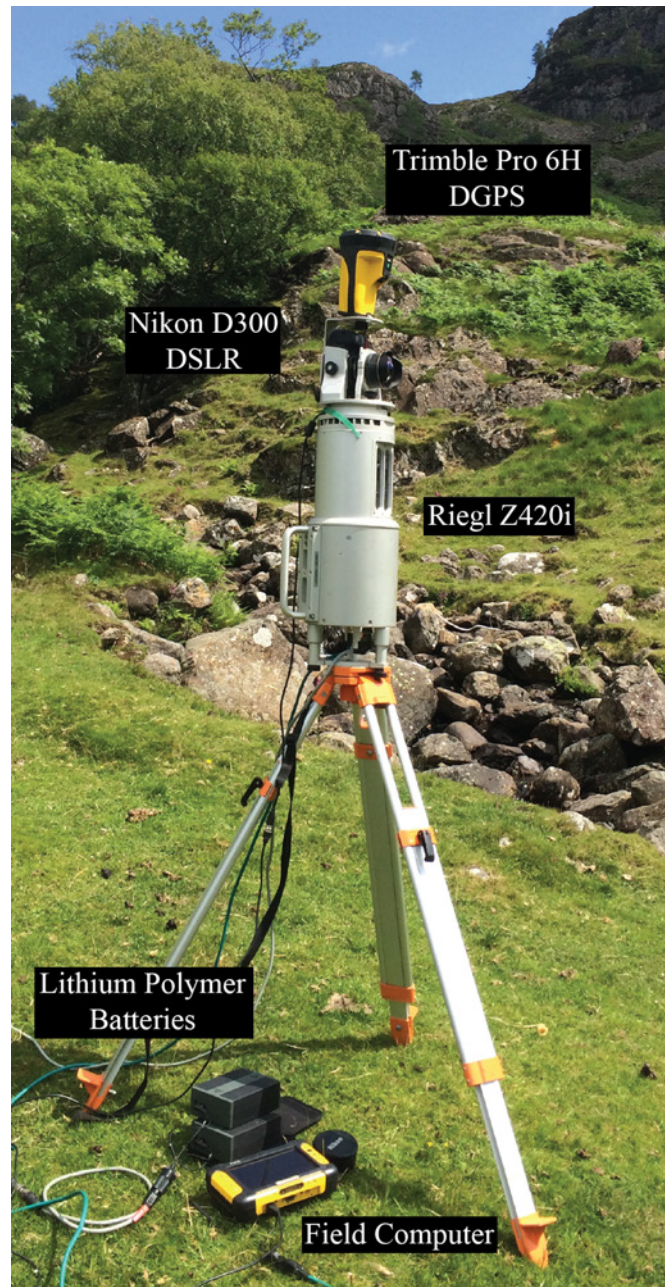


Figure 4.1: Lidar setup for each scan location.

4.3.1.2 Data Acquisition

The first step in the data acquisition process was to site the lidar scanner. This required an estimation of how many scans were required to capture the entire outcrop and minimise any shadowing effects. The scan positions should achieve

this without overlapping each other unnecessarily. For some scans, it was necessary to place cylindrical retroreflectors on the outcrop. This was the case for smaller outcrops. For larger outcrops, GPS measurements were taken for each scan position to allow good registration of the scans. However for outcrops which only required two or three scans it was necessary to place 3-5 reflectors spaced out across the outcrops. Ideally, these were placed in positions that were visible across 2 or more of the scan positions to allow tie points to be created. These were detected by the lidar when scanning and were used as both tie points to link each scan position together and also as extra points which could then be georeferenced using the GPS. The DGPS receivers used were the Trimble Pro 6H and Pro 6T units in conjunction with a Trimble GeoBeacon receiver. The Pro 6H provides decimetre accuracy, whilst the Pro 6T is only sub-metre. However the geobeacon allows real time corrections to decimetre scale. All GPS points in these surveys were accurate to at least 20 cm.

When the lidar was being set up, care was taken to ensure that it has a solid base as any movement due to wind causes blurring of the scan data as the receiver will change position during the laser flight time, either increasing or decreasing the two way travel time depending on the movement.

The scanning process begins with a 360° panorama scan of the outcrop. This is acquired at a point spacing (resolution) of 0.5 m and produces a scan of 1,980,000 points. Images were then acquired using the mounted digital camera. The number of images will depend on the focal length of the lens used, for example a 14 mm lens will require 7 images with a 10% overlap. These images are used to colourise the lidar point cloud. As the camera focal point and laser detector point are

known, a calibration is applied automatically to fit the image to the data. This can be modified manually later if incorrectly aligned.

Once the panorama is complete, smaller, higher resolution scans can be produced. The panorama is used as the basis for selection. It is visualised in 2D on the screen and a selection box is drawn around the target area. The distance to the outcrop is then calculated and then a resolution is set. This is usually around 0.025 m (25 cm). The number of points collected varies depending on the size of the outcrop. This can be performed on a number of subsections of the total panorama and allows targeted scanning of areas of interest and the ability to ignore superfluous regions (i.e. vegetation, scree slopes). This reduces the dataset size and makes it easier to filter the data. Fine scanning of the reflectors is also performed at this point. GPS coordinates are recorded for the scanner and the reflectors.

Once all target regions were scanned for that position, the scanner was moved and the process repeated, ensuring the same regions are fine scanned each time to provide consistency in the data resolution within the model. This is done until the entire outcrop has been captured.

4.3.1.3 Data Processing

	CPU	GPU	RAM	OS
Desktop PC	Intel Xeon, 3.60 GHz	NVIDIA Quadro K4000 3GB	64 GB	Windows 7 64-Bit
Laptop	Intel Core™ i7, 2.40 GHz.	NVIDIA GeForce GTX 765M 1GB	16 GB	Windows 7 64-bit

Table 4.1: Specifications of PCs used in this project

The dataset was then transferred to a high end desktop for processing. The specifications of these computers are shown in Table 4.1. The first processing step is the alignment of different scan positions for each outcrop. This was done in PolyWorks; 3D metrology software created by InnovMetric. It is used to

accurately merge multiple scans of the same dataset via an iterative process. The program assigns each laser point a vector, with the laser scan position residing at (0,0,0). This is referred to as the Sensor's Orientation and Position (or SOP) matrix. The data are stored within the Scanners Own Coordinate System (SOCS) and the orientation of the scanner as the Project Coordinate System (PRCS). For each scan position created when the scanner is moved, SOP defaults to the origin:

$$\begin{matrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{matrix}$$

The scans were imported into Innovometrics Polyworks v.9, and a wireframe model was created. Existing reflector tiepoints were then used as a coarse alignment for each scan. The GPS points were then imported and a huge translation was automatically applied by the program to again coarsely align the tiepoints and scanner positions to their GPS point. Feature matching was then used to align the scan more accurately. This was done manually by matching a distinct feature, such as an unusual rock formation or man-made object for example. The final fine alignment was done by the program iteratively matching the whole dataset. A search sphere, defined by the user (usually around 0.5 m) was then progressively decreased to the data resolution (usually 0.25 m if high resolution scans are used). Once the process was finished, a translation matrix was exported and was summed to the GPS location matrix to create a new SOP for each scan position in RiScan Pro. This process should yield merged, georeferenced data ready for interpretation. Any potential errors that are associated with the scan position and georeferencing are averaged out by the multiple scan positions.

Once this was completed, the data were imported directly from RiScan into Virtual Reality Geologic Studio (VRGS). VRGS is a Windows-based application used to manipulate and interpret 3D geologic datasets. Data are directly imported from scanner software (in this case RiSCAN Pro) and viewed as point clouds. The first step is to filter the original data. There are data filtering algorithms (Meng et al., 2010) which can be utilised, however due to the scale of these outcrops it is quicker and simpler to simply filter unwanted data manually. Unwanted data includes (but is not limited to) vegetation, poor quality scan regions, scree slopes and man-made objects. The data are also decimated as often there will be duplicate points and a higher point count will lead to greatly increased computation times and strain on the computer hardware which can result in the program becoming slow and unresponsive or crashing.

Tensor analysis can be performed on the point cloud. This is where a sphere of influence is defined by the user and properties within the dataset are calculated and can be analysed. The most useful properties for this project are:

- Plane dip - angle at which the plane dips
- Plane Azimuth - direction of dip in degrees
- Coplanarity - a measure of how flat a surface is
- Colinearity - a measure of how linear features are

The method of calculating these statistics is outlined in García-Sellés et al (2011). A radial basis function is defined in VRGS with each voxel in the point cloud being the ‘centre of mass’ in a moment of inertia calculation. The vectors that link these voxels to the centre of mass are calculated as proposed by Woodcock (1977):

$$T = \begin{pmatrix} \sum l_i^2 & \sum l_i m_i & \sum l_i n_i \\ \sum m_i l_i & \sum m_i^2 & \sum m_i n_i \\ \sum n_i l_i & \sum n_i m_i & \sum n_i^2 \end{pmatrix}$$

Where l_i , m_i , and n_i are the X, Y, and Z components of the individual vectors, without normalizing. Matrix T is a symmetrical matrix and can be solved to obtain its eigenvalues (λ_1 , λ_2 , and λ_3) and eigenvectors (v_1 , v_2 , v_3). Eigenvalue λ_1 and eigenvector v_1 correspond to the orientation with maximum density of vectors. Eigenvalue λ_3 and eigenvector v_3 correspond to the orientation with the minimum density of vectors and maximum moment of inertia, and therefore the pole to the best-fit plane. This can be used to determine the dip and azimuth across the search sphere. The coplanarity and collinearity of the sphere is determined using eigen analysis of the surrounding points. Eigenvalue λ_2 and eigenvector v_2 correspond to the orientation with mean density of vectors. These are calculated for each data point across the dataset and the attributed properties are mapped to each point in turn. This allows the variation across a surface to be visualised, as opposed to the attributes being averaged across surfaces. This, along with the RGB (Red, Green, Blue) values mapped as attributes to each voxel (coloured point cloud), leads to the large, computationally extensive datasets associated with lidar data.

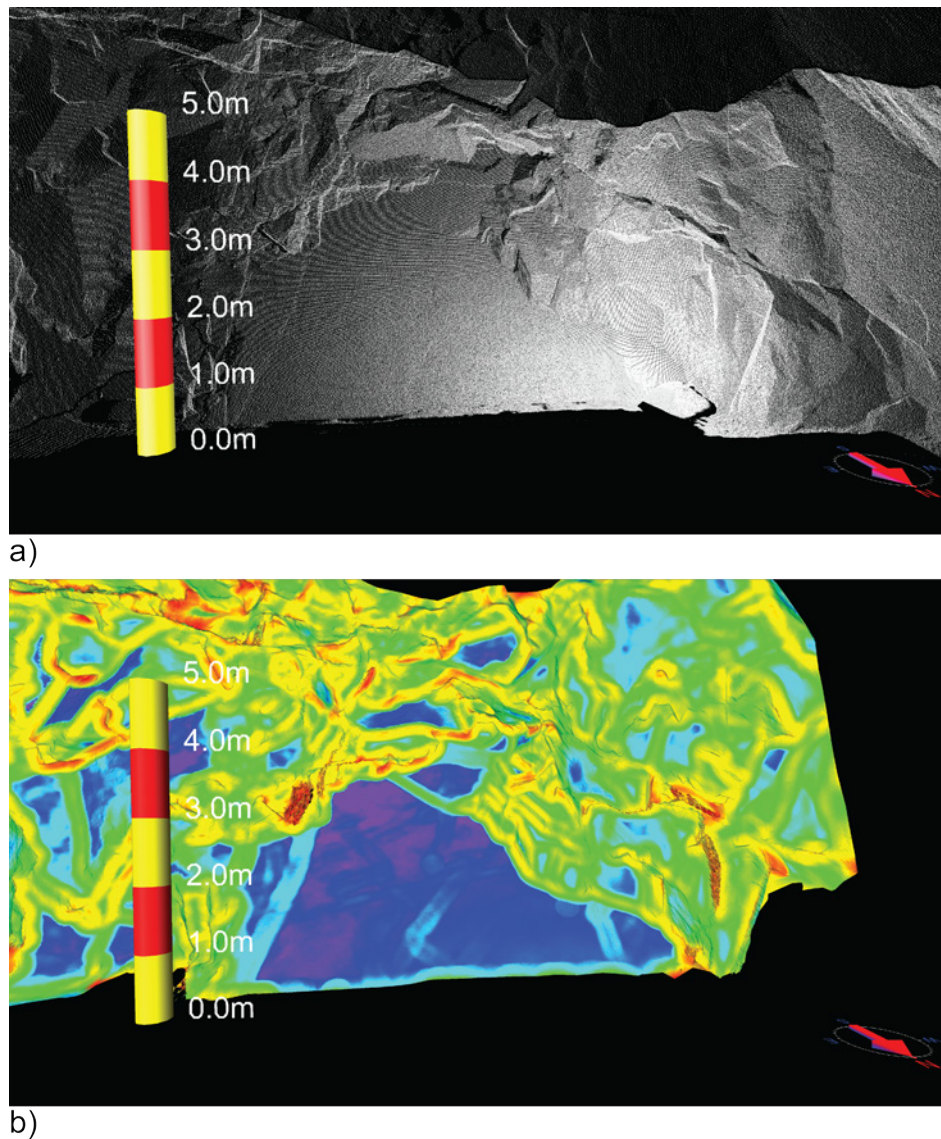


Figure 4.2: High resolution digital data capture of subsurface exposures of slate from the Seathwaite Fell Sandstone Member within Rydal Cave (part of the Borrowdale Volcanic Group): a) raw 3D point cloud, b) analysis of planar surfaces during fracture identification. The false colour map represents the degree of flatness of each surface. The colours are arbitrary, but overall blue colours represent fracture faces which are generally flatter, whereas red or yellow colours represent more rugose areas.

The dip and azimuth variables can be used for quantitative analysis, whereas the coplanarity and colinearity values are used in a more qualitative sense. They are used to identify the fracture planes in the datasets where they are not immediately

visible, either on the raw point cloud or the coloured point cloud. They can be used to generate a false colour map onto the points or surfaces. In the case of coplanarity, the colder the colour the flatter the surface (Figure 4.2) and for colinearity, the cooler the colour the more linear the feature. This proves useful when trying to visually locate and determine the extent of fractures.

Meshing (or triangulating) data involves linking the points in the dataset together using triangles. The higher the density of the points, the smaller the triangles and hence the higher resolution of the mesh. Lower densities produce larger triangles which smooth the appearance of the mesh and often data are lost (Bellian, 2005).

Triangulation in VRGS has 3 option settings:

- Scanner Position
- Current view
- From Above

The “maximum allowed edge length” can be set to stop points being meshed that are far apart and not related. This method can be problematic when creating a mesh of multiple scan positions. Choosing “Scanner Position” can cause problems where the triangles become stretched and deformed further away from the scan positions. This can be remedied by selecting the “Current View” option, but care must be taken as the perspective can still cause problems. It is often easier to split the point cloud into smaller sections and triangulate these individually rather than try to do the entire outcrop at once. Fractures are picked by selecting three or more points on a fracture plane. A best fit disc is then calculated and its dip and azimuth recorded. Once all data have been collected to form the DOM, it can be

plotted onto a stereonet to allow clusters to be identified or exported as a CSV file for numerical interpretation.

4.3.2 Photogrammetry (Structure from Motion (SFM))

4.3.2.1 Rationale and Description of Technique

Lidar data deteriorates when the distance between the lidar instrument and the target (in this case a rock-face) is less than 2 m, with distortion of the 3D point-cloud produced by ranging errors. Long distance from suitable scan positions to the target outcrops and surveys from oblique scan positions or outcrops that are in hard to reach areas also raises issues with data collection using lidar. Data collection needs to be efficient. Data collection and processing methodology for photogrammetry is different to lidar data. To address these concerns, photogrammetry was explored as an option. It was realised that a methodology developed within the research group could be utilised in this project. The techniques used are Structure From Motion (SFM) and Multi-View Stereo (MVS). The application of this methodology is described in Seers and Hodgetts (In Press). The SFM calculation uses image vectors found using feature detection algorithms (known as SIFT features) in the same way that traditional photogrammetry uses matched key points, i.e. it derives the 3D geometry of a scene using displacements (parallax) on the 2D image. As well as producing a low resolution 3D geometric representation of the scene, this also provides camera position information. These are position vectors of features, orientation information and camera extrinsics. They are used by the MVS matching algorithm to pair features and test pixels in coincident views for spatial consistency. This produces a high-resolution representation of the outcrop (Figure 4.3).

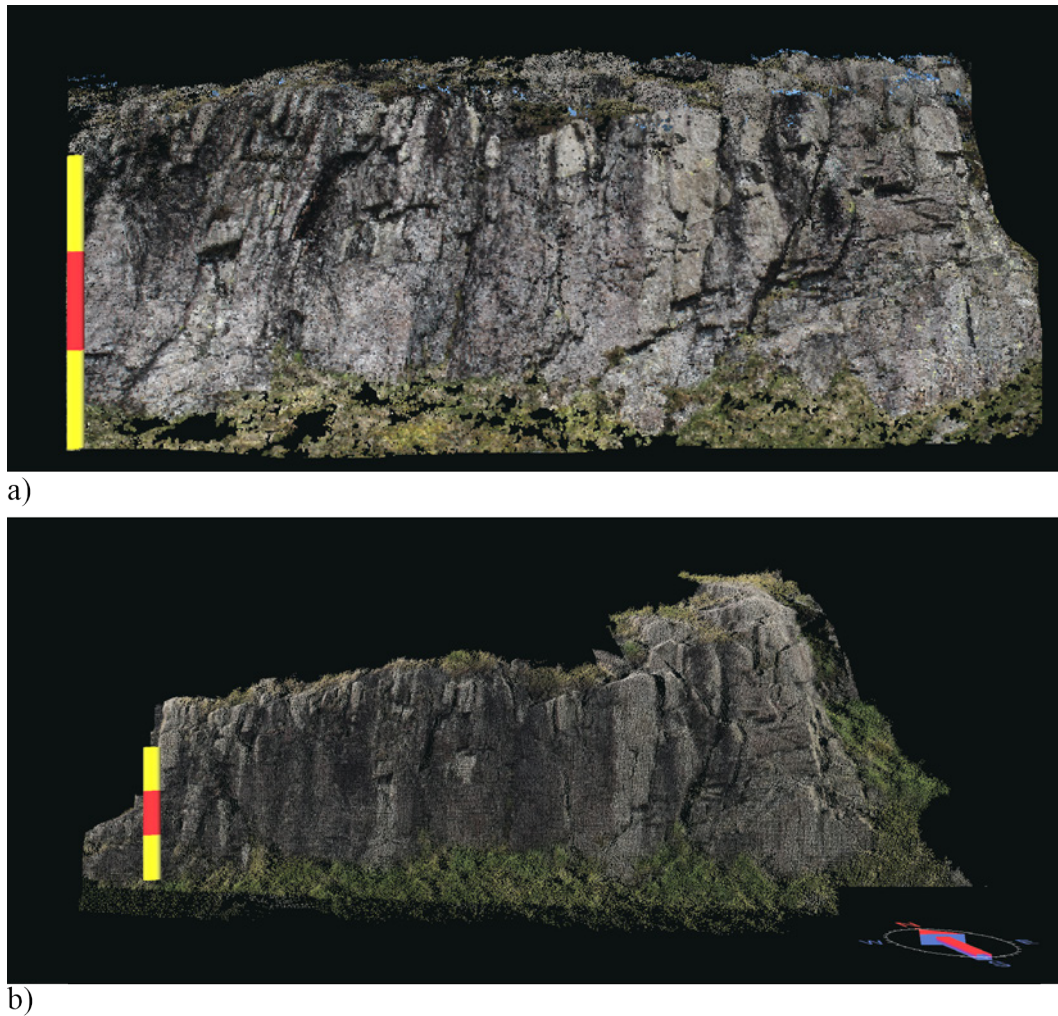


Figure 4.3: Comparison of Photogrammetric a) and lidar b) data acquired at Hardknott Pass (NY 23151 01501). The lidar data acquired covers a larger area but at a much lower resolution (point spacing). This is shown by the level of detail in a) compared to b) where many more fractures are visible. The scale bar is 3 m.

It is possible for the user to select overlapping blocks of images. This is especially useful in large surveys as the number of photos required can number in the thousands. To acquire clean, noise free surfaces whilst retaining the overall geometry of the scene, images need to be taken first at a suitable distance and coarsely matched to each other, then gradually matched to closer range images before performing the SFM calculation. These distances would vary depending on the size of the outcrop. In general, the outcrops in this project required an initial

set of photographs at around 10 – 15 m distance, and then the closer images at around 1 – 3 m.

Once a rigid configuration of all camera positions is obtained, the longer range images must be stripped away prior to performing multi-view stereo matching (aliasing between these and the close range images leads to noisy surfaces).

Another Matlab program has been written by Dr Thomas Seers to rewrite input files for MVS which implements this concept. A Sony NEX-5 16.1 megapixel camera was used for data collection. Once the initial images were captured, the camera's burst mode was used to acquire the closer photographs of the outcrops. These photographs need to have around 10% overlap to allow proper alignment. Once this technique is further developed, the plan is to attach the camera to a remote operated drone, which can then be programmed to fly a pre-set course to acquire the dataset remotely. Once the high-resolution model has been constructed, it can be visualised in MeshLab, a tool developed with the support of the 3D-CoForm project. Isolated points and vegetation can be removed and a Poisson reconstruction used to generate a triangulated mesh (Kazhdan et al., 2006). A Matlab tool described in Seers and Hodgetts (In Press) was used to trace lineaments on the outcrop. These were then projected onto the triangulated mesh allowing the picked traces to be mapped in 3D.

Initially, a laser level was used to mark N-S and an E-W trending laser points on the outcrop to georeference the dataset. The distance between these was known and this allowed for orientation and scaling of the photogrammetric model.

Unfortunately, this approach was unsuccessful as it was not possible to locate the laser points on the point cloud. It was realised that an approach that could be described as a manual SIFT could be used to georeference the data. This involved

identifying features that can be recognised on both the lidar data and the photogrammetric datasets and determining their co-ordinates in 3D space. These coordinates were imported into Matlab and the centroid of mass of both sets of points was calculated and the transformation matrix required to orient and scale the photogrammetric dataset relative to the lidar dataset was applied. We calculated a similarity transform (scale-rotation-translation) between the matched points using Horn's method (Horn, 1987). Registration of a vertex set is achieved from matrix multiplication using homogeneous coordinates: a 4x4 matrix which includes scale, rotation and translation in this case. A set value of '1' is added to the to the end of each x y z voxel in Matlab to set the scaling rotation and translation.

A Matlab tool, ("editing_tool") described in Seers and Hodgetts (2016b) was used to calculate the orientation of fractures and allow them to be grouped into sets, first statistically, then corrected manually. P32 can then be generated for the outcrop models.

Seers and Hodgetts (2016a), outlined how orientations derived from fracture lineament data could vary by up to +/- 10° from the calculated directions. However, as the data used to determine the fracture orientations were derived from the lidar data which use the fracture plane to determine the dip and azimuth of the feature, this was not a major issue, but care was required when grouping the fractures picked in the photogrammetric datasets to ensure they were not incorrectly assigned to a set.

As discussed previously, work previously undertaken on the Borrowdale Volcanic Group makes it a good choice for study as it allows validation of the approaches utilised within. For example, Degnan et al (2003) showed that subsurface

groundwater in the BVG will only flow along fracture traces and that porosity within the rock is effectively low enough to be ignored. Whilst it is acknowledged that there may be units within the BVG, and even volumes within those units, which could possess porosities that would encourage dual-phase flow (e.g. a poorly welded ignimbrite), these have been discounted from the modelling processes described later, as it would be impossible to account for such a relatively small percentage in such a large scale model.

4.4 Survey Areas

Locality selection in Cumbria was more difficult than first expected. The high-relief topography, resulting from the last glaciation, provided an unfavourable environment in which to undertake surveys. Often areas of reasonable exposure were found on the side of steep, U-shaped valleys. These were often too large to effectively scan from one side to the other. Scanning from the valley floors was also difficult as the steep angle to the outcrops leads to a large amount of occlusion on the outcrop. The problem was further exacerbated by the outcrops being obscured by vegetation cover or scree slopes on the sides of valleys. Whilst these data are easy to remove from the scans, it limited the amount of exposure that was suitable for scanning. A partial solution to this problem was found by scanning in underground locations such as mines. This afforded excellent exposure and the additional benefit of protection from the elements. As lighting was an issue in the enclosed spaces, a flash was used to illuminate the outcrops during data capture. Whilst this improved the data quality, it severely limited the range of lithology types as there are no ignimbrite mines in the region as it has no economic value. Localities that were scanned using digital methodologies are shown in Figure 4.4.

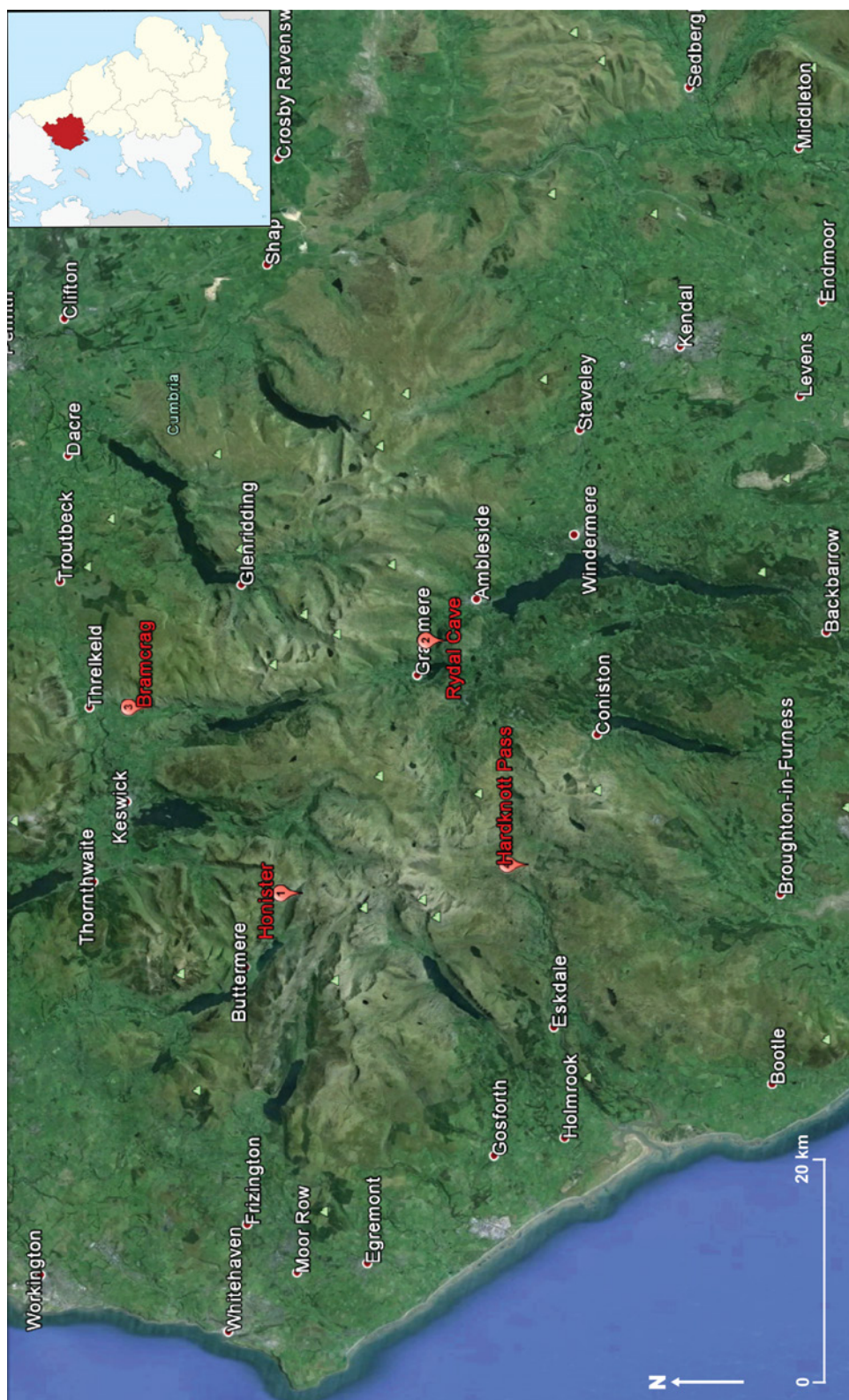


Figure 4.4: Locations of areas surveyed in this study. The OSGB coordinates for each survey site are as follows: Honister NY 22443 13567, Rydal NY 35463 05755, Bramcrag NY 32044 21973 and Hardknott Pass NY 23151 01501.

4.4.1 Honister

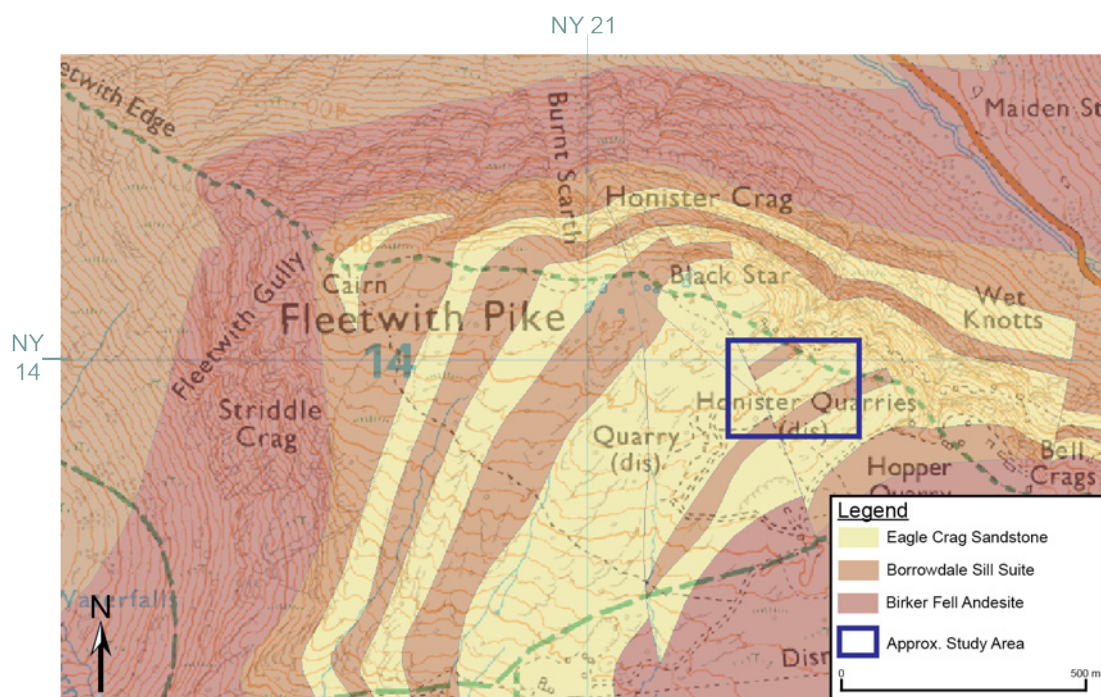


Figure 4.5: Geological map of the Honister study area. The exact location of the study is difficult to determine due to it being underground and so a rough survey area is outlined by the blue box (DiGMapGB-50).

Honister Slate Mine is both an operational mine and a tourist attraction, in the Borrowdale region of Cumbria (NY 22443 13567). The mine complex itself provides excellent subsurface outcrop analogues for the higher-strength geological setting, but also provides a superb example of a deep excavation in such a setting, although its geological location (high in the Cumbrian mountains, and less than 200 m from the surface) precludes it from being chosen as an actual location for a GDF.

Honister is famous for its green slate, used extensively as a decorative roof slate.

The Kimberley Mine was sampled as this was a non-operational section of the mine workings and therefore logistically simple to scan within. Two rock types are present within the Kimberley Mine: slate and andesite as shown in Figure 4.5.

The slate within the Kimberly chamber of the mine complex forms part of the Eagle Crag Sandstone Member. Contrary to its name, it is not actually a sandstone but a low-grade, metamorphosed volcanoclastic sediment, thought to have been formed by ash fall into glacial lakes. The volcanic provenance of the rock gives it its strength and distinctive colour. In its unmetamorphosed state, it had exceptionally low porosity, due to its small grain size.

The andesite present in the mine forms a large sill which is part of the Borrowdale Sill Suite. Geological information on this unit is sparse; it is a miscellaneous grouping for igneous rocks ranging from basaltic to rhyolitic compositions. It is thought that the sill was emplaced into water-saturated sediments. The absence of baked margins is thought to be a result of this environment. In total there are three layered slate bands; in stratigraphic order these are the Quay Foot band, the Honister band and the Kimberley band, each separated by large andesitic sills.

4.4.1.1 Data Collection

Three scan positions were used with one scan with the lidar unit orientated in a horizontal position and one with it in a vertical position. The Kimberley mine has two chambers. The main excavation chamber where the slate was mined out in the 1800's allowed sampling of fractures due to the presence of the slate in the walls. The second chamber is smaller and is quarried into the andesite sill. As the survey was undertaken in a mine, a flash gun was required to light the surroundings and GPS could not be acquired. A laser level was used to generate two horizontal points on the dataset aligned North-South using a Silva Compass Clinometer to allow orientation of the data.

4.4.2 Rydal

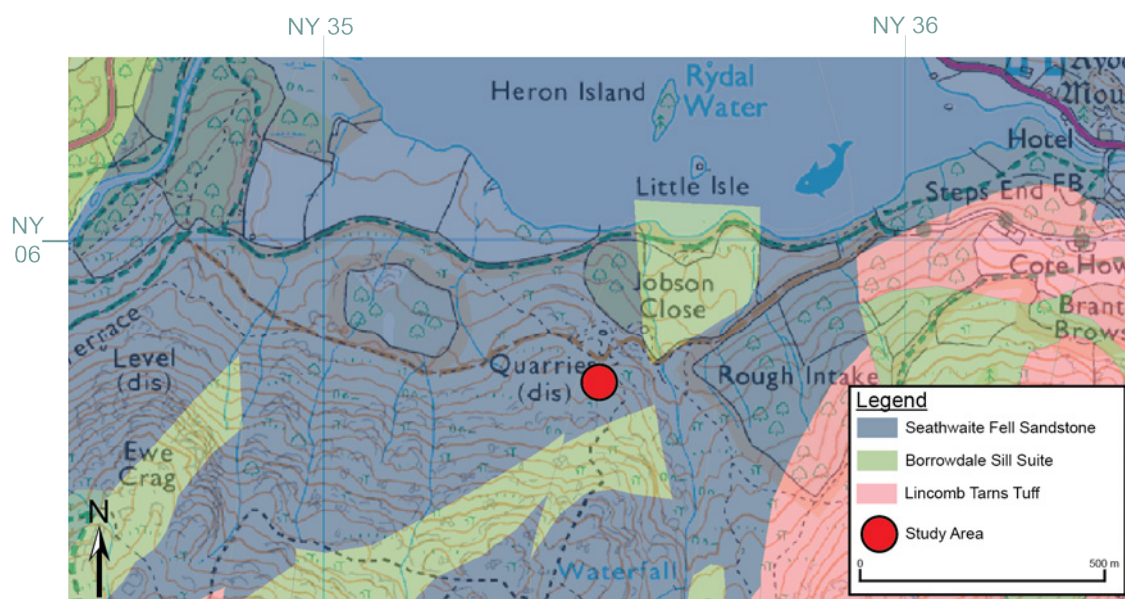


Figure 4.6: Geological map of the Rydal study area (DiGMapGB-50).

Rydal (NY 35463 05755) is a disused slate mine is a disused slate mine located near Rydal Water. It is another volcanoclastic slate mine whose rocks form part of the Seathwaite Fell Sandstone Formation (Figure 4.6). These rocks are heavily fractured on numerous length scales, from metre to millimetre scale. The quarry is in the form of a cave that is open at the northern end, providing excellent 3D exposure. Many of the fractures have caused blocks to fall from the roof creating very narrow, closed fracture sets. These can cause problems for lidar scanning as, due to the small angle between the two fractures which caused the block to fall, the feature could be imaged as one curved smooth fracture as opposed to two planar fractures.

4.4.2.1 Collection

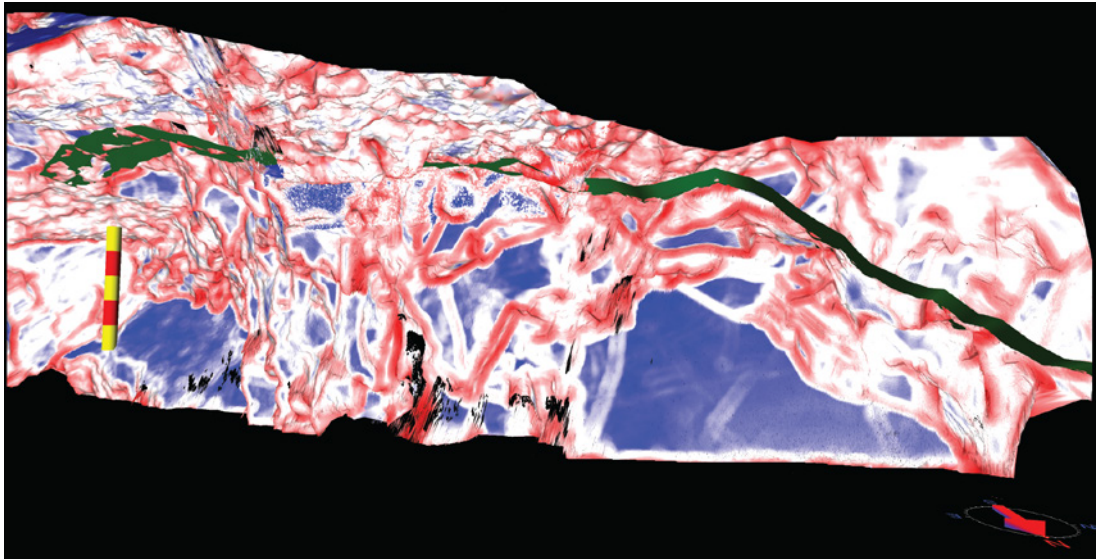


Figure 4.7: The varying scales of fracturing within Rydal cave. The coplanarity analysis has been visualised on the data, but using a Red, White Blue flat colour map as opposed to the spectrum used in Figure 4.2 to highlight individual fractures, and a 35 m long fracture trace picked as a green polyline. The scale bar is 4 m tall.

The cave required seven lidar scan positions to provide optimum data coverage. The dataset collected here was much larger than for Honister, mostly due to the extensively fractured nature of the cave (Figure 4.7). Part of the cave was submerged restricting access to that section. It was possible to georeference the data using GPS at this locality. This was achieved by scanning 4 retroreflectors which are georeferenced using the DGPS. At Honister this would have required at least 10 smaller scan positions in confined spaces to reach the entrance to the cave, which was deemed unrealistic.



a)



b)

Figure 4.8: Interpreted lidar scan of Rydal Cave. a) shows the raw point cloud data and b) shows the picked fractures. Scale bars are 20 m. Each “disk” shown in the image represents and interpreted fracture, picked by the user. The associated geostatistics can then visualised on a stereonet within the program or be exported and analysed in separate programs. The disk size is not representative of the fracture size, and the colours are arbitrary.

4.4.3 Bramcrag Quarry (Threlkeld)

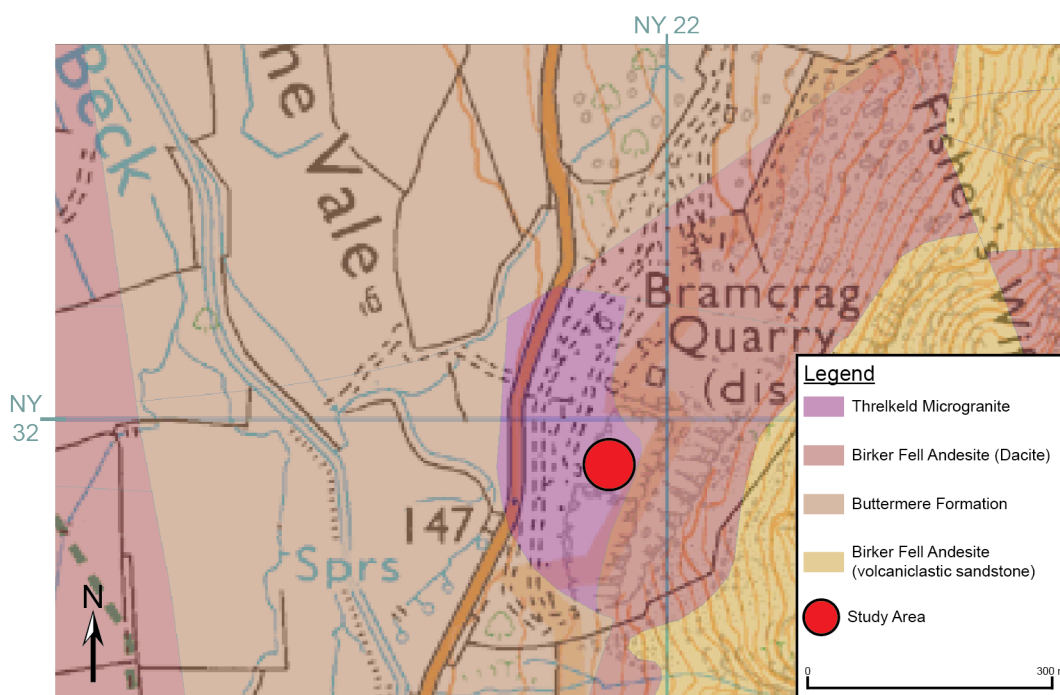


Figure 4.9: Geological map of the Threlkeld study area (DiGMapGB-50).

Bramcrag Quarry (NY 32044 21973) is a disused granite quarry. The rocks form part of the Threlkeld microgranitic intrusion (Figure 4.11). Its age is uncertain but it is thought to have been deposited contemporaneously with the thick ignimbrite deposits of the Upper BVG (Loughlin, 2007). The quarry is open and consists of a large exposed crag and a small walkway (Figure 4.10) that provides an adjacent face to sample, reducing sensoring effects that occur when only sampling the rock face in one orientation.

4.4.3.1 Data Collection

The lidar survey required four scan positions to capture the rock face, one of which was georeferenced and contained scans of three 3 retro-reflectors that were also georeferenced to geolocate the scan.

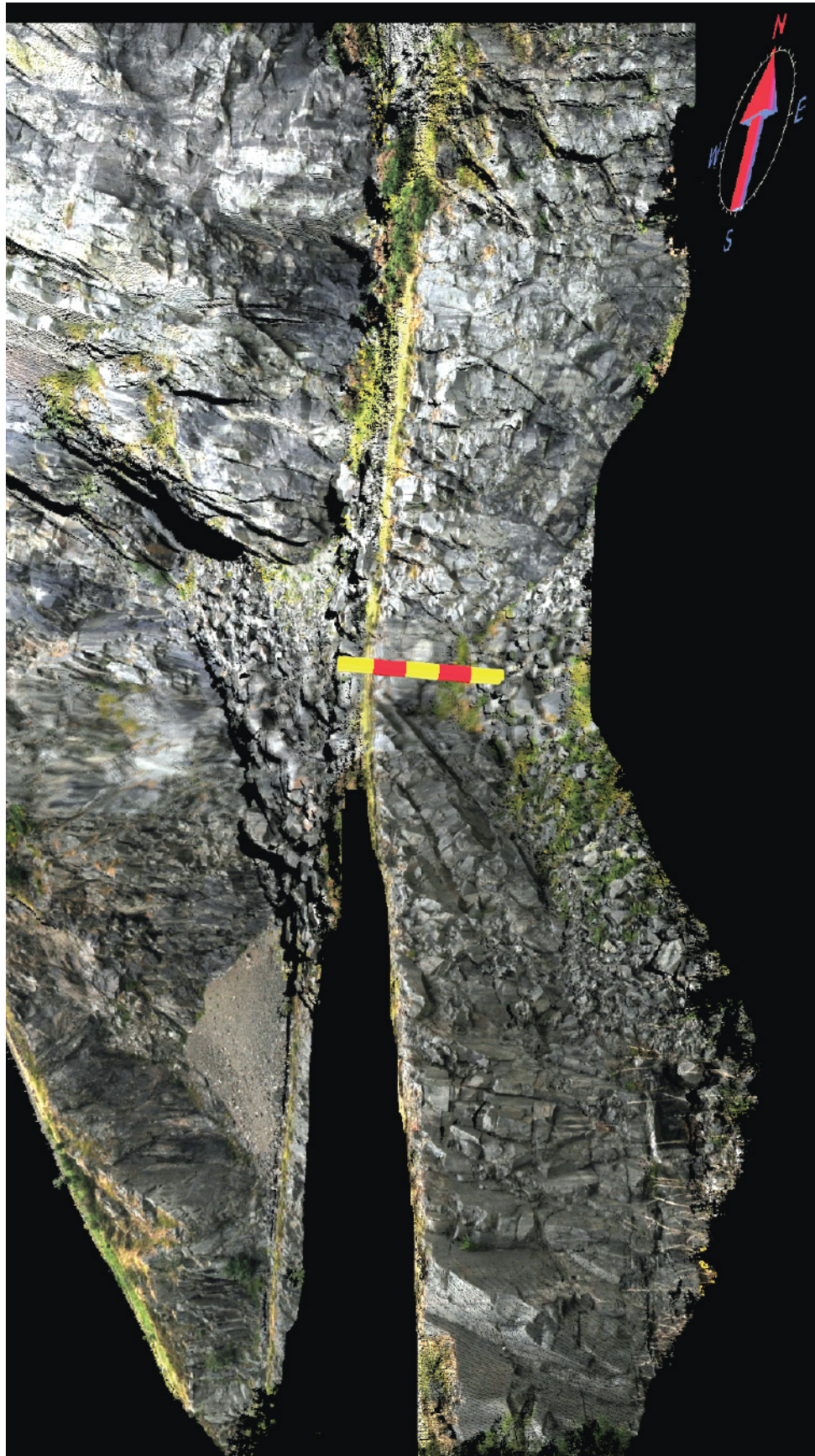


Figure 4.10: Lidar point cloud model of the Bramcrag quarry (NY 32044 21973). The walkway allowed a perpendicular outcrop face from which to sample fractures. This reduces orientation bias due to sensing. The scale bar is 5 m tall.

4.4.4 Hardknott Pass

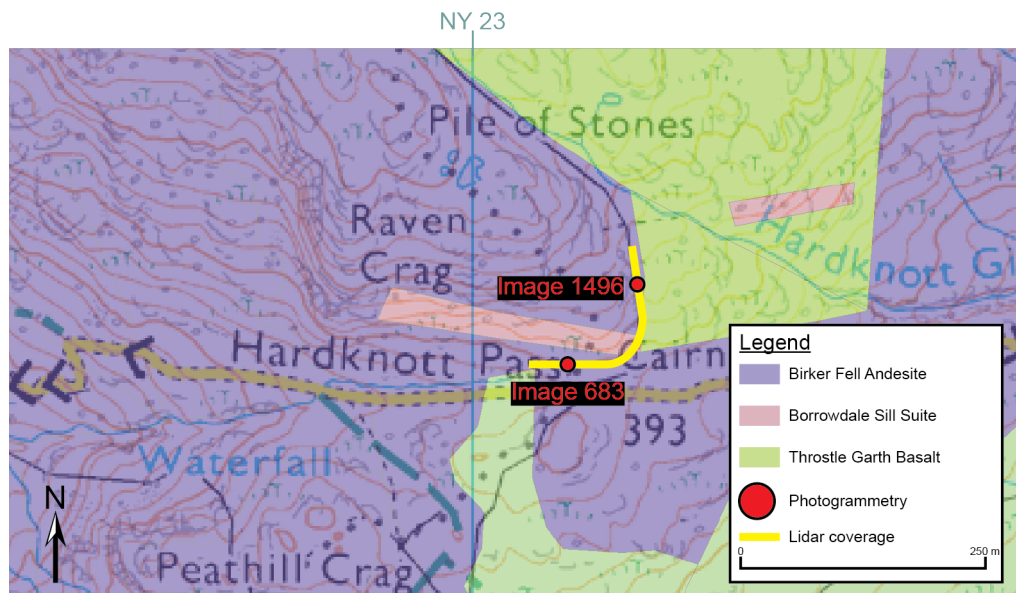


Figure 4.11: Geological map of the Hardknott Pass study area (DiGMapGB-50). The labelled red dots indicate the approximate location of the photogrammetric surveys and the yellow line indicates the total lidar coverage in the area. The red labels correspond to the P32 analysis shown later in Figures 4.21 and 4.22.

An outcrop at Hardknott Pass (NY 23151 01501) was scanned using both the lidar unit and photogrammetric methods. This allowed better data coverage and to investigate whether photogrammetric scans that have no spatial reference data associated with them can be transformed onto laser scan data and interpreted. The rocks form part of the Birker Fell Andesite suite and are the only example of this kind surveyed (Figure 4.11).

The lidar scan required four scan positions to fully cover the outcrop. The weather conditions were less than optimal as the the outcrop is located at the top of a mountain pass. High winds caused the lidar unit to oscillate, blurring some small sections of the scan. The point cloud data were georeferenced using the DGPS to around 10 cm accuracy and 281 fractures were picked on the outcrop.

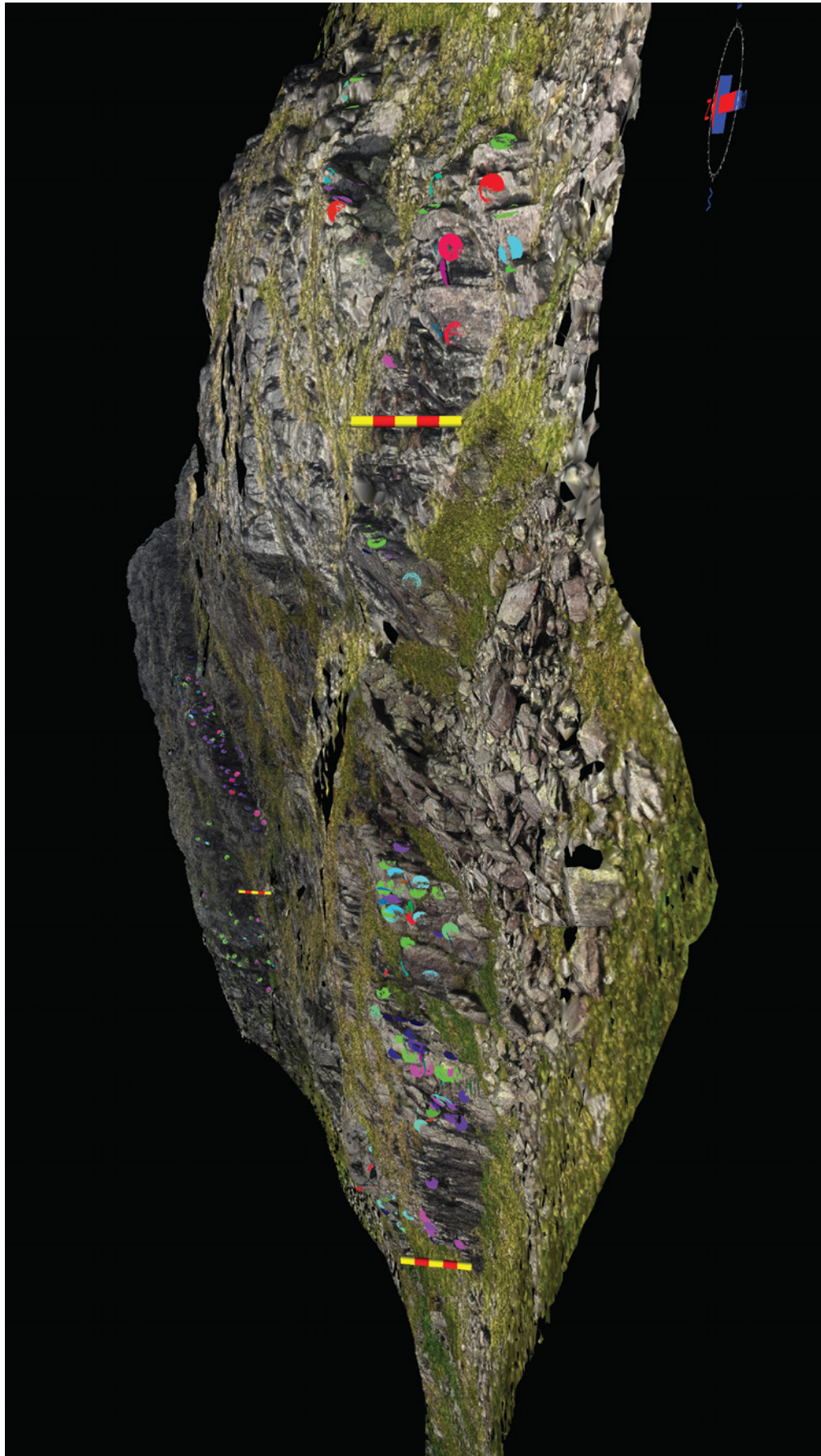


Figure 4.12: Interpreted fractures visualised on lidar scan of Hardknott Pass (NY 23151 01501). Colours of discs are arbitrary, but show locations of fractures picked. Scale bars are 5 m.

4.4.4.1 Data Collection

The photogrammetric scan required 2,422 photographs and the total processing time to create the model was around 16 hours. Two sections of the model were sampled that trended roughly N-S and E-W. This will reduce the sensoring effects of only sampling in one orientation. These are marked 1 and 2 on Figure 4.11. 85 fractures were picked on section 1, and 73 fractures were picked on section 2.

4.4.5 Data Analysis

	Number of Points	Photographs	Scan Positions	Approx. Vol. of Scan (km ³)	Fractures Picked
Bramcrag	27,146,919	28	4	5	638
Hardknott	20,737,380	28	4	1.26	281
Honister	15,984,000	56	8	0.101	200
Rydal	15,984,000	49	7	0.086	1063
TOTAL	81,850,299	161	23	6.447	2182

Table 4.2: Lidar dataset statistics

Table 4.2 shows a summary of the lidar dataset statistics collected for this project. Honister and Rydal have double the number of scan positions as they required horizontal scan positions to capture the roofs of the caves scanned. The data quality is excellent, however due to time constraints the coverage is sparse compared to the overall size of the study area. If we consider the total volume of the model is 1,916 km³ and the approximate volume of the scan is 6.447 km³, then the survey data represents only 0.33% of the total model volume. Comparing this to a study in the Nukhul half-graben in Suez, Egypt (Wilson et al., 2009a, 2009b), utilising a 9 km² continuous dataset comprised of 4 billion data points and 5,000 registered photographs. Although not a direct comparison, there is an order of magnitude difference in the number of points used.

It is important to note that the number of points does not have a direct correlation with the quality or quantity of information extracted. It leads to problems when

analysing in a regional context, however, for site specific models, the data coverage is more than sufficient.

4.5 Results and Discussion

4.5.1 Stereonet Analysis

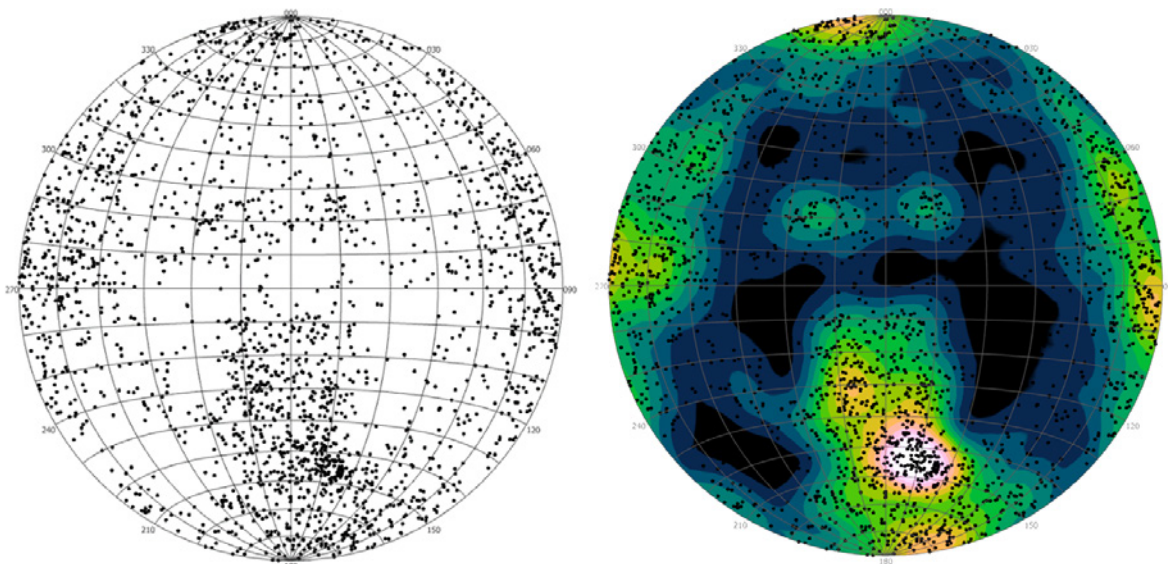


Figure 4.13: Equal area stereonet projection of total fracture dataset. The colours projected onto the stereonet highlight the relative clustering of the fractures on the stereonet. Bright colours indicate regions of more intense clustering than the darker or black areas. This is applicable to all following stereonets.

FracMan[®] (2015), a software program developed to analyse naturally fractured rock masses, was used to analyse the data in an attempt to identify fracture sets. The total dataset comprises 2,182 fractures (see appendix). When visualised on a single stereonet, there is a large amount of scatter visible in the data, with a dominant cluster appearing to be at around 65° dip and 175° azimuth when contoured. The scatter in the data means it is difficult to identify individual fracture sets, even using the Interactive Set Identification System (ISIS) module within FracMan[®]. This should allow extraction of fracture cluster statistics where it is difficult to identify the point at which they overlap. The complexity and spread of the results in the full dataset was so great that this was not possible.

However, it was possible to qualitatively identify that the dataset was dominated by the lower angle data (65° dip and 175° azimuth) but also what looked like a conjugate set of fractures that broadly trended N/S and E/W at high angles ($>70^\circ$ dip).

To investigate this, each fracture set was investigated separately to determine sets and mechanism of fracturing. These were then subdivided into clusters identified either via a visual inspection of the contours, or using the ISIS module to detect the overlapping clusters, as in the case of the Rydal dataset where the central cluster is thought to comprise two separate clusters. The process of calculating the fracture statistics is simple: A marker was manually placed at the approximate centre of the cluster by the user. It was found that splitting the data into individual clusters before running the ISIS calculation improved the chance that it would be successful. The calculation identifies clusters based on a probabilistic pattern recognition algorithm (Golder Associates, 2015). ISIS calculates the distribution of orientations for the fractures assigned to each set, and then reassigns fractures to sets according to probabilistic weights proportional to their similarity to other fractures in the set. The orientations of the sets are then recalculated and the process is repeated until the fractures sets are optimised (Golder Associates, 2015). ISIS allows the user to weight fracture properties preferentially to allow more realistic clustering to be performed. As the fracture data provided was limited to dip/azimuth data, this was not employed in this case. The process was simply based on the geometric distribution of the orientation and dip data to allow set differentiation. There was an attempt made to use ISIS to identify clusters present within the whole region dataset, however the degree of scatter of the data and lack of other fracture parameters to constrain the set

identification (i.e length, aperture, etc.) meant that it failed, so sets were identified separately. ISIS outputs the statistics depending on the idealised distribution curve used to model the fracture distribution:

- Fisher (Gaussian) - for simple, uncorrelated cause variations in the orientation
- Bivariate Normal - accounts for a distribution for fracture orientations where the variation of strike is greater than the variability of dip.
- Bivariate Bingham - is diagnostic of girdle distributions, such as those found by plotting data from multiple points in a fold structure
- Elliptical Fisher - model fracture sets having different amounts of variability in fracture strike and dip that plot as an ellipse on an equal area stereonet

The underlying mathematics for each are discussed in Golder Associates (2015).

The distributions allow some comment to be made on the fracture characteristics, yet the Kolmogorov-Smirnov goodness-of-fit test was ultimately the decider in which distribution was used. Any value greater than 5% is statistically acceptable, but the higher the value, the better the fit. The outputs from the ISIS calculations in FracMan[®] are summarised in Table 4.3.

Analysis of the individual stereonets at each locality provides only limited information. If the data are to be used as part of a regional scale fluid modelling approach, it is important to identify and eliminate any localised clustering visible on the stereonets. These are not regional features, but will be useful in determining what level of variability needs to be built into the model. Modelling the subsurface fluid flow on regional scale will only be possible for regional scale lineaments. Combining the datasets allows any regional scale patterns to be identified.

4.5.2 Outcrop Stereonets

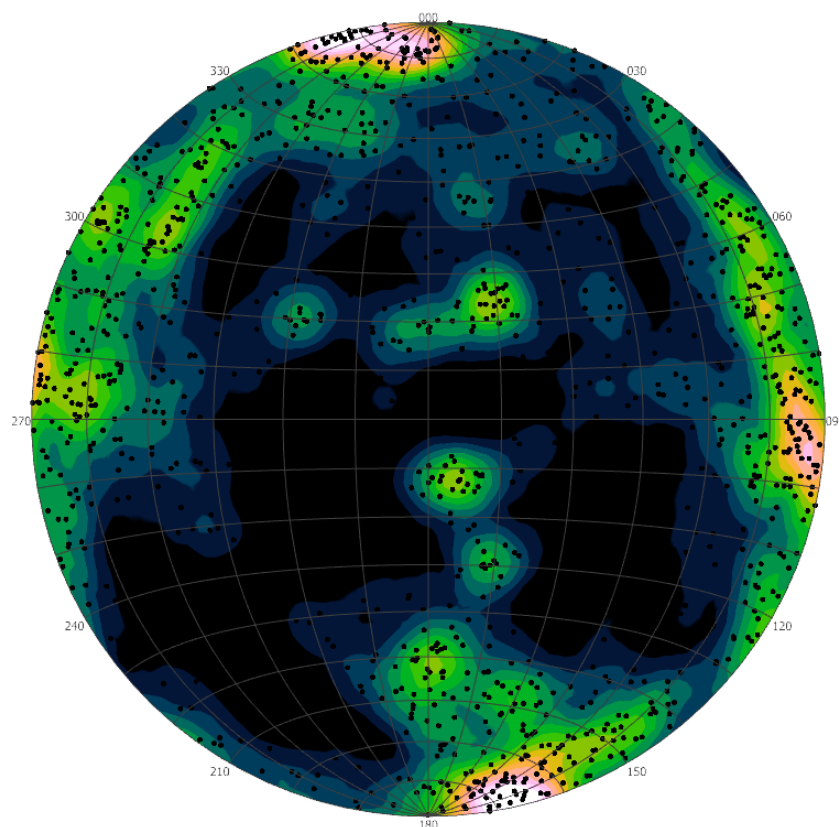


Figure 4.14: Honister, Hardknott and Bramcrag datasets. It shows more defined clusters once the Rydal dataset has been removed. There are two steeply dipping sets roughly aligned N-S and E-W and some more shallow datasets clustered around the centre.

It was identified that a large proportion of the scattering observed was due to the the Rydal dataset, and it's disproportionate weighting in the total dataset. Whilst this is probably the most comprehensive dataset in terms of both size and reduced sampling bias (all walls of a cave were sampled to avoid orientation bias), the measurements also account for almost half the dataset: 1063 out of 2182 ($\sim 49\%$). These data also exhibits the strongest correlations around $50\text{-}60^\circ$ dip and 160° . Removing the Rydal dataset and re-contouring the stereonets shows this has skewed the dataset, as shown by Figure 4.14. It appears that there are overlapping fracture clusters that are difficult to extricate.

In the non-Rydal dataset, there appears to be clustering at around 10-30° at various orientations. These could be bedding joints due to their relatively low feature count and dip angle. There are also 4 stronger correlations at >80° dip clustered around NNW, SSE, ENE and WSW. Therefore to obtain meaningful correlations, the datasets were analysed separately.

Rydal

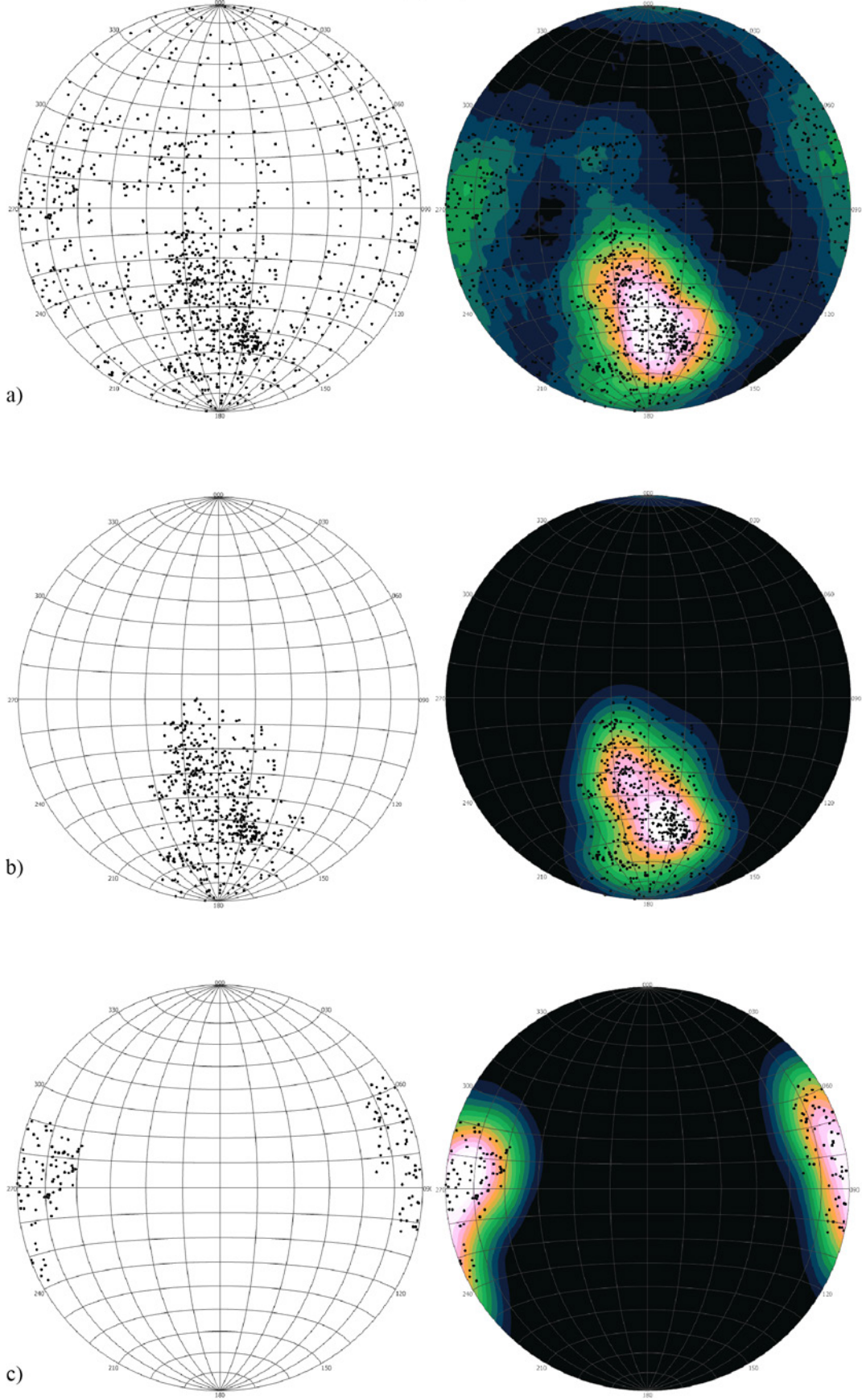


Figure 4.15: Equal area stereonet projection of full Rydal dataset and individual sets identified.

Bramcrag

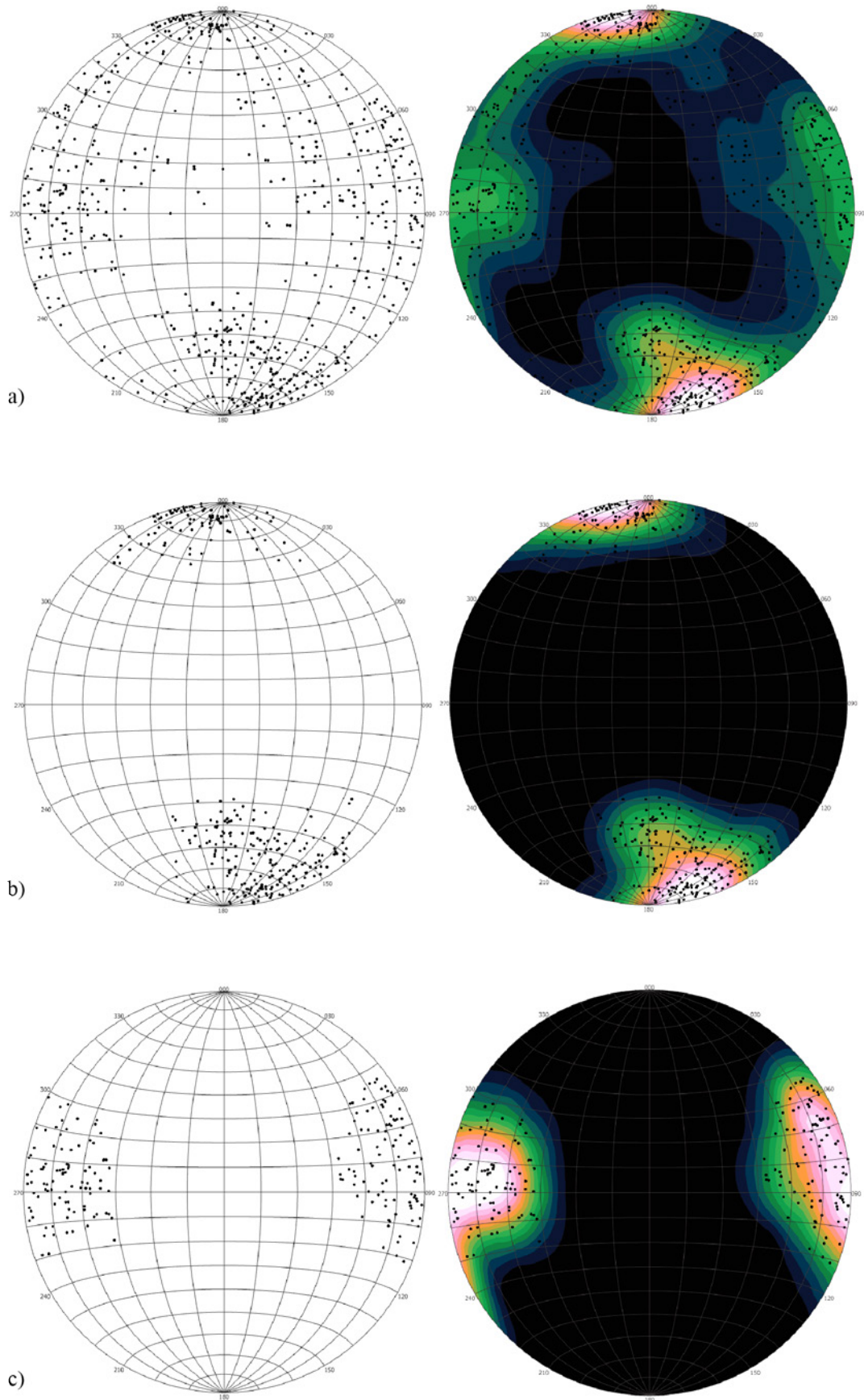


Figure 4.16: Equal area stereonet projection of full Threlkeld dataset and individual sets identified.

Honister

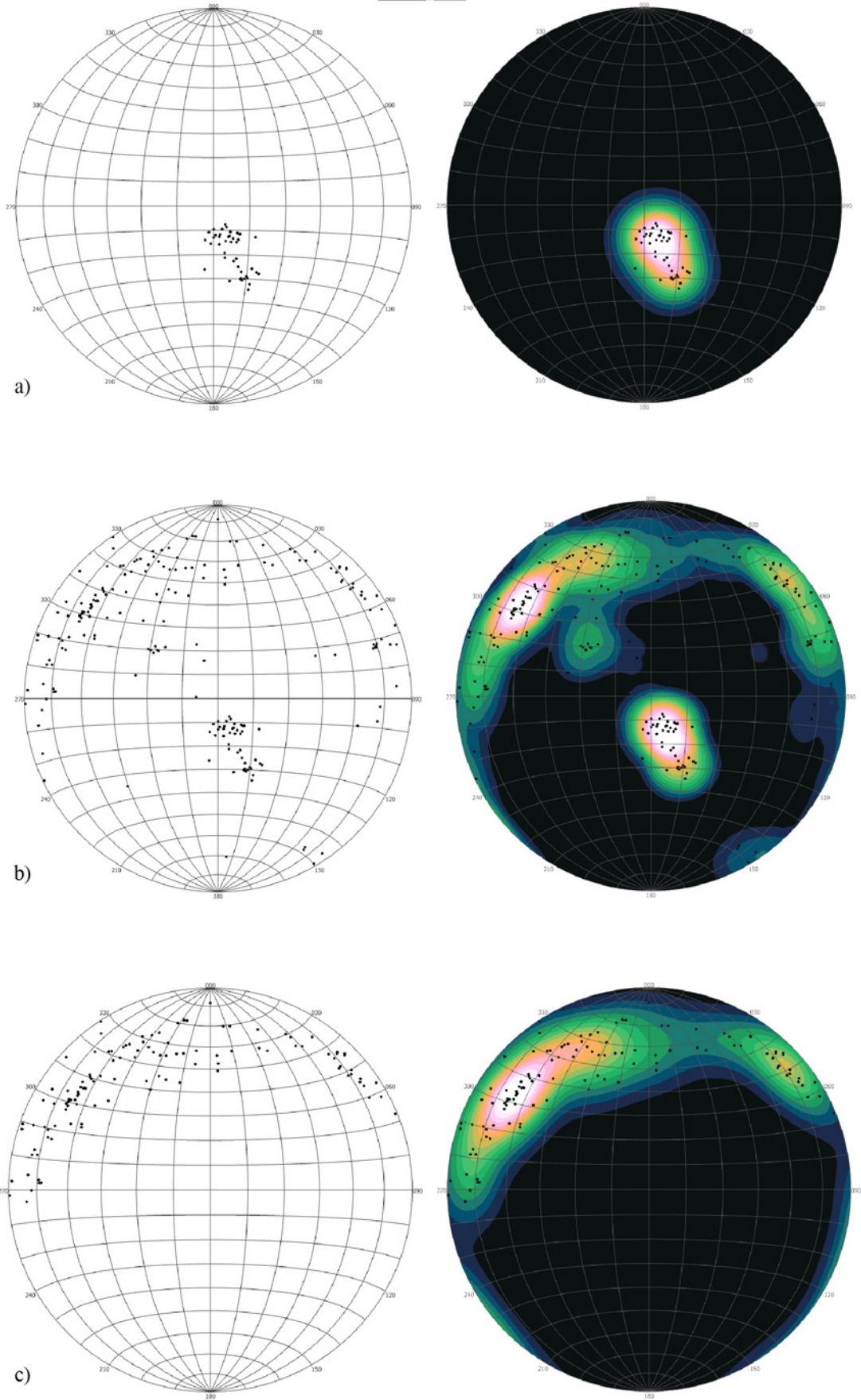


Figure 4.17: Equal area stereonet projection of full Honister dataset and individual sets identified.

Hardknott

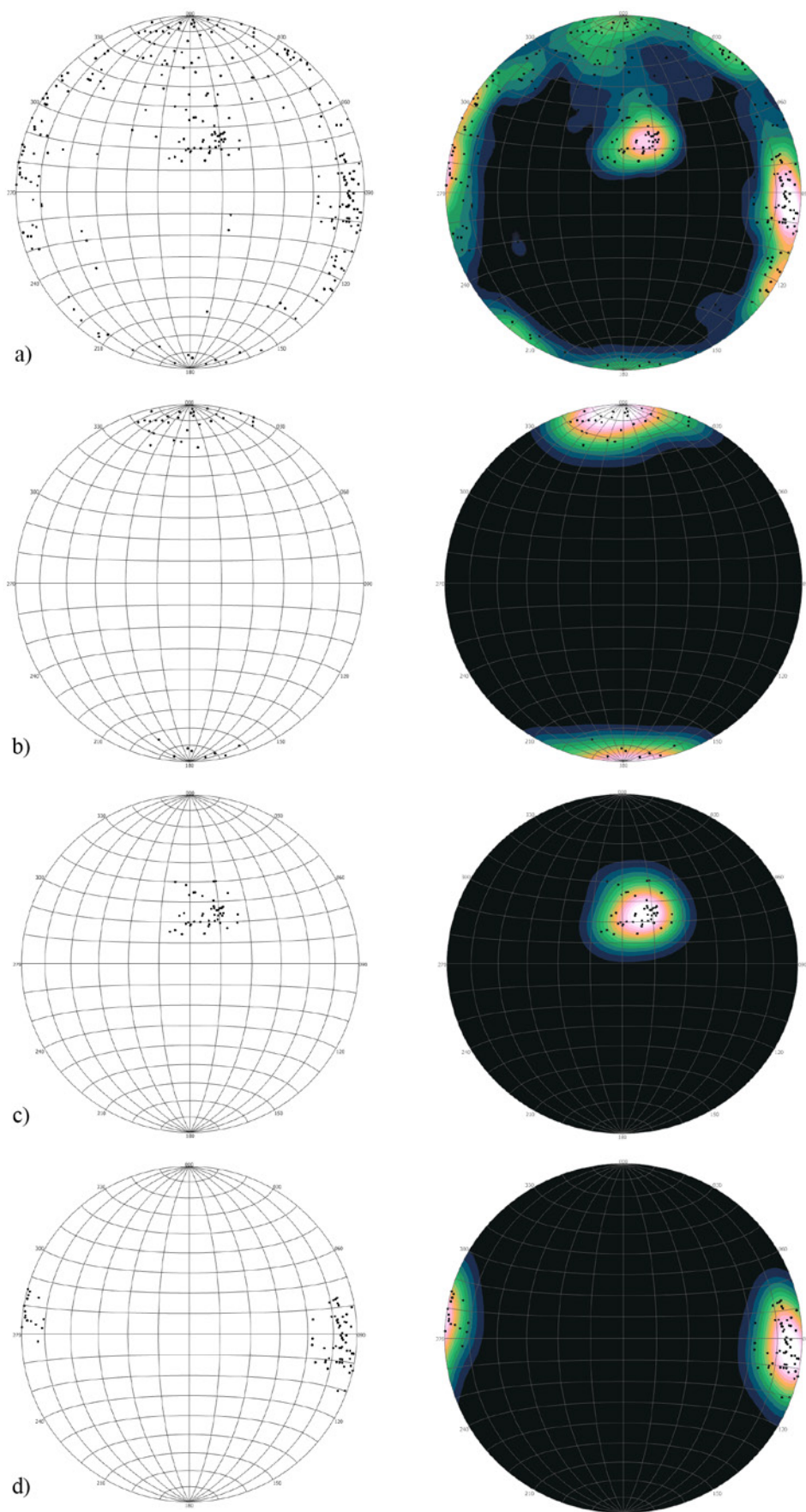


Figure 4.18: Equal area stereonet projection of full Hardknott dataset and individual sets identified.

	Set Name	Fracture Count	Dip [°]	Azimuth [°]	K_S Probability
Bramcrag	East/West	192	87.81	266.58	59.44%
	North/South	294	19.38	168.80	98.69%
Hardknott	Bedding	48	26.92	15.57	91.69%
	North	39	84.40	358.39	98.95%
	East/West	73	82.79	93.34	98.09%
Honister	Andesite	44	20.38	157.58	64.54%
	Girdle	119	71.75	333.41	54.19%
Rydal	Central_1	325	36.73	188.00	95.41%
	Central_2	266	61.66	174.79	84.83%
	East/West	150	86.30	265.57	31.94%

Table 4.3: Calculated fracture cluster statistics

Figures 4.15, 4.16, 4.17 and 4.18 show the equal area stereonet projections for each lidar dataset.

Three of the datasets contain a steeply dipping East-West trending cluster. The dips range from 82.79° - 87.81° and the azimuths are 266.58°, 93.34° and 265.57°. This is consistent with the fact that a small change in dip when the data are high angles causes an apparent orientation shift of 180°. Unusually, Bramcrag quarry is the only dataset that shows a North-South cluster. The provenance of this set is unknown, however it could be a localised stress or rotation presenting itself. All contain a lower angle clustering of some description.

In order to properly understand the lower angle (10-60°) datasets, we must first look at the high angle data. Discounting the low angle fractures, the strongest cluster patterns suggests there is a regional pattern to the data that closely resemble patterns identified outlined in Chadwick (1997), Hitchmough et al. (2007) and Seers and Hodgetts (2013). It suggests that the main fracture patterns observed relate to regional extension, related to Acadian orogenic processes during rifting in basin formation in the early Devonian (Cooper et al 1993). Once the low angle fracture clusters were removed, the extension-related clustering was even more pronounced.

The mechanism that formed the low angle dips is a confused picture. Two scenarios were initially proposed as to their formation. The first is that they are low angle thrust faults, possibly related to some localised volcanoclastic deformation or later compression. This seemed unlikely as the dips were too low. The second is that it was low angle bedding joint traces. This still did not answer the question as to why many of the data points seemed to exhibit dips $> 50^\circ$, past any reasonable angle of repose that would be exhibited by a deposited rock unit. These are obviously contradictory statements as the dips are both too low and too high for either scenario. The scenarios were re-evaluated and it is proposed that there are two mechanisms at work that explain the distribution of the fractures. The first component is indeed a bedding joint component that would explain the lower angle dips below $< 30^\circ$.

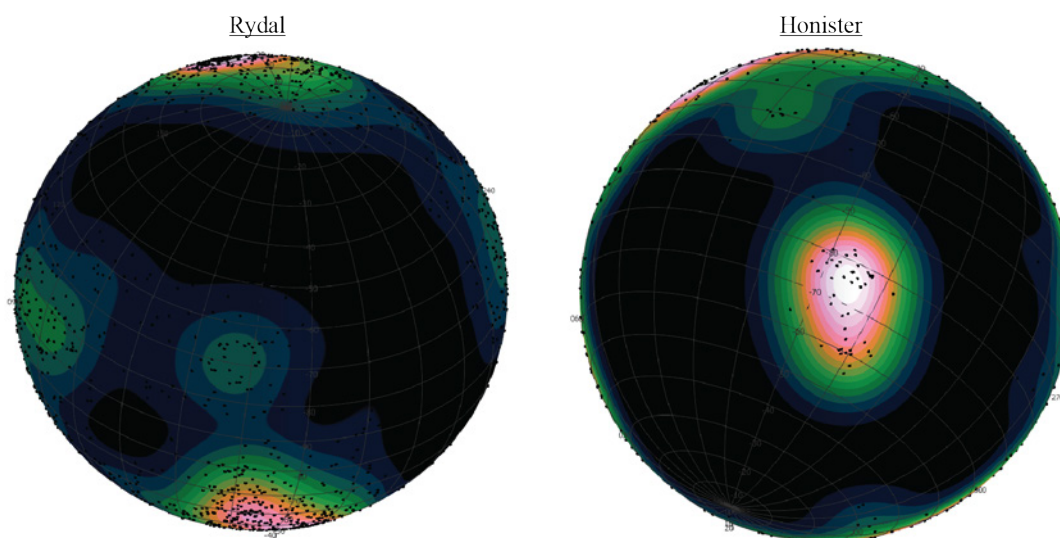


Figure 4.19: Manually rotated datasets visualised in 3D to illustrate one possible explanation for the complexity of the data.

It is proposed that the second component relates to low angle bedding joints or fractures that have been rotated after formation. This would account for the majority of the wide variation in the cluster in the southerly dipping datasets.

This is backed up by predictions in Branney and Kokelaar (1994), who estimated a 20° change in dip due to volcanotectonic activity. This could be a major component of the rotation with other, later tectonic activity accounting for the remaining dip change.

These datasets can be manipulated in 3D in FracMan[®] to estimate the extent of the rotation. It is impossible to do this precisely as there is no way to determine their original orientation as the rock units have undergone numerous phases of deformation in the intervening 430 million years. Cooper et al (1993) describes the mechanisms of deformation that affected the early Palaeozoic, including extension related to the volcanism above the subduction zone, a southerly propagation of a foreland thrust, generated by the collision of Avalonia and Laurentia. Later structural evolution was dominated by extensional tectonics, as the Lake District Block was situated next to rapidly subsiding basins. Variscan inversion further uplifted the Lake District massif and was followed by further extension from the Late Permian to Early Jurassic. Around 65 Ma (Lewis et al., 1992), the Lake District block was uplifted around 1750 m (Chadwick et al., 1994). The timing of these events is exceptionally difficult to place due to the lack of correlation across stratigraphy.

This means precise reconstruction of the original datasets is impossible as the tectonic history of each survey location is not well constrained. The amount and direction of rotation is unknown. Estimating a rotational vector is possible using the 3D stereonet projection in FracMan[®]. The values are not a statement of total rotation just a reconstruction of a possible total net rotation at the locality. The numerous different phases of deformation means the dataset could potentially be rotated in opposing directions, the degree to which is impossible to determine. The

rotation of the datasets can also be used to explain the absence of strong North-South clusters in the individual datasets: their dips have been modified by rotation.

4.5.3 Photogrammetric Results

The Matlab utilities (`line_tool` and `editing_tool`) yielded data that can be used to further characterise the fracture networks at Hardknott Pass. Two photographs that represented perpendicular faces of the outcrop were selected to reduce censoring effects where sets parallel to the outcrop face would not be sampled. Figure 4.20 summarises the data output from the analyses. The data shows that for the Hardknott dataset, the fractures sampled at outcrop are relatively small and trace length is < 5 m. The data suggests, as expected, that the outcrop is moderately fractured and gives a quantitative measurement of apparent fracture trace length. The P32 values were calculated across the surface of the outcrop in search kernel (with a radius of 1.5 m), not from the outcrop as a whole. This provides a distribution of fracture intensity values across the outcrop, not one single value. The graphs of the N-S and E-W sets show a normal distribution of values (with some skew), whereas the bedding joint set exhibits a broadly logarithmic distribution. This is reflective of the fact that the bedding joint will mainly be formed from individual eruption cycles or changes in the eruptive force (i.e. larger clasts, more material). In the Lower BVG, beds from these eruption styles will be relatively thin, compared to a large ignimbritic or mesobreccia deposit. In the area of high P32 values in the bedding joint set, the beds are small (< 5 cm) in thickness. As a result the P32 values are significantly higher for this

set, peaking around $4.7 \text{ m}^2/\text{m}^3$, compared to around $3.25 \text{ m}^2/\text{m}^3$ for the E-W set and $2.8 \text{ m}^2/\text{m}^3$ for the N-S sets.

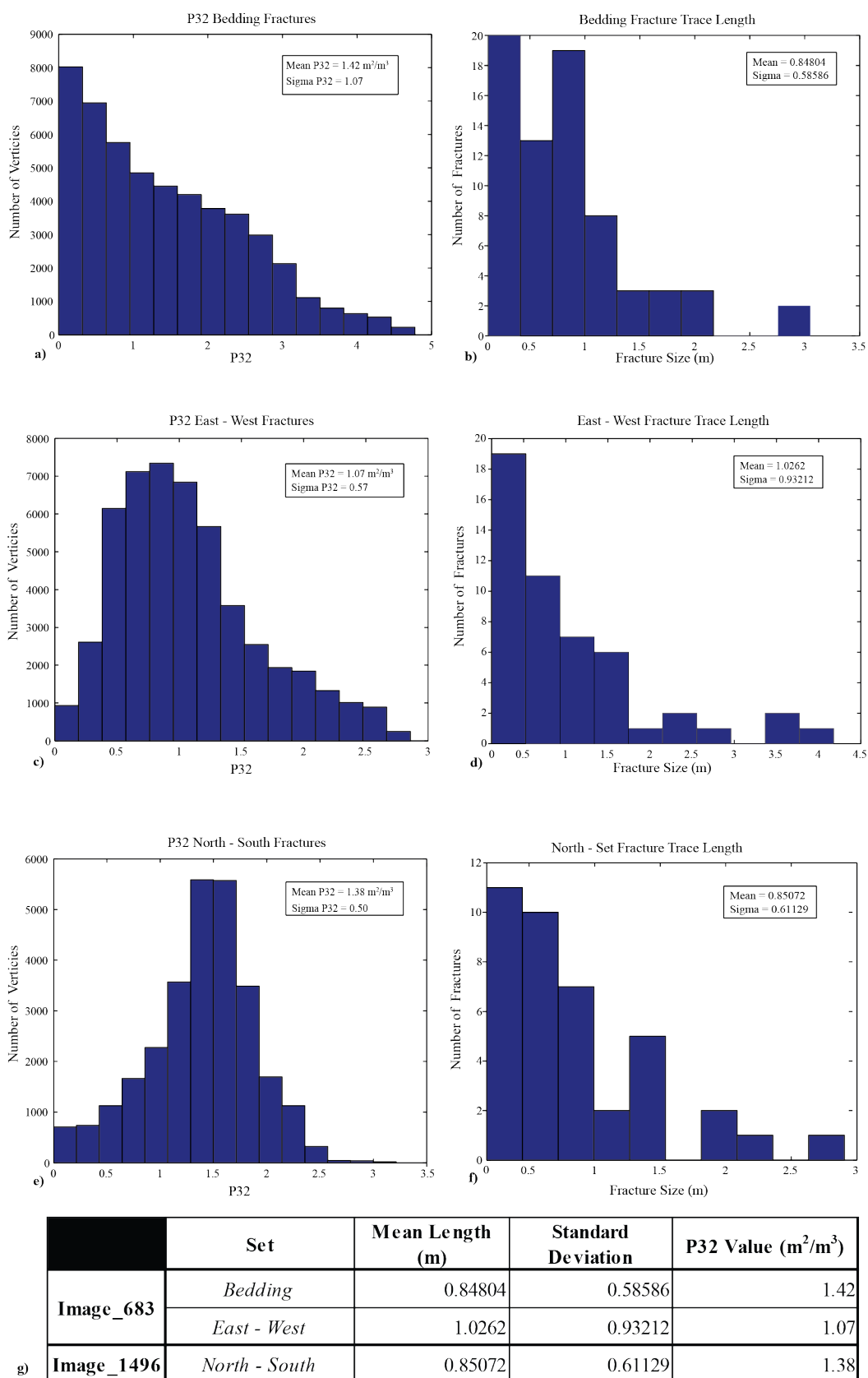


Figure 4.20: Photogrammetric analysis results. a), c) and e) show the calculated P32 intensity values for the three sets at Hardknott, and b), d), and f) show the calculated fracture trace length in metres for each dataset. g) shows a summary of results used in the Petrel DFN modelling.

The two other sets have no such depositional control on their distribution. They are likely to have formed as a result of stress and therefore can exhibit a different pattern of intensity, controlled by existing weaknesses in the fault or proximity to larger features.

These data can be projected onto the outcrop itself to map the distribution of P32 across the sampled areas. In reality, the intensity of fractures varies across the rock face, say, with proximity to a large fault. Figures 4.21 and 4.22 show the triangulated mesh of the photogrammetric scan with the P32 intensities visualised for each fracture set. It shows that the relative intensities vary depending on the fracture set identified and also across the outcrop.

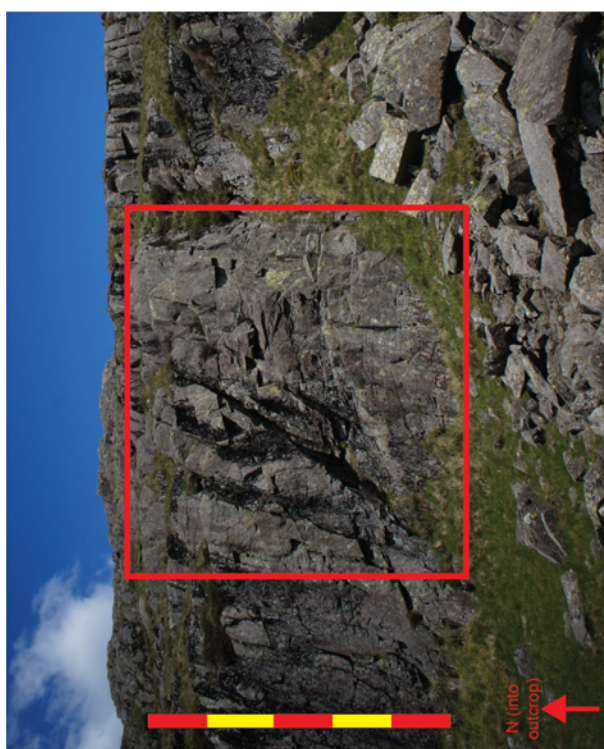
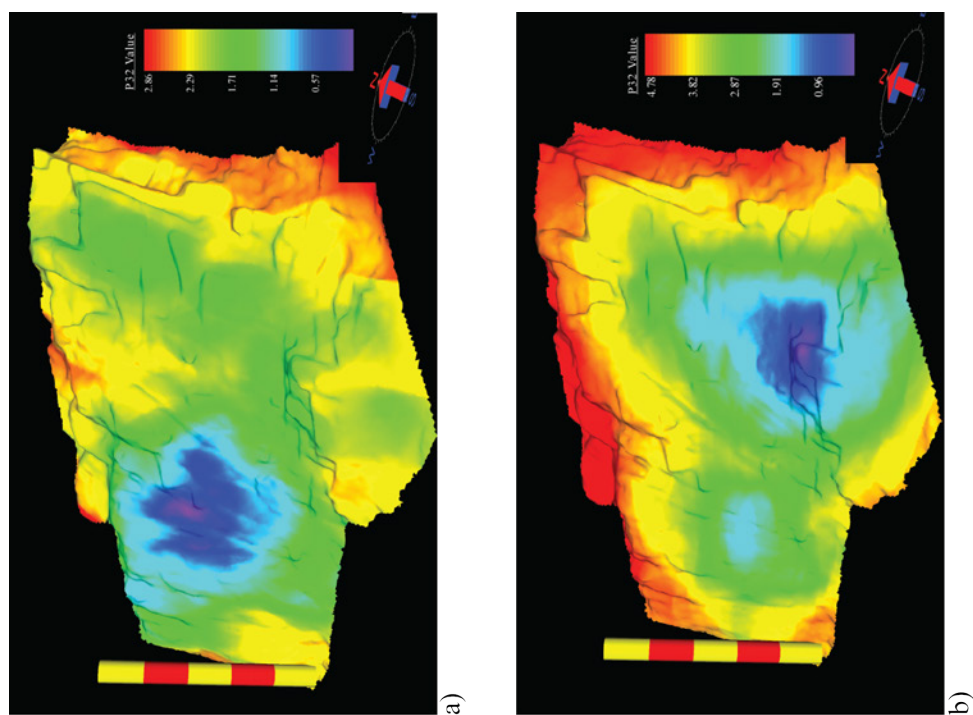


Figure 4.21: Spatial variation of P32 intensity across the Hardknott Pass outcrop face on image 683 (location shown in Figure 4.11). a) shows the intensity of the E-W set and b) the bedding joint set. Colder colours indicate a higher P32 value and warmer colours lower. The red box highlights the approximate extent of the mesh and the scale bar is 5 m.

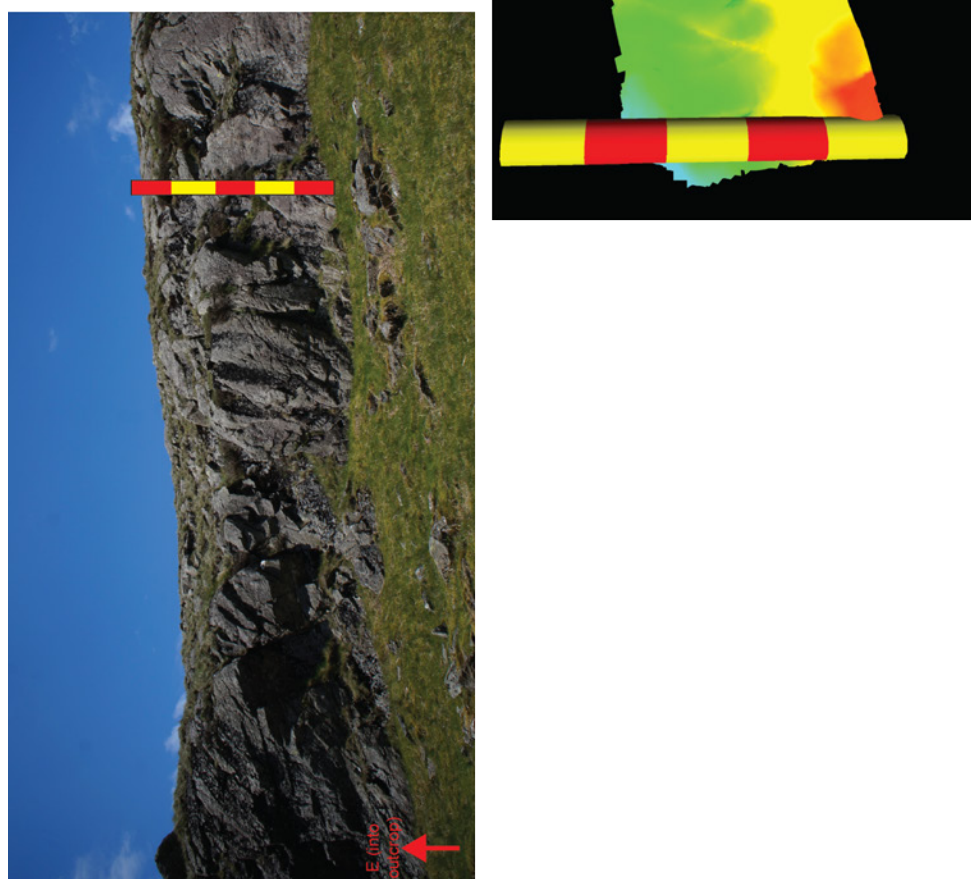


Figure 4.22: Spatial variation of P32 intensity across the Hardknott Pass outcrop face on image 1496 (location shown in Figure 4.11). These data represent the N-S bedding joint set. Colder colours indicate a higher P32 value and warmer colours lower. The scale bar is 5 m

The distribution maps can be used in the future used to develop high resolution fracture models as part of the site investigation process. They give high-resolution, quantitative spatial information as to the distribution of the fractures within a rock volume. This can be used not only as part of stochastic DFN generation, but would be essential in mapping out smaller deterministic models once the site characterisation progresses.

4.5.4 Summary of Results

In this project:

- 2,182 fractures were interpreted from 4 outcrop lidar datasets.
- 158 fractures were interpreted from one photogrammetric dataset.

From this it was possible to infer the following:

- The scatter on the stereonet when visualised together indicates a complicated tectonic setting.
- Separating the individual localities allows a clearer picture to emerge, one that shows a dataset dominated by high angle. extensional fracturing in conjunction with lower angle bedding joints.
- Many of the datasets appear to have been rotated and this can be used to explain the wide variation in fracture orientations and dips.
- P32 values could be calculated from the Hardknott Pass dataset which allows detailed quantitative analysis of fracture intensity across the DOM. These were between 1.07 and 1.42 m²/m³.
- Length values were also calculated, ranging from approx. 0.8 to 1.03 m

4.6 Comparison to Previous Work: Nirex Bleng Valley Report

It is worth comparing the approach in this project to previous work undertaken by Nirex. A good example of a Nirex survey in this study area is the Bleng Valley report. This section is modified from Barnes et al (2002). These data were collected between 1993 and 1995 and was reviewed in 2002. The study details the creation of a stratigraphic and structural interpretation in Blengdale and adjacent areas. It combines outcrop data, geochemical analysis and also geophysical surveys to form an understanding of the area.

Extensive lithological characterisation by field mapping was performed to increase the understanding of units that were observed in the Nirex boreholes, supplemented by petrological and geochemical data. The exposure was poor and so geophysical surveys were undertaken to try and improve correlation between the outcrops.

Fracture surveys were performed within the study area and the main method of data collection was manual scanline surveys, with data projected onto hand drawn field diagrams (Figure 4.23). It was noted that even though there was some exposure, it was often of poor quality and afforded limited fracture data. Indeed the exposures were so poor, no quantitative analyses were performed on the datasets. Qualitative, broad observations were made about relationships.

The data provided in the appendices comprised annotated field sketches and poles to plane stereonet plots. In the author's opinion, it was unusual that there was no accompanying photograph of the outcrop in the report to allow comparison and validation of the field sketches. In total, 369 fractures were sampled and exhibited

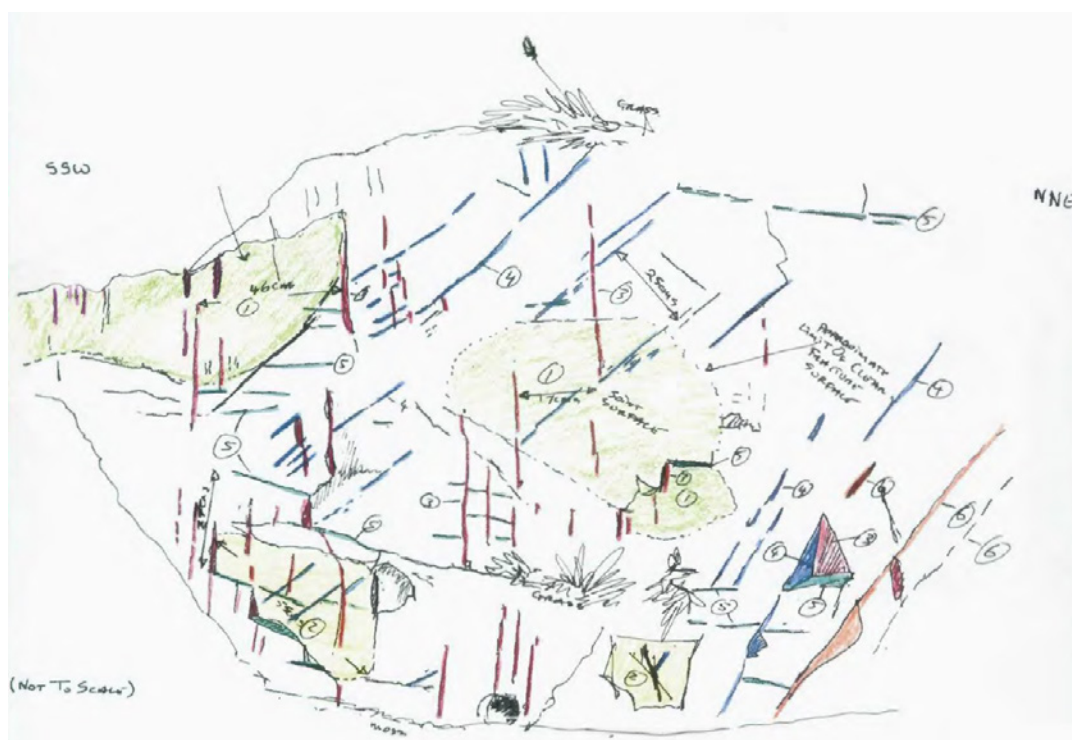


Figure 4.23: Hand fracture sketches from Barnes et al., (2002) (not to scale), locality BV 19 on Fig. A 11.1, [30960 50095]) as described in the report. Different colours are used to identify fracture sets and hand annotations to highlight important information and a rough outcrop alignment (SSW - NNE). Although an excellent example of a hand field sketch, compared to the lidar data shown previously, there can be no argument that this is a far inferior technique.

a widely scattered pattern with no identifiable trends. An attempt was made during this project to revisit these localities, however the increase in forest density over the last 21 years means many of the outcrops themselves are unreachable and the River Bleng was also in flood meaning riverside outcrops were inaccessible. However it was possible to compare the datasets collected for this report and the digital outcrop models collected here. Whilst direct comparisons are unfair as exposure was limited in the study area for the report, it is clear that the digital data is a far superior approach. It is unusual to only be provided with unscaled hand sketches and not annotated field photographs, at least for comparison (see Agosta et al. (2010) for good examples of this). The quality of both the sketches

and the associated fracture data collected will depend on the relative field skill of the geologist, which is both difficult to quantify and varies widely. Visualising the data onto unscaled diagrams is not useful for quantitative analysis and revisiting these sketches once out of the field is only useful to jog a geologist's memory, not for reinterpretation.

Contrast this with digital outcrop models which are correctly scaled, allow direct interpretation from their surface and reduce the human error of field data collection almost completely from the interpretation process. Data can be revisited, reprocessed and reinterpreted at a later date if required. Whilst the stereonet data provided is useful, the hand sketches (Figure 4.23) do not serve any useful purpose in the report and were of little use when trying to locate the outcrops when they were revisited for this project.

This method of data collection highlights the labour-intensive and inefficient methods employed in the last attempt to site a UK GDF. What is worth noting is that this report contained research that formed part of the site selection process, but was not published by Nirex until 2002, even though the work is cited in peer reviewed papers from 1990's (Bowden et al., 1998; Littleboy, 1996), again feeding the notion of the 'grey literature' mentioned in Black and Barker (2016).

4.7 Fracture Data Quality

It is worth addressing the question of what sample size is representative of the fracture distributions in the study area, as this was one of the more difficult parts of the methodology. It is accepted that the number of fractures collected in this project does not constitute a statistically robust dataset to model the entire of the BVG. However, the extent of the BVG should not be confused with either the

higher strength geological setting for a GDF (which does not have an ‘extent’ per se) or with the extent of a GDF itself. In this study, the BVG is only an analogue to the geological setting and therefore the entire BVG could be chosen as a modelling size, or just 1 m³ of it: either would be correct. Thus, calculating a definitive sample size that would provide a robust dataset is impossible. To determine whether a sample size is statistically robust, you must first know the total sample size. This would require knowing the total number of fractures present in the study region at the scale that is relevant to the DOMs, down to GDF depths. Whilst it could be possible to estimate, the uncertainty in this value would be huge. For modelling purposes in this project, the fracture characteristics have been simplified across the geological units, however in reality, they vary depending on proximity to faults, rock types, depth and even locality within the study area. This is coupled with the fact that the subsurface geology is so poorly understood, even if each unit is successfully characterised, it would be difficult to ascertain the extent of these rocks in the subsurface to GDF depth.

Instead the fracture data must be viewed from a different angle. Fracturing is a result of tectonic stresses and these produce fractures with broadly similar parameters, in a predictable manner. They do not produce fractures that are randomly orientated: that is mechanically impossible. The picture is complicated somewhat by multiple tectonic realignments that can produce overlapping sets. However cluster analysis should still allow these sets to be untangled.

It must also be noted that if the area has such a complicated tectonic history, with fracture sets that are impossible to distinguish from one another, then this is probably not a suitable area in which to host nuclear waste. The principle of deep geological disposal is built around being able to characterise a body of rock to a

point where predictive models can be created. If there is no way to determine how the region's fracture patterns were generated and how they are generated, then the area should not be considered as a suitable area in which to dispose of nuclear waste.

4.8 Conclusion

This methodology was developed with the aim of improving fracture and lithological characterisation and evaluating new techniques. The approaches described here are a step forwards in the host rock characterisation process. Although there were some problems with restricted exposure, it proved that outcrop analogues can be used to help condition subsurface modelling for use in the site selection process. The lidar and SFM techniques are a much needed step towards modernising geologic data collection. They will provide larger, more accurate datasets to the investigators that can be used to generate more robust and reliable predictions, in a more cost-effective manner. It also significantly reduces the number of bore holes needed, which as mentioned previously is a necessary requirement of site surveying to maintain structural integrity of the site. When compared to the previous works which were simple borehole fracture studies and limited outcrop and geologic mapping, the quality, reliability and versatility of the data is vastly improved.

In terms of fracture studies, this will allow calculation of more complex fracture parameters (i.e. P32 intensity from photogrammetric scans instead of P10 from borehole studies) to be extracted and utilised. Once a site has been proposed, the possibility of creating deterministic fracture models for smaller studies which

would allow representative modelling of the fracture networks in a region to determine subsurface fluid flow behaviour.

If direct measurement of the rock units to be used as a potential host rock cannot be directly sampled (i.e. it does not outcrop), it could be possible to use an outcrop analogue to provide vital information. This is especially true if we consider the BUSC nature of this setting, in that the sedimentary rocks will also need to be modelled. This may require geobody mapping to provide geostatistics for use in the channel modelling.

4.8.1 Software

Bespoke software modules were created for the existing in house programs for this project. For example, VRGS was modified to accept new data types (e.g. ESRI Shapefiles) and the LineMapper software was developed specifically to extract lineament data directly from outcrop. It would be unfair to compare these to Polyworks[®] or FracMan[®] software as these are commercial products that are not modified to suit a specific need.

Nonetheless, this could point to how an idealised approach to the process should be developed in the future. Many ‘off the shelf’ programs will be broad in scope to appeal to the widest market possible. The TOUGH suite of programs was developed with nuclear disposal in mind and projects such as DECOVALEX (DEvelopment of COupled models and their VALidation against Experiments), that attempt to address how coupled site modelling should be approached, were created (DECOVALEX, 2016). This was to fill, or attempt to fill, gaps in the modelling approaches or workflows. However, these are designed for a more

advanced stage of the site selection process and are unsuitable for use in this project.

The same approach should be applied to the site characterisation and, specifically, the geologic modelling. Selection of software packages should also be based on the lithology to be characterised. For example the BVG would require a specialist fracture modelling software such as FracMan® to characterise the numerous, complex fracture networks in the region, whereas this may not be needed in a low strength sedimentary rock setting, such as a clay or salt formation as the materials behave in a mechanically different manner and fracture networks are not as complex or may not even be present, but require specialised modelling to predict how, say, the salt may deform in the future as this will be critical to the post-closure safety assessment as the host rock in that case could also form part of the barrier as it will deform and contain radionuclide release as it undergoes ductile deformation (Gera, 1972).

The software (and indeed hardware) limitations of lidar data are well documented (Hodgetts 2013). Often data volume way outstrips the computational power available. It must be recognised that collecting large volumes of lidar data for fracture measurements across an entire region would be counterproductive, so surveys should be targeted to operate within current technical limits.

Chapter 5: Static Modelling

Chapter 5

Static Modelling

5.1 Introduction and Rationale for Modelling

Once the outcrops have been fully characterised, the feasibility of creating static geological models for the BVG was investigated. This involved taking both existing and new digital datasets and combining them to attempt to build a representative model of the geology in the study area and potentially move forwards into flow modelling. The modelling approach in this project was based on the reservoir modelling field used extensively in the hydrocarbon industry. The model was built in Petrel™ (Schlumberger, 2013) a well established and powerful software package that can be used for large scale modelling and simulation. Ringrose and Bentley (2014) provides an interesting analysis of the purpose of these models. It offers 8 different scenarios for which a model is created, some of which are applicable here. These are models for:

- *Visualisation* – presentation and illustration of the subsurface
- *Volumetrics* – volume calculations of rock volumes within the modelling area

- *Front end to simulation* – production of a lithological model that will ultimately be used for flow simulation

The benefits of this modelling approach in terms of volumetric analysis and simulation case creation is clear: it allows a robust and well tested methodology to be used in the output of data vital to the creation of any safety case.

The visualisation aspect is more important for the nuclear industry than the hydrocarbon industry. As briefly discussed previously in Chapter 2 and also in more detail in Chapter 6, engaging and convincing interested stakeholders (be it local communities or governmental planning authorities) is a vital part of any GDF siting process.

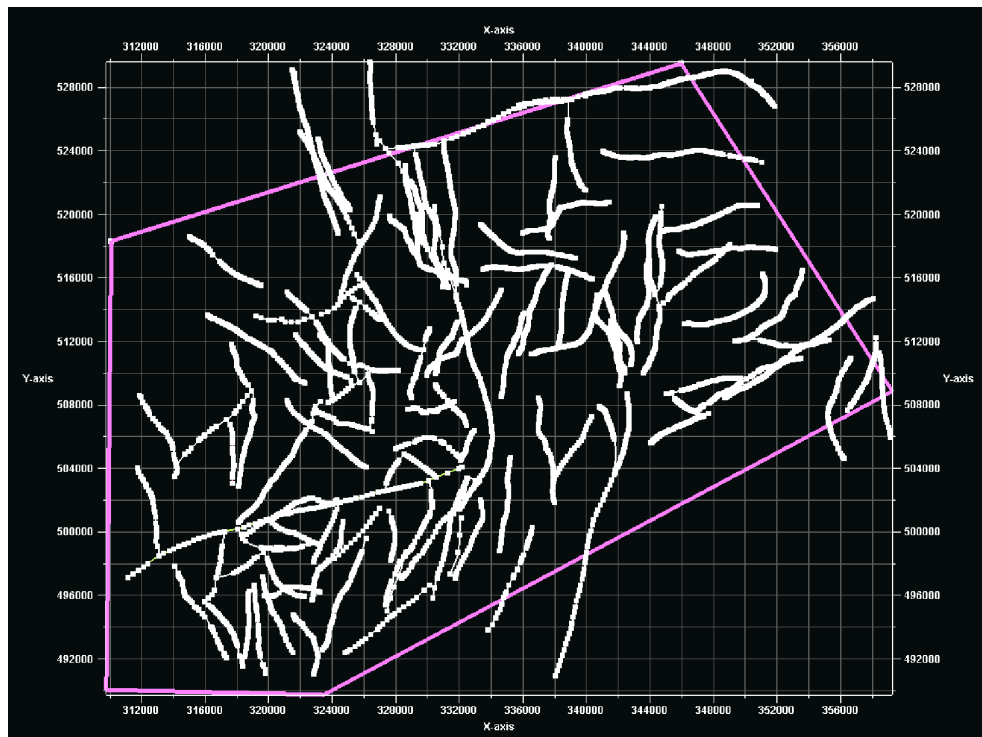
Having a clearly defined modelling workflow is vital. It was accepted that the modelling approach would be different from a hydrocarbon reservoir as there was no seismic data available and borehole data would be limited. There is also a more subtle difference, as unlike in many hydrocarbon plays, the BVG has a single phase system for flow (i.e. fracture-driven) as opposed to most hydrocarbon wells which are dual phase (i.e. porosity- and fracture-driven). This means the geological properties of the rocks is largely ignored. It was envisaged that the shortcomings in data volume could be overcome by using stochastic modelling methods such as variogram analysis (Curran, 1988; Pyrcz and Deutsch, 2003) and the stochastic horizon generation tools that come as part of the software package.

5.2 Methodology

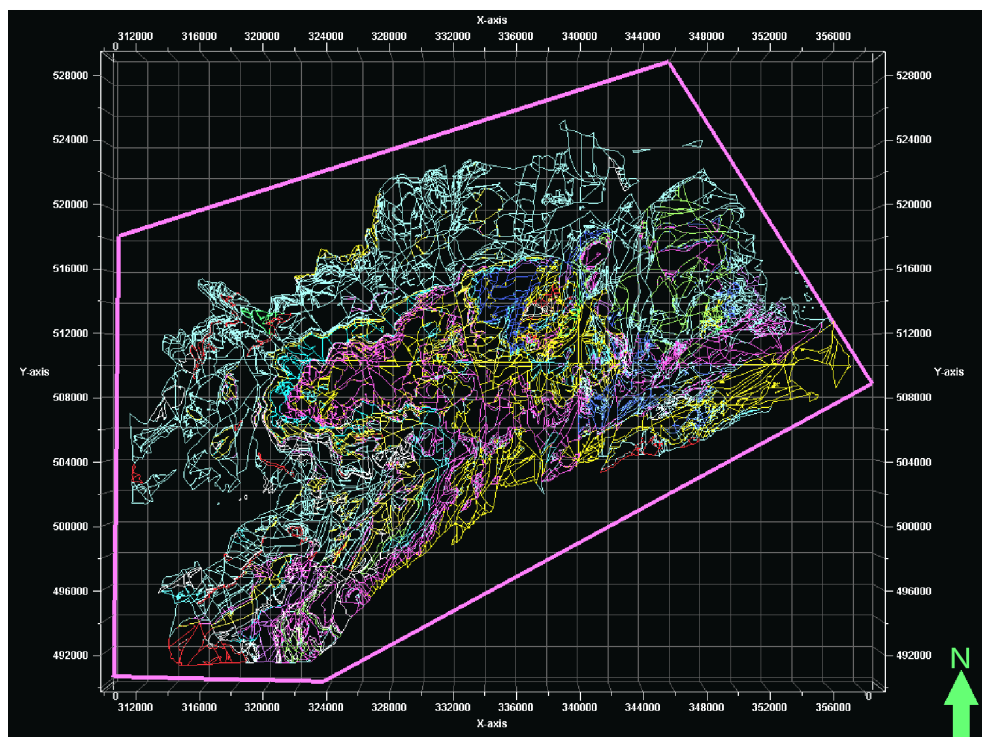
5.2.1 Description of Techniques

The model was built using regional scale faults as a structural framework. The fault data was provided by the BGS as part of their open access database. The data are in the form of polylines from the Edina DigiMap service (DiGMapGB-50). These are the 2D surface expressions of the faults in the region (Figure 5.1). Some manual data conditioning was required as some continuous fault traces were split into individual polygons in the dataset. This was done using existing geological maps; the major faults were identified and checked to ensure that they had not been split. The data needed filtering as modelling all the faults in the area was not possible due to the large number of faults and their complex interactions. An initial 5 km trace length cut off was applied to reduce the number of faults, but this was decreased to 3 km as many of the faults in the central fells region of the model were < 5 km in length and coverage became poor.

An existing 25 m resolution Digital Terrain Model (DTM), acquired using airborne lidar, was imported into the model and used as a surface over which to drape the fault traces. Draping the fault traces over the topography converted them into 3D objects and this allowed for the dip and azimuth of the fault to be estimated. This process was undertaken in VRGS. The data were imported from PetrelTM and then, using the same dip/azimuth tool as for the fracture surveys, the trace was picked along its length. The program then estimated a dip and azimuth of the fault trace using the moment of inertia analysis described in Section 4.3.1.3 using the method outlined in Fernández (2005). Where it was required (or where the dip was known from existing literature) the dip/azimuths were amended manually.



a)



b)

Figure 5.1: Fault trace a) and geology polygon b) datasets used as the framework for modelling.

The geology polygons represent the entire outcrop extent of the BVG in the Study area and are used as a guide when creating the model boundary (purple). The boundary must extend slightly past the modelling section to negate edge effects, and a simple morphology is desirable. Units are in OSGB Co-ordinates (metres).

Many of the faults in the region are steeply dipping normal faults, a relic of the volcanic faulting in the area (Branney and Kokelaar, 1994) and many were reactivated (Kokelaar et al., 2007) by later stresses. It should be noted that the network modelled here is a necessary simplification of the structural framework in the area, and does not take into account multiple fault strands, listric faults, faults below 3 km or blind thrusts not visible at the earth's surface.

Once the faults were interpreted, they were reimported back into PetrelTM as 3D polygons, which could be imported in as fault sticks. Manual processing was required to ensure the fault geometries were correct and to insert (where required) fault junctions, terminations and finally conversion into fault planes.

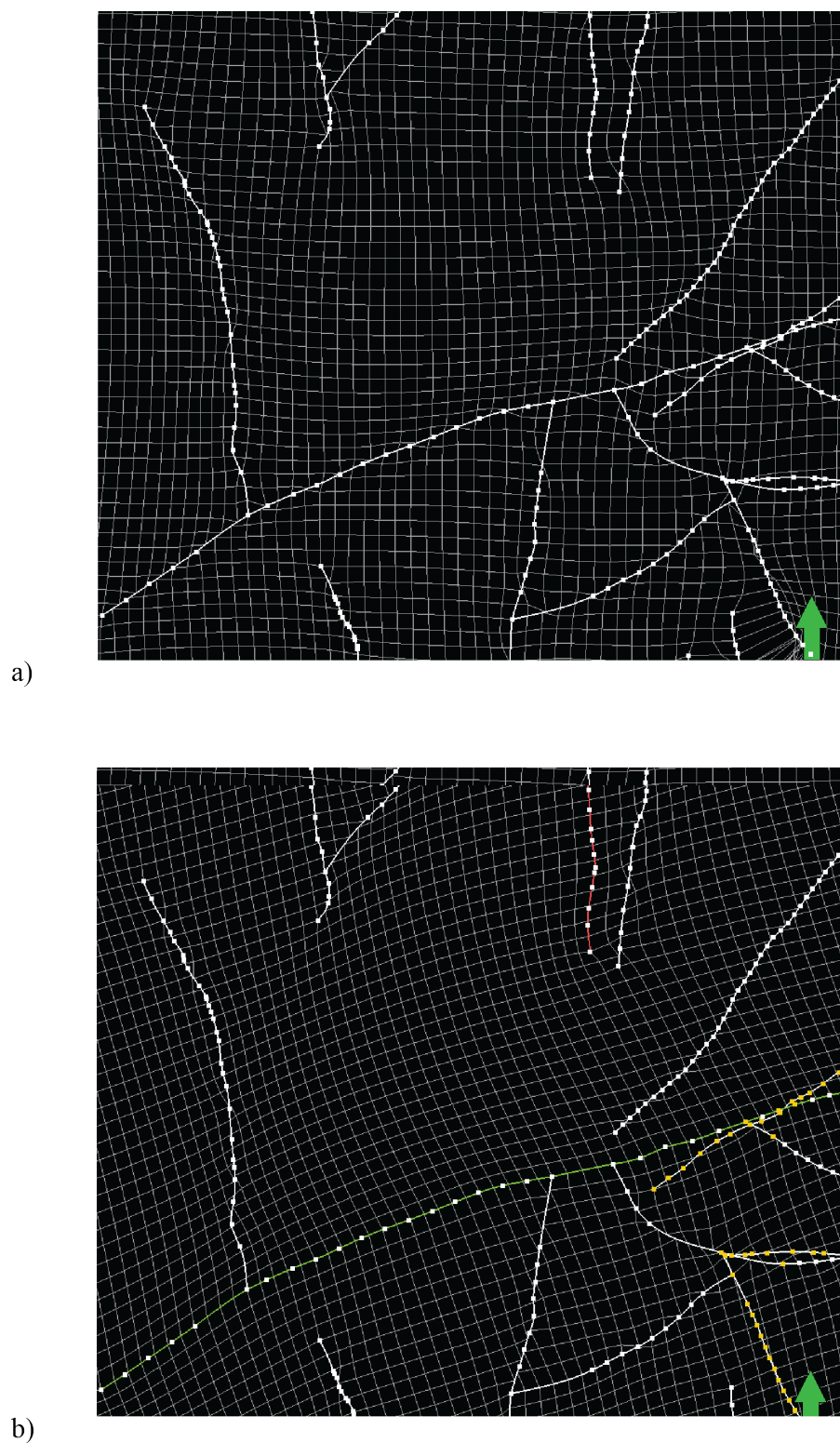


Figure 5.2: Rotation of modelling grid to reduce cell distortion. Grid a) is unrotated and along fault traces there is significant deformation. However when the grid is aligned to match two faults (shown in red and green in grid b) the distortion is reduced. It should be noted that due to inherent variation in fault orientation, there will still be some cell distortion (data provided by DiGMapGB-50, (2010) arrows point North).

These formed the skeleton around which the modelling grid was built. The cells within the model are hexahedral objects and are deformed in 3D to accommodate discontinuities within the host rock. Ideally, these grids were deformed as little as possible to preserve the model integrity. To help with this, the model grid was rotated to fit the general trend of faults within the data, in approximately perpendicular directions. This was achieved by choosing two faults in the X and Y direction that were representative of the general fault orientations in the area. In this grid, the two faults were roughly aligned to two faults that trended NNW - SSE and NNE - SSW, in line with the data (Figure 5.2). In a dataset with as many discontinuities as modelled here, this process could only reduce the amount of distortion in the model. It can not eliminate it entirely due to the natural variation in orientations across the dataset, and even along the trace lengths of the faults themselves.

5.2.2 Lithological Data and Horizon Creation

The BGS also provide data on the surface solid geology of the UK at 1:50 000 scale. This was again downloaded from Edina Digimap and converted from shapefiles to points using ArcGIS (ESRI Inc., 2010). The data can also be split by feature classes in ArcGIS. As one feature class is the BGS rock classification, this means each individual geological unit can be imported and visualised separately (Figure 5.1). The BGS also provide 1:50 000 solid geology maps with regional scale cross sections (British Geological Survey, 1982, 1991, 1996, 1999, 2004, 2007). These can be georeferenced and imported into PetrelTM as images and further interpretation. These two data sources were used in conjunction with the fault data to check the dips and azimuths of the faults, where they coincide. If a fault intersects a cross

section, then the estimated dip was checked to ensure it is broadly the same. Care has to be taken however, as many of the fault traces and subsurface contacts on the cross sections have been based on the section builder's interpretation and limited by modelling constraints, and not necessarily quantitative data. As the cross sections were created for each individual BGS map and some for the GB3D project (Mathers et al., 2014), they are not necessarily correlated to each other. This means they are not used as definitive data points, rather they are a guide. The fault planes were then extended or cut to uniform depths as a requirement of the modelling process. These were cut to 1000 m above Ordnance Datum (OD) and 1500 m below OD.

Using the publicly available data and digitised cross section data from the BGS, the subsurface geometries and contacts of the area were plotted. Whilst there are over 100 discrete rock units in the BVG, it was decided that it would be only possible to model three groupings of units. The interpolations and assumptions required to model at any higher resolution would be so great that the model would not be geologically valid. The rationale will be discussed in depth later in Section 5.3. To generate the modelling grid that forms the geocellular reservoir model, a modelling boundary is required. This should encompass all of the data with a small buffer as the model tends to break down towards the model edge. A simple geometry to the modelling boundary is also desirable. The modelling boundary defined for this study encompassed an area of 1,277.46 km², and with a modelling depth assumed to be 1.5 km (which is the potential maximum depth of the GDF), meaning that the model encompasses a total volume of 1,916 km³.

One data source that was expected to form an integral part of the project but did not was the existing Nirex raw datasets. It is known that these exist as many are

part of published data (Degnan et al., 2003; Gutmanis et al., 1998). The data that was used to compile the reports is part of what is referred to as Nirex's "grey literature" in Black and Barker (2016). The only Nirex data source that was used were the Bleng Valley report (Barnes et al., 2002) and any data that could be extracted from existing journal publications (as opposed to raw data). This problem is not limited to this project; it has been highlighted as a concern in the new geological screening process currently ongoing. It is a closed loop as the researcher may only be able to find the information if they know it exists, or who to ask for it. The Bleng Valley report was provided directly by one of the report authors as it could not be accessed via conventional means. This is something that needs to be addressed in future projects, as information vital for siting a GDF is unavailable.

5.2.3 Generation of Modelling Objects

It was decided that three modelling zones would be created. These were the "Granite", the "Lavas" and the "Explosives". These divisions represent the three broad styles of eruption present in the area and also the broad representation of the stratigraphic succession in the area. The BVG includes around 107 distinct units (see Millward, (2004b) for full descriptions). The geometries and properties of many of these are poorly understood and it would be impossible to model all of the units separately. One vital data source that could be used for subsurface correlation is borehole studies. These would allow the collection of lithological information and borehole geophysical surveys that could be used to populate areas of the model with little data. This data would at least allow generation of surfaces using a technique such as variogram analysis (Pyrcz and Deutsch, 2003).

Unfortunately, publicly available borehole data was not available at suitable depths to condition the model. The lack of this kind of data means that a more robust approach was needed to identify major horizons and use these as zone boundaries. It has been assumed that the rocks in each zone will behave in a rheologically similar manner as they are broadly the same type of rock. It is reasonable to assume the granites are homogeneous as they are part of the same igneous event (Millward, 2004a). The geometries of the Granite and Lava zones (that are mainly comprised of the Birker Fell Andesite formation and other contemporaneous units), are relatively simple to model as the contact between the granitic intrusion and the lava is simple. The granite was modelled as a simple intrusive body that deformed the Lavas and Explosives. The contact between the explosives and the lavas is reasonably well constrained. It can also be assumed that where the data is missing, the geometries can be inferred with some certainty as they are simply collapsed rotated blocks. Individual lava flows and eruptions have been simplified and assumed to be homogeneous within the unit. The contact between the lavas and the explosives will not be erosional as volcanic eruptions drape existing topography, and what erosion occurs is not on a significant scale (Sparks et al., 1997). Pyroclastic flows will remove loose material (e.g. talus or scree) but will only smooth and striate bedrock. Most of the complex contact created in the subsurface will be as a result of volcano-tectonic collapse (Branney and Kokelaar, 1994).

The same cannot be said for the contacts between explosive units. As detailed in Chapter 3, it is thought that the eruptive event was coupled with extensive volcano-tectonism and this has led an extremely complex stratigraphic relationship in the area. Whilst it is reasonable to assume that the lava flows covered a large

proportion of the area during their eruption, the same cannot be said of the explosive units. These are much more unpredictable and compartmentalised in nature. This being the case, it was decided to treat them as one unit.

5.2.4 Model Resolution

Once the structural element of the model was created, a pillar grid was developed. The X and Y dimensions of each cell within the model were set. These need to be able to represent an acceptable level of detail but also be coarse enough to allow the computer to visualise and generate horizons in an acceptable time frame. When building a model, it is also important that the horizontal and vertical resolutions of the model will accurately mirror any features within the model. The general rule used is that

$$\text{Horizontal/Vertical Resolution} = 0.5 * \text{Minimum Object width/height}$$

This ensures any features will be modelled as fully connected objects. Of course this is a major over-simplification. It is recognised that any robust modelling approach to GDF site selection will require a much more detailed understanding of the subsurface geology, and also have an appropriate quantity of data that can back up the modelling at a specific resolution.

For a model of 1500 km³ volume, a 10 m x 10 m grid would either crash Petrel™ or take too long to render. As the model was constructed with only three “homogeneous” modelling zones, the only limiting factor was the size of the fractures to be modelled. In turn these are determined by the computational limitations so this was considered to be the limiting factor for horizontal resolution. The vertical resolution was impossible to define, but in short it was not

possible to define horizons within the model with the quality and amount of data collected during this project.

5.2.5 Stochastic Modelling of Explosive Contacts

The ‘explosive’ section of the model represents emplacement during numerous large caldera-forming eruptions. There are thought to have been three (possibly four) main depocentres for the vents (Branney and Kokelaar, 1994). The fourth is the so-called Gosforth Basin and this was not considered as there is little concrete evidence to support its existence. The three that were considered in this model are the Scafell Caldera, the Helvellyn Basin and the Haweswater Caldera.

It was initially assumed that to mitigate against the lack of subsurface data in the area, it would be possible to model the explosive units using simple collapsed stratovolcanic geometries, where layer thickness decreases from the central “vent” (an approximate 2D representation of the that main vent of the volcano) and there is a collapsed portion in the centre created during caldera formation. Trend maps can be created to simulate the decreasing thickness of beds away from the vent.

When the cross sections were analysed, it was noted on the Keswick cross section (British Geological Survey, 1999) that the explosive units appeared to only show geometries observed in the collapsed sections of the caldera (Figure 5.4). It was also noted that there was a break in the explosive units laterally on the surface, with the older lava units outcropping, then the explosive units reappear as steeply dipping ($\sim 80^\circ$) beds. This is probably due to northward compression during the preceding tectonic events (Branney and Soper, 1988). The result is a broad, to very broad syncline and a tight anticline at the southern end. The whole area has undergone numerous glaciations and associated erosional events and this has

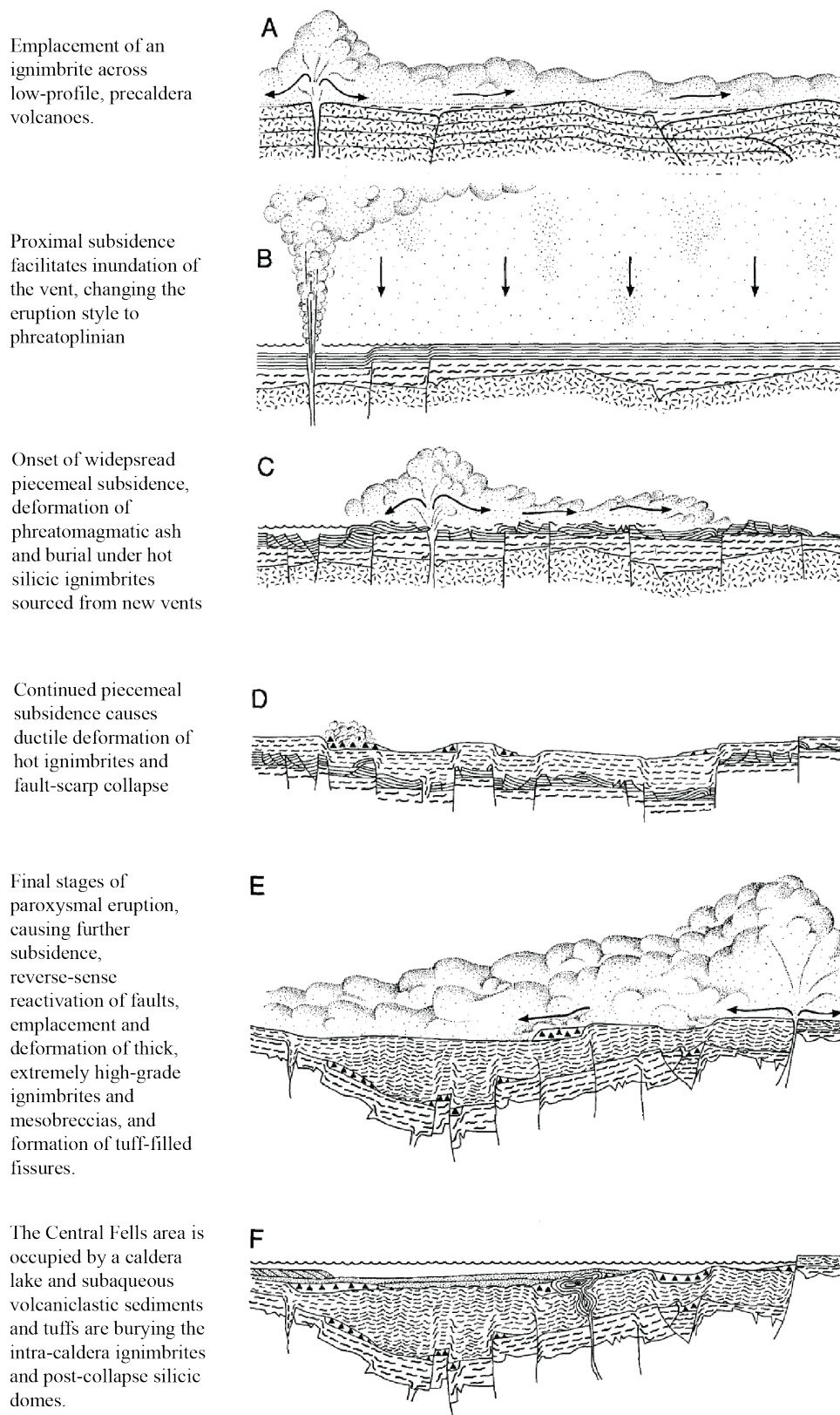


Figure 5.3: A schematic representation of the evolution of the central Fells caldera (Modified from Branney and Kokelaar, 1994). The processes that deposited the rocks are also surmised to be the reason for the high level of heterogeneity over such short lateral distances.

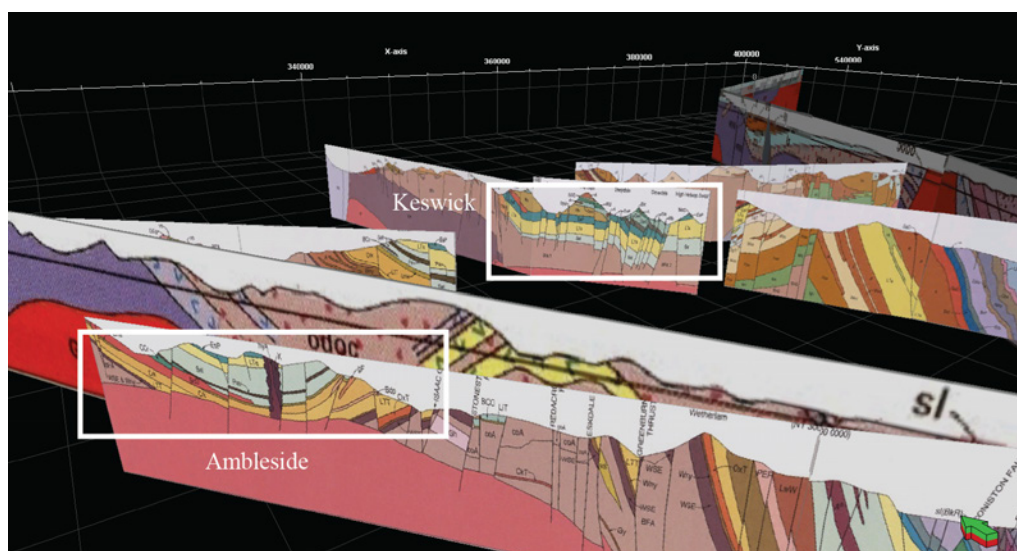


Figure 5.4: BGS cross sections highlighting the geometries of the explosive units within the models. The morphology of the contact between the explosive units (bright colours) and the underlying granite (pink) or Lower BVG Units (flesh colour) are not consistent between cross sections. Indeed, the bed thicknesses vary across faults without explanation. The distance between the Ambleside and Kewick cross sections at the highlighted intervals is around 14 km. Modified from British Geological Survey (1999). (Units are in OSGB Coordinates).

removed much of the overburden, explaining the appearance of the younger lavas here.

This meant that we could not model the volcano as first envisaged. It is relatively simple to model the Scafell depocentre as they have been interpreted as sub-horizontal beds that have a relatively uniform thickness, as seen in the Ambleside cross section (Figure 5.4). More difficult, are the high angle bedding to the south as these have a steep dips, something which PetrelTM does not model correctly.

Further to this, Branney and Kokelaar (1994) suggested that the caldera collapsed in a piecemeal fashion with numerous vents releasing material. This would further reduce the accuracy of this modelling approach, as there would be no simple

central vent trend to model, but rather a chain of vents. The position of these vents are made even more difficult to constrain, as there is a great deal of conjecture as to where they were actually located as many have not been preserved, except a few features which are infilled ignimbrite “dykes” which have been hypothesised to be vents that have filled with ejecta.

The level of deformation in the area, coupled with the extraordinarily high level of uncertainty in the degree of rotation that occurred during these piecemeal eruptions, complicates the matter even further, raising uncertainty in the geometries of any contact in the subsurface.

This meant that without further detailed subsurface investigations, it was not possible to introduce any meaningful complexity into the explosive unit when modelling. Any further zoning or subdivision of the unit, would only be superficial and not representative of any real variations within the layers.

The lateral distance between hard conditioning datasets that could be used to condition the modelling approaches is large enough to mean that correlation between them is impossible, given the laterally discontinuous nature of the rocks. There is 14 km separation between the Ambleside and Keswick sections alone, across the most complex section of the region (caldera). This means that it was impossible to constrain any vertical parameters in the model to any meaningful level of certainty.

5.3 Discussion

5.3.1 Model Uncertainty

Although a viable model was unable to be generated, it is worth discussing where uncertainty was generated in the existing data and where it would be generated in a future model. All modelling, due to its very nature, contains uncertainty and understanding and attempting to quantify this is vital. For this project, uncertainties can be classified as lidar, lithological and structural.

5.3.1.1 Lidar Uncertainty

The generation of DOMs also generates uncertainty within the modelling process. These uncertainties are addressed in Wilson et al. (2009b) and Fabuel-Perez et al (2010). Errors in alignment and positioning of the lidar unit (and therefore the rest of the scan data) can propagate through the data interpretation process. The error for each point is considered to be negligible, and the positional error for each scan location is reduced by scanning at multiple positions and utilising differential GPS to reduce the error to a point where it can be considered negligible.

Uncertainties (specifically ones associated with the lidar unit used in this project) are discussed in Buckley et al., (2008) and are further summarised in Table 5.1 . If the errors associated with each step are not minimised, they can soon accumulate to the point where they will have a large impact on the dataset. In this project, great care was taken to ensure that at each stage the errors (and therefore uncertainties) were kept to a minimum, meaning that uncertainty in any lidar measurements can also be considered to be negligible.

In terms of the uncertainty generated by the fractures, it is important that we differentiate the uncertainty in identifying and picking fractures from the lidar and

Item	Frequency	Error Budget	Significance for Geology Results	Dependence
<i>Lidar Scanner</i>				
Internal lidar calibration	Once	mm - cm	Very Low	Manufacturer calibration
Instrument Precision	Each system model	cm - dm	Low	Instrument Specification
Beam divergence overlap	All measurements	cm - dm	Low	Closed resolution: range
Target material	All measurements	cm - m	High for darker materials	Reflectivity of material: range
Obliquity of laser	Each scan	cm - dm	Moderate in overlapping scans	Scanner position: outcrop topography
Range shadows	Each scan	m	High if data interpolated	Scanner position
<i>Camera</i>				
Calibration	Irregular update	cm - dm	High for geology interpretation	Camera calibration validity
Camera mounting	Each camera mounting	cm - dm	Affects image or scan integration	Mounting calibration
Extra image registration	Each image	cm - m	High: essential to check	Choice of tie-points
<i>Processing</i>				
Scan registration	Project	cm - m	High: essential to check	Choice of tie-points or success of surface matching
GPS position	Project	cm - dm - m	High if absolute coordinates required	GPS equipment used; obstructions, etc.
Point cloud editing	Each scan	cm - m	High if incorrect points removed	User
Point cloud decimation	Project	dm - m	Potentially high	Choice of algorithm and parameters
Triangulation	Project	dm - m	Generally low	Meshing algorithm; user editing
Texture mapping	Project	cm -m	Potentially high	All input data; mesh quality; image quality; camera calibration; image registration
<i>Interpretation</i>				
Quality of interpretation	All objects	cm - dm	Low	Outcrop quality; geology understanding; digital outcrop quality

Table 5.1: Uncertainty associated with lidar scanning. (Modified from Buckley et al., 2008)

also the actual geostatistics associated with the fractures (orientation, length, etc.). The high resolution of the dataset (~ 2.5 cm) coupled with the coloured point cloud data that allows visual identification or confirmation of fractures means that the errors associated were very small, especially when the size of the fractures picked is taken into account (~ 1 m). The uncertainty associated with the geostatistics will be discussed later as part of the structural uncertainty.

5.3.1.2 Lithological Uncertainty

The lithological uncertainty was the primary source of uncertainty in the model, and ultimately led to the failure of the static modelling approach attempted here.

It was envisaged that it would be possible to generate a geological model from digital outcrop, existing geological map and inferred cross sectional data.

However, there was little quantitative subsurface control data available as it was not possible to obtain detailed borehole information at the depths required. These limitations in the datasets meant that the level of uncertainty in any model generated with the data available would be geologically invalid and not worth pursuing.

It was not possible to create as detailed a 3D geological regional model as hoped for. For completeness, it is worth considering the sources of uncertainty if the model received enough data to be valid and the modelling approach continued.

The BVG was emplaced during a chaotic geological setting, with the lithologies undergoing significant tectonic deformation and rotation caused by the massive caldera forming eruptions. Most BVG units are not laterally continuous and often abut, pinch out or are absent across faults. Along the Lake District Boundary Fault (LBDF) displacements have been estimated to be four kilometre scale

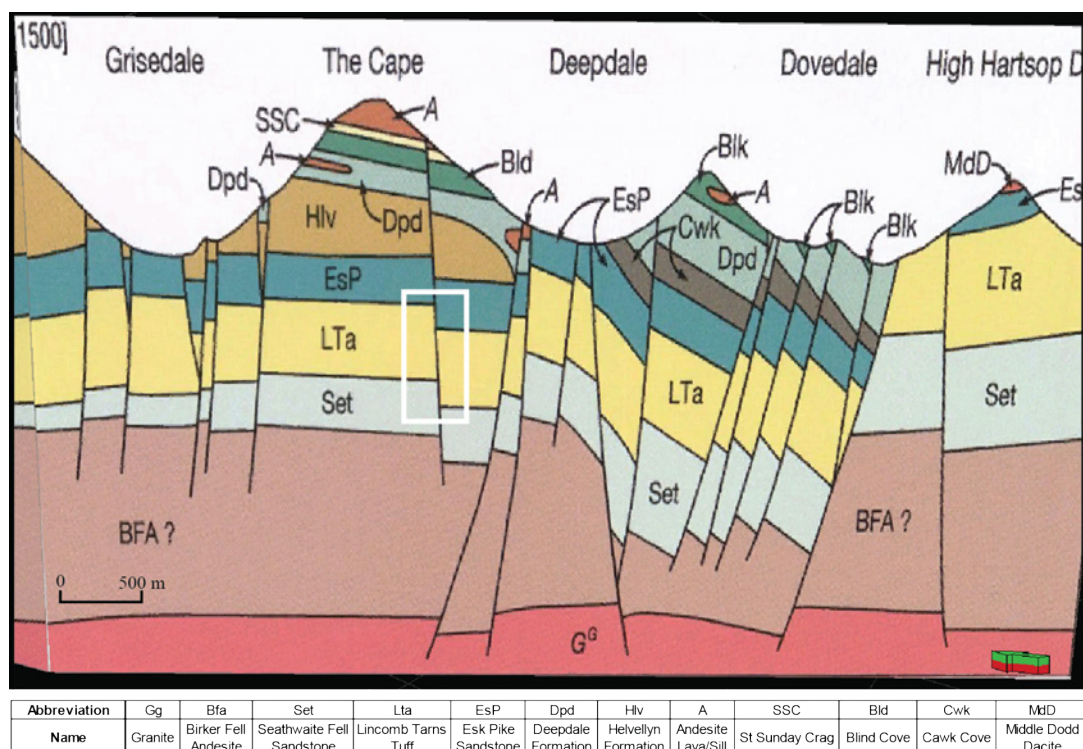


Figure 5.5: The portion of the Kewick cross section highlighted is an example of bed thickness not correlating across faults. There is ~10 m difference in bed thickness in the Lincomb Tarns Tuff (LTa) formation across the steep vertical fault. (Vertical exaggeration = 3 x's, modified from British Geological Survey, (1999), green arrow points north)

(Barnes et al., 2002) meaning correlation of units is impossible as they do not appear on both sides of the fault. This is thought to be representative across the area.

The cross sections in the region were useful but the separation between each section was usually around 10 km. A short analysis was performed on fault throws on the cross sections. This revealed a difference in bed thickness across fault traces (Figure 5.5). There are two explanations for this. The first is that they are growth faults which are syndepositional to tectonic activity during sediment emplacement. However this produces a distinct morphology in the beds that is not present in the BGS cross sections. The beds appear to be different thicknesses on either side of the fault, yet they are drawn as tabular with no soft sediment deformation.

The second (and most likely) explanation, is that beds have been drawn to accommodate the units within the sections and also to ensure that they correlate to other sections in the GB3D model. Although this may not be a problem on the scale of this modelling project, it shows that care must be taken when looking at smaller detailed models as the existing data. Whilst a useful overview tool, it requires more detailed, high resolution surveys to be carried out.

These are the only subsurface constraints in the model. They are vital, but there is little distinction between what parts of these sections are interpreted data (such as gravity or magnetic surveys) and which are inferred due to a lack of data or modelling constraints. The data provided by the BGS goes some way to reduce the level of uncertainty as they compiled the model as part of the GB3D initiative which will form part of the National Geologic Screening programme, the first stage in the revamped GDF investigation process. This still does not hide the fact that there is very little actual subsurface data available for the region. Borehole data is limited to the West of Cumbria (mainly Sellafield) and deep drilling is non-existent in the central fells, due to National Park restrictions and the lack of interest in the area. Outside of the limited Nirex RCF investigations analysed, borehole data was not available. This was especially true for the central fells, where the added complexity of the units formed by the explosive eruptions and associated collapses, made it extremely difficult to constrain the subsurface contacts.

The information utilised in this study is only a best guess approximation to the geometric behaviour below the surface. In order to try and ascertain the depth to the top of the granite batholith which underlies the Lake District, contour maps produced from gravity surveys (as part of Bott (1974) and Lee (1986)) were imported and the contours digitised in the model.

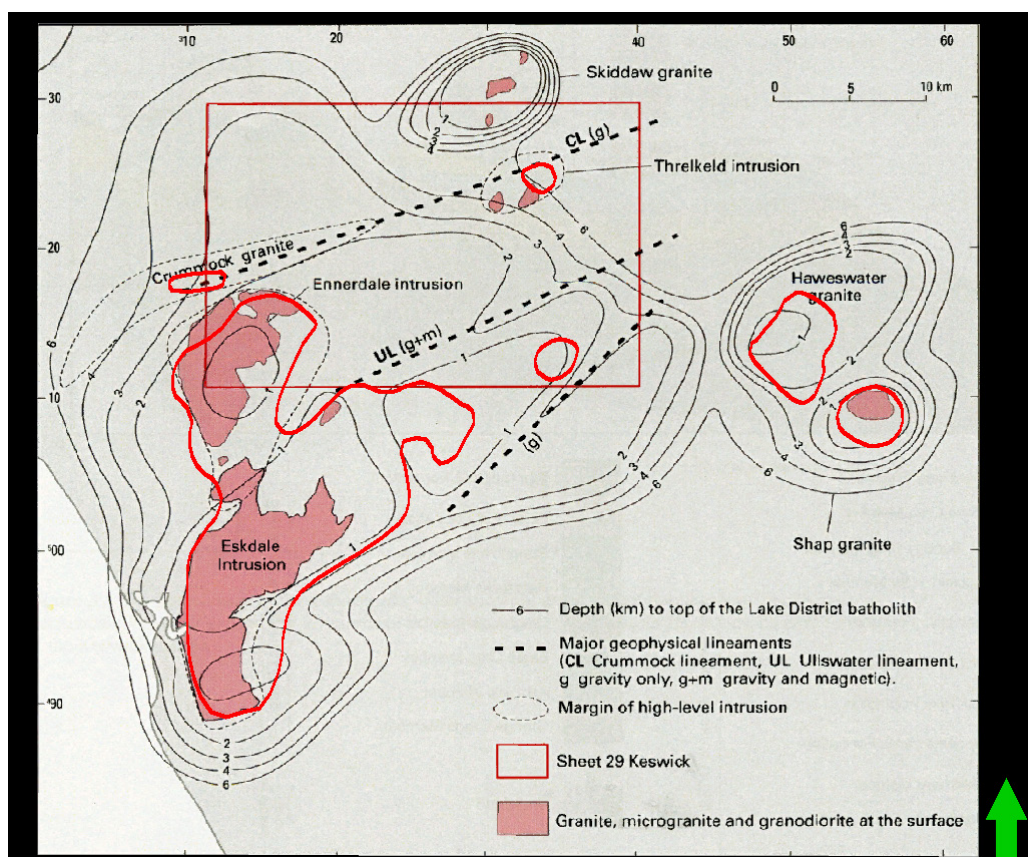


Figure 5.6: Map view comparison between Gravity surveys. Bott (1974) is represented by digitised red lines and Lee (1986) is the base map. The base map and digitised lines show the predicted contours at 1 km (or potential repository) depth. The disparity between not only the depth but also the morphology of the edge of the granitic intrusion is significant, especially in the Haweswater area where there is roughly twice as much granite surface area in the 1974 interpretation.

These provided contrasting, and markedly different interpretations of the subsurface. Both gravity surveys did not match with the later cross sections (i.e. the sections taken from the geological memoirs) and further cross sectional data provided by the BGS. The gravity surveys had been reinterpreted at least three times (Bott (1974), Lee (1986) and the BGS most recently in 2010), to produce the new 1:50,000 regional scale maps.

This was the greatest source of uncertainty within the model. The interpretations could differ by 100's of metres in 3 dimensions (Figure 5.6) and this changes the subsurface contacts dramatically. This is especially true of geophysical data.

Seismic surveys, aeromagnetic surveys and gravity surveys can often produce many valid models that represent different subsurface geometries, the only difference being the variation in the geophysicist's interpretation (e.g. depth conversion (Bickel, 1990)). Although this kind of error was not part of this project due to the lack of quantitative subsurface data, it is important that any future study recognises the potential impact of this.

5.3.1.3 Structural Uncertainty

Outcrop data are known to be limited by sensoring effects and there is also little to no information on fracture length and aperture. This has been discussed in Chapter 2 in more detail.

Modelling the fractures introduced a further uncertainty in the structural modelling. The modelling scale of the fractures is in between the lidar/SFM data collected (outcrop scale) and the BGS fault data (regional). Using different power law distributions to predict fracture properties, is a robust way of achieving this but is still a non-deterministic way of estimating the fracture patterns.

True fracture length is obscured by the fracture's intersection with the outcrop plane. This leads to an under-estimation of the fracture length which needs to be corrected for (Agosta et al., 2010).

As mentioned fault throws can be kilometre scale and correlation of beds across the faults is virtually impossible. Estimating the dip and extent of the faults is simpler. There are two ways to obtain this information at two scales. As with fractures,

their faults, dips and their throw can be estimated at outcrop level either manually or using digital methods. This will only be true for metre to hundred metre scale features. For larger scale (hundred metre to above kilometre scale) the fault throw can only be determined by looking at regional scale data, either geological mapping or geophysical surveys. For the faults in the geocellular model the surface expression of the faults was determined using the same method as was used for fracture picking in VRGS as described in Chapter 4. This is a good estimate of the fault dip and azimuth, but is still only an average as the faults will often not have a linear surface expression. As the structural framework method has been used in PetrelTM, the faults form an integral part of the model. Faults in these models can often be expressed as vertical features to eliminate modelling complexity, however this is not a suitable compromise for a complex, high-resolution model.

Deterministic fracture network generation from outcrop data and its limitations is covered in Seers and Hodgetts (2016). It outlines a quantitative method to determine the robustness of outcrop derived fracture statistics. It utilises eigen analysis to determine the reliability of trace orientation. It was found that 58%, 67% and 73% of the traces may be placed at 95% confidence levels of approximately 10°, 15° and 20° respectively. The study utilised data that was collected as part of fracture analysis in this project. It highlights the care that must be taken when using outcrop derived geostatistic datasets from outcrop.

5.3.2 Multiple Realisations

To address the problem of the major uncertainties in the model, it is envisaged that multiple realisations of a model would be created to provide a suite of models to see which best represents reality. In practise this will comprise of at least three

model DFNs. This can be varied to produce different flow regimes. As well as this, a “most likely situation” can be modelled along with a range of “least likely models” to generate a suite of models to represent different scenarios.

It is envisaged that units and fracture networks are generated stochastically; using a different seed number will allow many different realisations to be generated and modelled as different cases. Using the inbuilt workflow tools, these different realisations can be generated quickly and upscaled for modelling.

There will be no “definitive” model of the geology in an area. It will be the most realistic model of geology in the area given the data utilised. This will hold true for any future models, including the ones generated for the GDF site selection process.

5.4 Initial Findings

The scarcity of data, coupled with the complexity of the structural and lithological framework means that creating the model was not be possible. It would not yield any useful data as any of the geometries within the model (horizons or zones) would be based on speculation as opposed to hard data. The uncertainty was so great that it was decided that it was not feasible to continue. The techniques that were to be used to generate the final stages of the model are well-established and there would be little value in continuing the process as it is unlikely to raise any new or novel insights into the modelling process.

5.5 Smaller Modelling Approach

It was realised that the generation of smaller models that are specific to a locality surveyed is a more achievable outcome. There is only one rock type at each of

Rydal, Hardknott and Bramcrag and two at Honister and the size of the models would negate the need to scale the fracture statistics. It was decided that as the Hardknott Pass locality had a full complement of fracture data that was required to generate a DFN, it would be modelled. This does mean, however, that whilst fluid flow models specific to a locality can be created, the lack of regional information pertinent to the higher strength geological setting and also to a rock mass of the volume required for a GDF, those fluid flow models could not be upscaled into a GDF or geological setting-scale model that might be suitable for input into any GDF siting programme.

5.6 Discrete Fracture Network Generation

A simplified lithological and structural model could be generated for each locality. Once this is complete, Discrete Fracture Networks (DFNs) (Dershowitz and Einstein, 1988) could be generated. This is a stochastic process that allows generation of multiple fractures within the modelling zones created, in this case: one. Certain key parameters are required to generate the DFNs.

- Whether P31, P32 or P33 will be calculated
- Fracture Length parameters including the length distribution required for prediction and modelling
- Orientation information: mean dip, mean dip azimuth and concentration, which is used as part of the calculation of variation from the means by calculating the Fisher distribution (Fisher, 1953; Priest, 1993)
- Aperture data: mean and standard deviation will be taken from previous work as no data is available from outcrops

A new set is created for each one that is identified during cluster analysis in Chapter 4. The upscaling process, which was not performed for this project, is the step required to transform the static model into a lower resolution model suitable for dynamic simulation in ECLIPSE or a similar program. The lower resolution allows the simulation to be performed faster, due to the reduced computational load.

5.6.1 Results

A small, outcrop-scale DFN was generated for the Hardknott Pass locality to demonstrate how the digital datasets can be combined to produce a robust, modern approach to fracture modelling. The lidar data provided the orientation information (dip, azimuth and concentration) and the photogrammetric data provided the P32 intensity measurement information and also the mean fracture trace length and the standard deviation. The lidar scan data acquired also formed the basis for the rough outline of the model. A simple polygon was drawn around the 2D perimeter of the data after import into PetrelTM. As there is only one rock type in the locality and no faults, a simple model was produced. The corner point griddling approach described previously was not viable as there are no faults with which to generate the structural framework. Three fracture networks were then created which correspond to the sets identified in Chapter 4. The data used to populate the modelling parameters is described in Table 5.2. To scale the fracture trace length and populate the model, a logarithmic distribution was assumed and a Fisher distribution was assumed for the fracture orientation variability. PetrelTM only has a relatively simplistic DFN modelling approach compared to, other programmes such as FracMan. It was decided due to time constraints to model the

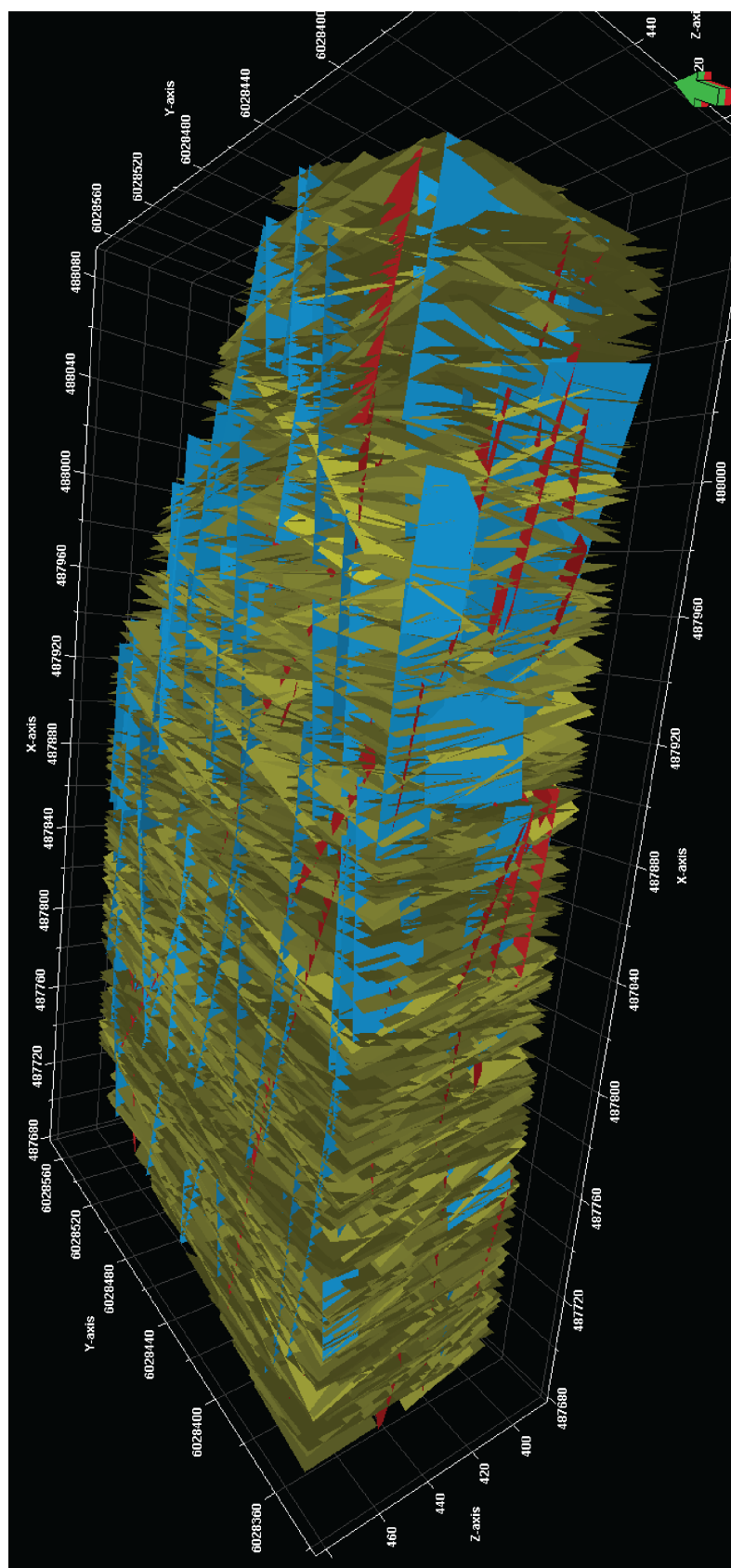


Figure 5.7: The combined DFN generated for the Hardknott locality. The fracture networks are show visualised as a composite model including the bedding joint sets (red) East-West (blue) and North-South (gold). (Co-ordinates are in OSGB, metres)

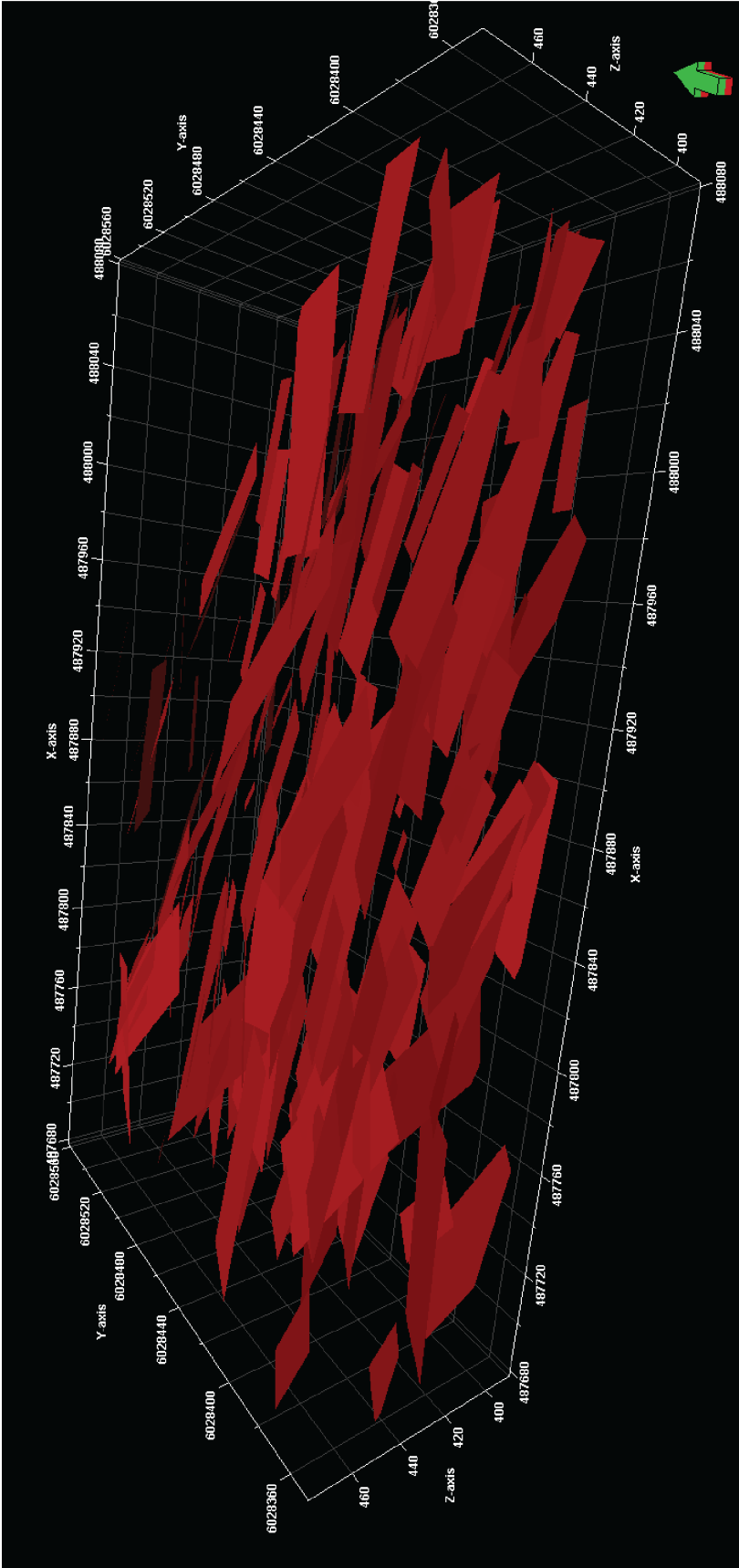


Figure 5.8: The Bedding joint DFN generated for the Hardknott locality. (Co-ordinates are in OSGB, metres)

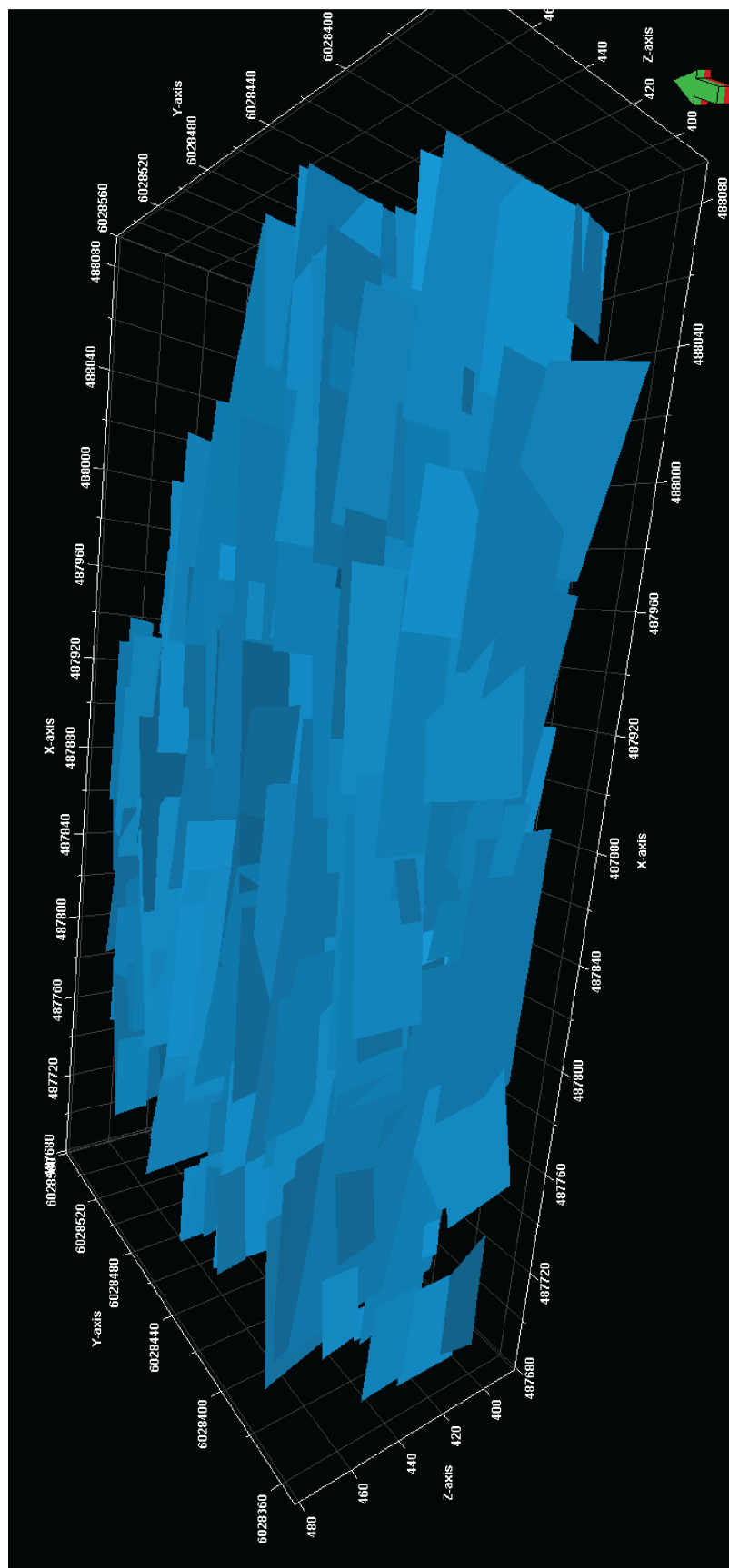


Figure 5.9: The East - West DFN generated for the Hardknott locality. (Co-ordinates are in OSGB, metres)

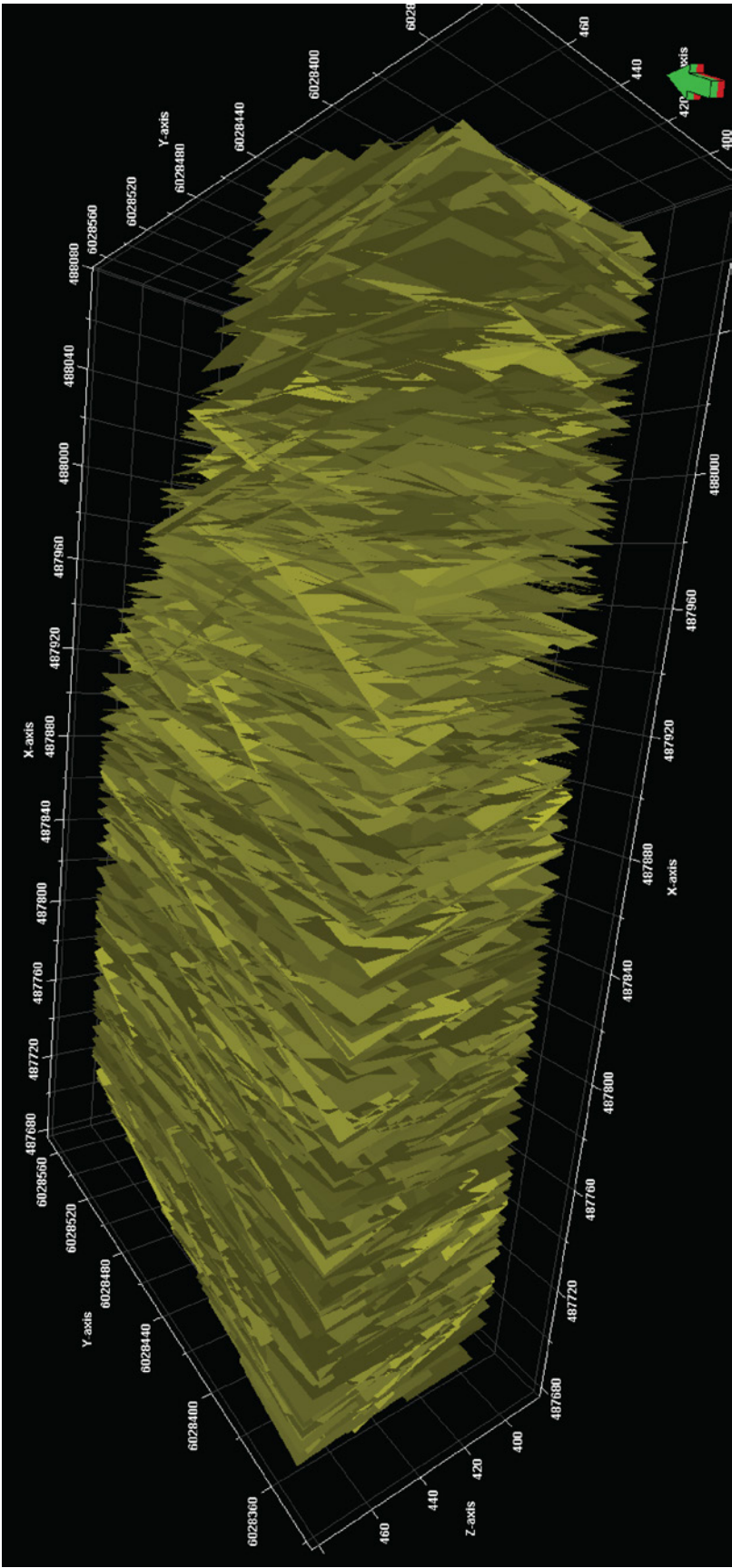


Figure 5.10: The North - South DFN generated for the Hardknott locality. (Co-ordinates are in OSGB, metres)

DFN in PetrelTM as the benefits of the outputs of a more complex approach was outweighed by the time saved working in PetrelTM. The fracture networks generated are shown in Figures 5.7, 5.8, 5.9 and 5.10.

		Bedding	East - West	North - South
P32		1.42	1.07	1.38
Length	Mean	0.84804	1.0262	0.85072
	St. Dev	0.58586	0.93212	0.61129
	Maximum	10	10	10
Orientation	Mean Dip	26.915	82.787	84.395
	Mean Azimuth	15.565	93.338	358.386
	Concentration	59	18.65	37

Table 5.2: DFN input parameters.

5.7 Evaluation of Methodology and Software

It became clear as the project progressed that the idealised modelling workflow would not be able to generate a usable 3D model for simulation. The workflow itself was not flawed from the onset, rather a fatal combination of a lack of subsurface conditioning data and unacceptably high uncertainty meant that it was not possible to generate a final model that could be used to simulate fluid flow and provide meaningful flow data. This is summarised in Figure 5.11. It was possible to generate a low resolution, three zone model with associated DFN's, however it was decided that any flow data derived from this would be meaningless on such a coarse scale. The subsurface borehole data was not available over the course of the project, and was confined to a small region of the study area (i.e. the Sellafield site and the PRZ).

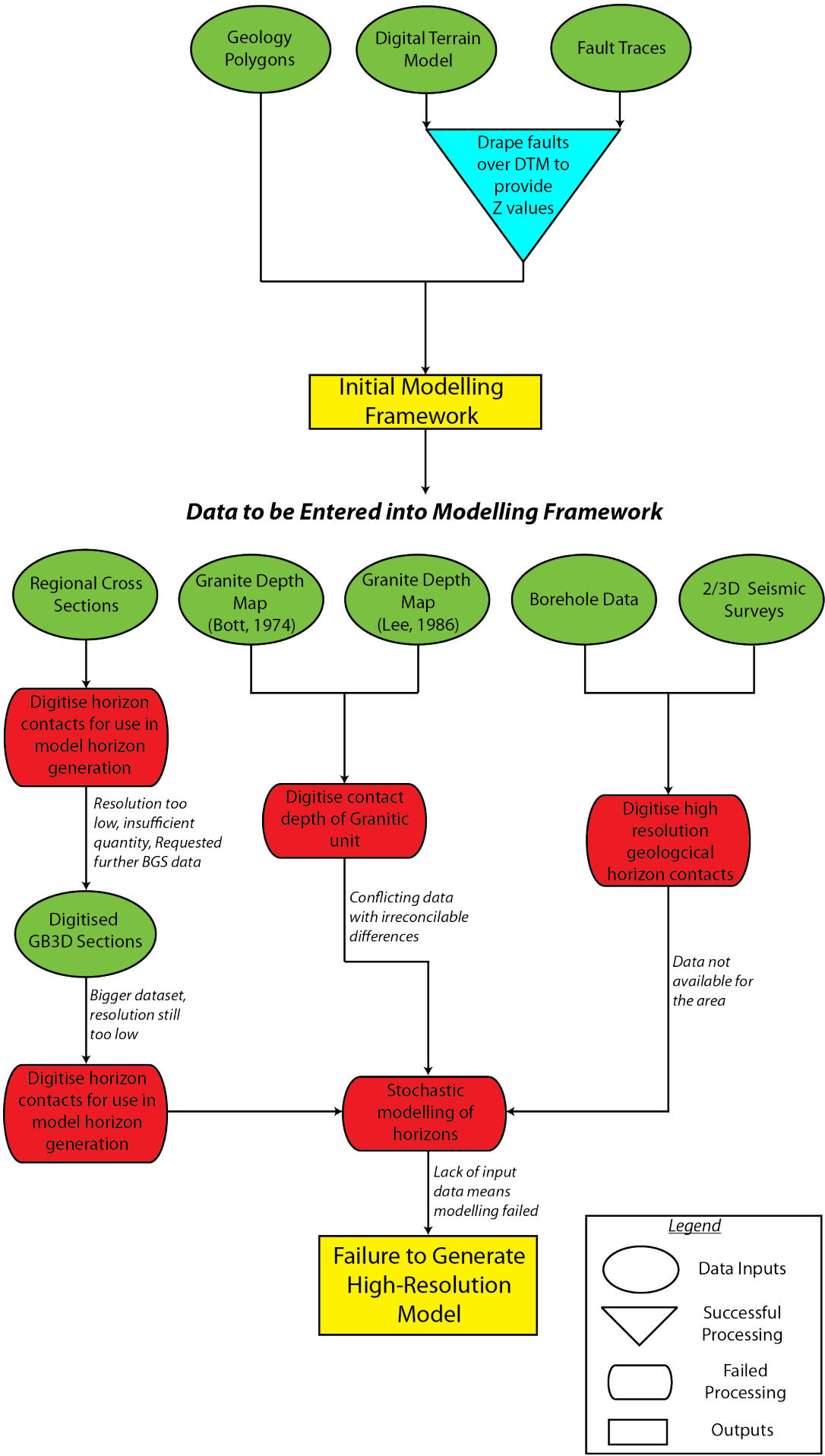


Figure 5.11: Summary of static modelling workflow and issues. This is an evaluation of the idealised workflow that was envisaged at the beginning of the project and where it worked or fell down. A modelling framework was able to be built using the fault polygons and a coarse grid generated for use in horizon generation. However the spacing and resolution of the datasets (not to mention the complete absence of any deterministic subsurface controls) means that the model could not be completed to a satisfactory standard.

In terms of the software performance, PetrelTM is a reservoir simulation program, developed for modelling simple, sedimentary settings. It is not designed to handle complex structural settings such as the BVG (see Chapter 2). The number of faults in the study area and the complex subsurface geometries, coupled with the lack of subsurface control data meant that it was not possible to achieve the initial aim of creating a model suitable for upscaling and, eventually flow simulation, using PetrelTM. One of the major limiting factors is that the software relies heavily on the premise that anyone using it will be following standard hydrocarbon modelling workflows (what the programme is specifically designed for). Simply, this would involve a seismic reflection survey of some kind, multiple wells to provide borehole data (such as sonic and gamma logs and core analysis) and other complementary data (e.g. magnetic or gravity surveys for onshore plays). These often provide a robust and well constrained set of subsurface parameters, in the form of picked stratigraphic horizons and fault sticks. This drastically reduces the uncertainty in the subsurface which allows more flexibility with regards to the extent to which stochastic methods can be implemented.

These robust initial datasets were not present in this survey. This means that the uncertainty in the subsurface was so high that it would not be possible to generate any meaningful subsurface contacts. The level of heterogeneity over such relatively

small differences would require a much higher resolution modelling approach to allow differentiation between the units.

Fundamentally, the software is limited by the pillar gridding approach utilised by the software. No horizon geometry can properly be modelled if it dips past around 30°. This is probably due, in part, to the fact that seismic data, especially 2D seismic data does not image steeply dipping reflectors particularly well (Marfurt and Alves, 2015). This is often not a problem in hydrocarbon exploration as these steep reflectors are not present or do not require modelling. In a region that has undergone such a complex tectonic history, not only would the static modelling be a long, drawn-out process, but to accurately flow simulate an area this size, whilst still retaining the necessary model resolution, would require either an exceptionally powerful computer, and/or an exceptionally long processing time frame.

PetrelTM would be suitable for use if another preferred geological setting was to be investigated, such as an evaporitic or low strength sedimentary rock setting, or even a high strength unit where the geometries of the beds are uniform and relatively tabular. When modelling the Granitic and Lava units within this study, the modelling performed reasonably well as these have relatively uniform shapes. It should be noted that the lava units especially were simplified amalgamations of units and these were modelled at a coarse resolution with many of the faults in the region removed.

In PetrelTM 2013, the structural framework modelling utility was introduced to allow more complex geometries and fault networks to be modelled. This would seem to address issues raised in this project. The process for creating such models is simple. First, a faulted 3D mesh is created from a fully-bounded representation of the fault network. A temporal volume attribute representing the lithologies in

the area is interpolated on this mesh. Once this calculation is completed, iso-surfaces of the attribute which correspond to the location of the original input data points are extracted as horizons in the structural framework and a zone model is computed. This yields a volume representation of geological layers. This approach, although appearing to be perfectly suited to address the issues highlighted by pillar gridding, are limited by the quality of the input data once again. Whilst it would be possible to estimate the geometries of the faults in the region using their surface expressions, it would be impossible to accurately estimate the temporal volume attribute. There is simply not enough data. The suitability of Petrel™ is therefore difficult to assess. It is an excellent modelling tool, when the geometries are simple and even a small amount of seismic data and few boreholes would allow generation of a reliable model for flow simulation. Where the geometries are complex, as is the case in this project, the software limitations when dealing with complex geometries become apparent. This is not to say that the structural framework approach would not solve these issues, rather there was insufficient data to test this approach. Even so, it would be extremely challenging to model a potential host rock that was similar to the one used in this project in Petrel™.

5.7.1 Alternative Programs

Alternative programs are widely available. These include, but are not limited to, the follow list (company name in italics):

5.7.1.1 AutoCAD: *Autodesk*

AutoCAD is a generic 3D modelling software programme that can be used to create simple geologic models. It is good for modelling simple sedimentary settings but it is not a geology specific application and such has no specialist tools such as stochastic channel modelling or DFN generation.

Website: <http://www.autodesk.co.uk/products/autocad/overview>

5.7.1.2 GSI 3D: *INSIGHT*

GSI 3D uses DEM data, surface geologic expressions and borehole data to allow the creation of cross sections that can be correlated to form a 3D model. It relies more on ‘correlation by intuition’ rather than the mathematical approaches used in other software. This allows the geologist more control over the geometries in the subsurface, however would struggle in areas with limited borehole and subsurface data.

Website: <http://subsurfaceviewer.com/ssv/index.php?id=3>

5.7.1.3 Roxar RMS: *Emerson Process Management*

Roxar is a full suite of reservoir management tools, from geophysics through to depletion planning.

Website:

<http://www2.emersonprocess.com/en-US/brands/roxar/reservoirmanagement/software-releases/Pages/RMS%20Releases.aspx>

5.7.1.4 Move: *Midland Valley*

Move is the core module that allows complex 3D modelling to be performed. It allows a greater range of modelling approaches, including; 2D and 3D Kinematic

Modelling, Geomechanical Modelling, Fracture Modelling, Fault Response Modelling, as well as Fault Analysis and Stress Analysis.

Website: <http://www.mve.com/software/move>

5.7.1.5 RockWorks: *RockWare*

RockWorks allows visualisation and modelling of spatial data for a wide range of disciplines. It reads existing data and allows model visualisation, volumetric reporting, mine planning and borehole management. It does not allow generation of subsurface parameters, rather it is an analysis tool.

Website: <https://www.rockware.com/product/overview.php?id=165>

5.7.1.6 Genesis: *SGS Geostat*

Genesis is a mining-orientated software package that allows subsurface modelling. It has extensive meshing, 2/3D, section creation and drill hole planning tools.

Website: <http://www.geostat.com/genesis/en/index.php>

5.7.1.7 SKUA: *Paradigm*

SKUA is a reservoir modelling package that places more emphasis on reducing the amount of simplification needed to model a reservoir. It also allows 3D kinematic restoration of the reservoirs. Modules are available to allow full life cycle analysis of any potential reservoir.

Website: <http://www.pdgm.com/solutions/>

5.7.1.8 Vulcan: *Maptek*

Vulcan is package with mining-specific features such as mine planning and design, blast planning and production planning, alongside handling geological, geophysical

and well/borehole datasets. It also allows geostatistical analysis and creation of 3D block models in grid format.

Website: <http://www.maptek.com/products/vulcan>

5.8 Conclusions

In this project, there was no way to reduce the lithological uncertainty to produce a model that represents individual units within the model, or even how to differentiate the units in large temporal groups as defined in Millward (2004b). A solution to this problem is the grouping of the lithologies into three, highly simplified modelling units, which will generate a more realistic set of modelling parameters, to accurately reflect groundwater behaviour during modelling. Whilst this removes detail required for a high resolution model, it increases the confidence in the unit geometries modelled. Most of the variation that causes the uncertainty can be removed by lowering the resolution.

Most of the fractures sampled here seem to reflect regional patterns and should be modelled at a scale in excess of 50 m (depending on the total size of the model). However, if we assume a similar sized model to the one in this project (1,916 km³), then the lithological detail would not be required to make a workable model. This is not a best practise solution, but rather an acceptable workaround to produce a coarse-scale model to validate the approach.

Once work has progressed to a specific site, a more detailed approach will be required to characterise the geology there. Depending on site location, accessibility and topography this would ideally include borehole analyses (core logging, downhole geophysics), seismic reflection analysis and detailed outcrop or outcrop

analogue studies to provide as much information as possible to reduce modelling uncertainty.

However, it was possible to generate a smaller, outcrop sized model, and populate this with three fracture sets using the digital data derived in Chapter 4. Building a model on this scale in PetrelTM was accomplished within a day. This shows some potential for building some repository-sized flow models within PetrelTM, depending on their complexity.

**Chapter 6: Effective Communication
of Complex Geology for Radioactive
Waste Disposal**

Chapter 6

Effective Communication of Complex Geology for Radioactive Waste Disposal.

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Abstract Understanding subsurface geology is a key frontier in geoscientific research, and the understanding of this remote realm is important for as diverse a set of activities as radioactive waste disposal, unconventional energy resource extraction (e.g. shale gas or geothermal energy), and carbon capture and storage. An ever-increasing body of technical knowledge is providing a firm scientific basis on which the long-term performance and safety of these activities can be developed with confidence. However, such confidence is not shared amongst ordinary members of the public who have many very real safety concerns about the ground deep beneath their feet. On the whole, they do not have a broad grasp of the geosciences or sufficient technical knowledge to address these worries. This is particularly prevalent in the geological disposal of radioactive waste arena, where public reservations are widespread and deep-seated. As a consequence, progress in this sector has been faltering over the last 30 years, not least because public concerns have not been addressed adequately by the industry. The blame for this can be partly laid upon less-than-successful communication, and in particular communication of geoscientific facets of the geological disposal process. This paper examines styles and approaches to communicating geological intervention concepts in geological radioactive waste disposal in the UK and further afield, focusing on geological structure. It goes on to describe how recent innovations in the area of digital geological data capture, 3D geological modelling and 3D/4D visualisation of complex geology may contribute to improvements in geocommunication, resulting in better public perception of risk and uncertainty, and ultimately leading to an increase in public acceptance of such geoscience infrastructure projects.

Keywords: Fault, tectonic, nuclear waste disposal, GDF, digital outcrop modelling, lidar, photogrammetry

6.1 Introduction

Effective communication of complex geology to wider, non-scientific audiences is a critical part of any major infrastructure project that is likely to evoke strong feelings amongst the affected population. Without this, the project is unlikely to succeed. The need for a balanced, scientific and evidence-based decision making process should be the main starting point for all projects, but it is often lost in the outcry that such projects provoke. It is far too easy for these processes to descend into a war of words that contain very little scientific substance.

An ever-increasing body of technical knowledge provides a firm scientific basis on which the long-term performance and safety of activities such as radioactive waste disposal and shale gas extraction can be assessed with confidence. However, such confidence is not shared amongst ordinary members of the public who have many very real safety concerns about the subsurface and who, mostly, do not have a broad grasp of the science involved to both raise pertinent questions and understand the technical explanations provided (Brownell et al., 2013). This is particularly prevalent when we consider geological disposal of radioactive waste, where public reservations are widespread and deep seated (Whitton, 2010). As a consequence, progress in this particular field has been faltering for the last 30 years. The level of technical understanding of how to encapsulate or immobilise the waste in an underground facility is progressing, yet the progress made in the site selection and investigation process is nominal, and stakeholder concerns have not been addressed adequately in past or present programmes.

The nuclear industry has a history of being secretive, mostly through its association with nuclear weapons, indeed the Sellafield nuclear site began as a plutonium manufacturing plant for the early weapons development programme. Partly a relic of the Cold War, this view needs to be changed to allow progress in the field. The internet (and social media especially) means that the population is more aware of the issues facing projects such as radioactive waste disposal than at any other point in history. Used properly the internet is a fantastic platform from which to educate and promote informed discussion about the issues facing large projects such as geological disposal of radioactive waste. In reality much of the information released via the internet is inaccurate and often misleading meaning the science behind the arguments are lost.

The UK is currently no closer to siting a Geological Disposal Facility (GDF) than when it began investigations in the late 1970's. The process to create an underground Rock Characterisation Facility (RCF) to undertake research for deep geological disposal in west Cumbria, managed by UK Nirex, was halted by the UK Government at the end of a 1996 public enquiry (McDonald et al., 1996).

Community engagement was cited as one of the reasons behind the denial of planning permission (Whitton, 2010). More recently, for the Managing Radioactive Waste Safely (MRWS) process, which began in 2008, the UK Government decided to adopt an approach based on "volunteerism", where communities put themselves forward to be considered as a host for a GDF. After initial screening, a decision would be made on the suitability of the area. This is a variation on the Finnish approach, whereby sites were identified and relevant local authorities approached to host the GDF, but were allowed to withdraw or refuse outright with no repercussions (NDA, 2013). Four local authorities expressed interest initially. The

MRWS process was halted in 2013 when three of the authorities went through an initial geological screening process only to be blocked when one of the three (Cumbria County Council) used its veto.

A modified process commenced in 2015 with the launch of a ‘pre-volunteering’ geological screening process, which began with public consultation on geological screening criteria and will eventually lead to guidance as to the regional geological suitability of areas in the UK. The aborted MRWS process utilised outreach and engagement activities to promote a more open dialogue with communities that were interested hosting the GDF, but were often countered and defeated by activities of the media and local and national promoters in the ‘against geological disposal’ camp. For example, the media repeatedly use the phrase “waste dump”, implying the site will resemble an archetypal landfill site used to dispose of normal household waste; a massive distortion of the truth.

One of the recurring themes raised during the recent MRWS process and the previous Nirex investigations has been the suitability of the host geology, particularly at proposed GDF depths and how this can be determined. The emphasis on subsurface characterisation is unusual compared to other major infrastructure projects, yet it is vital in securing both the planning permission required and also the community backing that is vital for the project. The effective communication of complex geological systems and features in a way that is informative and appropriately detailed is therefore essential. Stakeholder groups typically have different needs regarding the level at which complex information is communicated, yet these are often not taken into account, with communications of geology regularly pitched at the wrong level (Skarlatidou et al., 2012). It is often assumed that the general public (who are presumed to have a limited technical

background knowledge) require ‘dumbed down’ information, whilst the educated scientist requires a full technical explanation. These are usually the only two categories of stakeholder identified; yet there is a broad spectrum of needs in between.

Another issue is that the level to which information is ‘dumbed down’ is unquantified. This usually leads to the general public not receiving enough information to gain a proper understanding or the media re-interpreting and communicating incorrect conclusions. The scientific community, particular the decision makers or “intelligent customers” such as Radioactive Waste Management Ltd (RWM), connected with the process require the full geoscientific complexity to be communicated so the correct decision can be made. Therefore, communique such as reports and peer-reviewed articles should not contain ‘dumbed down material’ in any form (e.g. NDA, 2010). It is also important to distinguish between writing in dumbed-down language vs writing reports in plain English. Scientists often fall back to using subject-specific jargon to explain their work (Brownell et al., 2013). Terms that are taken for granted by geoscientists will often be indecipherable to the general public.

There is a widely held view that the general public requires their information to be “dumbed down”. This is the result of the assumption that the lay community will not understand the science, ignoring the presence of what could be termed an “informed public”. It is true that many of the scientific formulae and descriptions are outside of the realm of understanding for many stakeholders and, realistically, add no value to communicating geosciences. Yet a simple statement of results is often not enough. Science should be communicated in such a way that technical details and methods are retained but communicated in more relatable ways to

enable understanding to be disseminated to stakeholders with a limited scientific knowledge of the issues.

One of the most important aspects in the development of geological disposal of radioactive waste is the understanding of faults and fracture patterns within host rocks, and this paper uses this topic as an example of information that requires careful presentation to stakeholders as it is a complex problem that is difficult to visualise. In particular we use the findings obtained during this project, as case study material.

Here we examine at previous styles and approaches to communicating geological concepts in geological radioactive waste disposal in the UK and further afield and describes how recent innovations in the area of 3D geological modelling and 3D/4D visualisation of faults and fractures could contribute to an increase of public acceptance of such contested geoscience infrastructure projects.

In particular, we investigate how new 3D digital data collection and visualisation techniques can not only be used to capture more, higher quality data, but can be used to communicate geoscientific complexity to any audience, whilst showing how real data feeds complex scientific understanding.

6.2 Communication of Geoscience for Complex Subsurface Infrastructure Projects

6.2.1 Why communicate geoscience?

Effective communication of any technical information pertaining to large infrastructure projects is not only the law (Localism Act, 2011) but is also a societal responsibility of the governments and companies. The mistakes made in

Nirex RCF project highlights the long-lasting damage that can be done by opening very limited dialogue with local populations. Projects such as this will be taxpayer-funded and therefore every person in the UK who pays taxes has a right to the information being used to make decisions.

On a practical level, information should be released as a means of engaging people and making them a part of the process. This is vital to ensure continuing support of long-running projects such as nuclear waste disposal which will take nearly 100 years to see through (DECC, 2014). This would include regular updates and outreach to the general public which would form part of a wider education programme and allow greater feedback on public questions and concerns. This engagement is a vital part of a transparent decision making process.

This culture of inclusion in the decision making process can go some way to alleviating problems that have been caused in the past and avoid the animosity generated (Elam and Sundqvist, 2007). It allows communities to feel involved in the decision making process. Lecturing to communities about what is best for them in a paternalistic manner is not conducive to a harmonious relationship between the industry and the local people. They should be involved in the process and this should be emphasised to them. At times even though they are involved, they are not made to feel like they are, for example Kemp (1990).

One problem with the entire process of public engagement is that scientists have a poor record of communicating their findings to the general public, yet if the data are presented by a public relations team, then the public may view this as suspicious. Scientists need to adapt their presenting styles as many are tailored to highly technical audiences, who have an inherent trust and understanding of the methods used to validate their conclusions. Scientists often consciously try to

avoid patronising their audience, preferring to simply present results and assume a high level of prior knowledge. Current communication of complex structural geology in geological disposal and other arenas is poor. This is partially due to the lack of good quality subsurface data and the unsuitability of previous visualisation methods to view any data that was suitable for presentation.

6.2.2 Public vs Expert Perception

Geology faces competition from more attractive scientific subjects such as nuclear science, medicine or even topics from within the earth sciences such as climate change. Developments in fault and fracture characterisation methodology just do not have the same societal impact as, say, a new climate prediction model, yet this is a vital part in the GDF siting process.

The underlying aim of all communications of complex geology is to present the risks associated with the projects, especially those associated with the disposal of radioactive waste (Skarlatidou et al., 2012). Skarlatidou et al., (2012) highlight the importance of understanding the different ‘mental models’ of different stakeholders in the understanding of risk. Communication of risk to lay people typically involves providing them with information they require to make independent and informed judgements about risks to safety, health and the environment (Morgan et al., 2001). The mental models approach assumes that lay people may lack an understanding of a specific risk because important scientific information or evidence may not be known to them. The problem is that they may not be aware that such information exists. Their understanding is only based on what they already know or on other familiar phenomena.

The human memory can be thought of as a database comprising schemas that control how a person perceives a problem. These schemas depend on personal knowledge and experiences and, because a mental model may contain several schemas, it is important that the schemas are complete and accurate to ensure that the layperson's mental model is as complete as possible.

Skarlatidou et al (2012) found that the majority of lay-stakeholders have a negative view of the 'nuclear waste repository' concept, using pessimistic words to describe their understanding of the process and expressed many misconceptions, and yet have a positive view of nuclear energy in general. Academic institutions and scientific papers appear to be trusted the most and government bodies the least by lay-stakeholders, (although most thought that the latter should be the ones in charge of disposal). According to the "Eurobarometer" (a tool whereby the European Commission have monitored public opinion on range of topics, including radioactive waste, in member states since 1973, see European Union (2016)) independent scientists were the most trusted source of information (Skarlatidou et al., 2012). Furthermore, it was noted that lay people appeared to lack fundamental information and that their confidence would be increased by more information being publicly available. However, on the other hand experts appeared to be more interested in scientific and engineering research and on the importance of transparency in the decision-making process. Lay people placed the potential impact on people as their highest priority, with potential impact on the natural environment as the second highest (Skarlatidou et al., 2012).

As shown in Figure 6.1, the mental models approach allows the communication requirements of experts and lay-people to be shown alongside each other.

Skarlatidou et al (2012) note that both stakeholder groups require a combination

of media to communicate issues surrounding radioactive waste disposal effectively. They also note that there would be large gaps in information and misconceptions that would need to be addressed in communications to lay people in order for them to have a balanced view.

Lay People	Experts
1. Radioactive Waste <ul style="list-style-type: none"> • How produced • Ratios • Life of waste • Types and categories (and health impacts for each category) • Nuclear power stations and storage of nuclear waste • Accidents (e.g., deaths from cancer) • How to reduce 	1. Radioactive Waste <ul style="list-style-type: none"> • Generation process • Types • Packaging • Volume • Radionuclide decay and duration
2. Disposal <ul style="list-style-type: none"> • Disposal methods • Geological disposal concept • Area needed for geological disposal 	2. Disposal <ul style="list-style-type: none"> • Disposal methods • Geological disposal concept
3. UK Plan <ul style="list-style-type: none"> • UK site selection approach • Timelines and process • Plans for future waste • How long will remain on site 	3. UK Plan <ul style="list-style-type: none"> • Briefly, how the site selection process will take place
4. Site Selection <ul style="list-style-type: none"> • Why a site is suitable compared to other sites • Criteria used to select site (provide maps) 	4. Site Selection <ul style="list-style-type: none"> • Geology characteristics • Benefits of suitable sites (provide maps)
5. Risks <ul style="list-style-type: none"> • How long will waste be dangerous • Side effects • Effects on future generations • Terrorist attack 	5. Risks <ul style="list-style-type: none"> • Explain that it is not an atomic bomb • Importance of repository's stability • Consequences of not disposing of nuclear waste • Information about accidents

Figure 6.1: Information needs as described by expert and lay participants (after Skarlatidou et al, 2012).

6.2.3 Communication of Geoscience in Scientific Media

The main method for communicating geoscience research is through scientific media such as academic journal articles, conference presentations, books and (depending on their importance or topic) science magazines. These usually involve some sort of peer review process and are open to scientific scrutiny and criticism. However, these media are typically not accessible to people outside of the scientific community, with journal articles often located behind inconvenient and somewhat

expensive paywalls (barring the open source papers such as Plos One). For example, the total cost to a publisher to print an article is estimated at \$3,500–4,000 (Van Noorden, 2013) and the corresponding cost to purchase is high. For example, a full Nature article will cost \$32 for a non-subscriber to purchase (Nature, 2016). Attending academic conferences is prohibitively expensive and science magazines do not enjoy a large circulation. This means that outside of academic circles, new research is not widely available; the general public will not pay around \$32 per article to research a topic of interest. This is even truer for textbooks which can cost over £100. This means that the main methods of reliable scientific communication are unavailable to the general public.

Project reporting for major infrastructure projects in the government have to be available to the general public unless the information is commercially sensitive or relates to National security issues. All projects undertaken on behalf of the Nuclear Decommissioning Agency (NDA) or subsidiaries (such as RWM) have to be released upon their completion. However these publications are rarely in a public-friendly format. The nature of the work means the information is often released in long, in-depth technical documents, pitched at a level way above that required by the general public.

6.2.4 Communication of Geoscience in Non-Scientific Media

The majority of the public will never come into contact with scientific media. The only contact many people will have is through mass media, such as television, radio and (most importantly) the internet. In the U.K. scientific discussion is often limited to debates or interviews on news programs or panel shows (such as Newsnight). These programs are more of a discussion between opposing views

rather than a presentation of scientific issues. Programs on the BBC are required under their charter to present a balanced argument for contentious matters.

Whilst this allows for fair discussion, panel members who are invited on are not necessarily experts in the field, but rather hold a particular opinion. This can lead to the presentation of views that, whilst strongly held, could be incorrect, or be based on opinions not scientific fact.

Stewart and Nield (2013) go into great detail around the presentation of earth science topics to the general public. It shows there is an interest in the earth sciences amongst the public, but they are often presented under the cloak of a sensationalist title. In the Top 10 rated BBC Horizon programmes from 2000-2011, 3 were earth science topics. Their titles suggest why: ‘Mega-tsunami’, ‘Supervolcanoes’ and ‘Extreme Dinosaurs’. The top 10 is unlikely to be breached by a programme entitled “Fractures and faults and their relationships to fluid flow”. As outlined in Stewart and Nield (2013) ‘disasters and dinosaurs’ sell as that is what the public is interested in. However, “dinosaurs” do not enter into nuclear waste discussion and the theme of ‘disasters’ is one that the nuclear industry is keen to avoid.

Newspapers are often a source of poor scientific information. Although newspapers can be held to account for libellous statements, they are under no obligation for misrepresenting scientific work. Ben Goldacre pens an excellent blog (Goldacre, 2016) and column in the Guardian in which he tries to raise awareness of proper scientific methods and popular stories that promote bad practise media (Goldacre, 2011). In 2009 he highlighted how a Professor’s published work was misrepresented by the Daily Telegraph, then any requests for corrections were ignored (Goldacre, 2009). This highlights a significant problem, in that work can be reported upon

without consulting the authors and therefore relies upon the technical understanding of the journalist writing the article.

The most widely used source for information is the internet. In a presentation in 2015, The Head of Google Search, Amit Singhal, stated that the company performs over 100 billion searches a month, or 1.2 trillion per year (Recode, 2015). This equates to 2.2 million searches a minute. Information is more accessible than ever before. Whilst it is the largest information repository in the world with answers just a few seconds away on most smartphones, there is very little control on what can be posted.

This leads to two problematic situations. One is the rapid dissemination of incorrect information on a topic, usually from uninformed or biased sources seeking to further an agenda, or simply through ignorance. The second is that information is subject to confirmation bias. That is to say it is now easier for people to bring arguments to the fore that support their own views, regardless of their authenticity. This could include anecdotal evidence, information out of context or even deliberate misinformation. This can lead to a distorted image of what consensus exists. If only one viewpoint is being discussed, then it can appear this is the only view to take.

6.2.5 Communication of geoscience to a young audience

This generation is probably the most important to target during any nuclear waste disposal process. The siting process will run for ~ 20 years (DECC, 2014) meaning this is the generation that needs to be engaged if the process is to be successful. 15-20 year olds will be 25-30 during the process and their support is vital. Yet many will have no understanding of what is involved.

Geology is a subject that is rarely taught in schools as a stand alone subject. More often it appears as a small part of other subjects, particularly geography or chemistry. It is an optional subject that is taught at the discretion of the school, however earth sciences is required to be taught as a small part of the National Science Curriculum and the Geography Curriculum (The Geological Society of London, 2014). The Geological Society released a leaflet on teaching Geology (2014) and this outlines that around 200 schools teach geology at GCSE and A-level. In 2012 there were 24,372 schools in the UK, 5,889 of which are secondary level, and therefore teach specific subjects. The two datasets are not directly comparable, but it is not unreasonable to assume that geology is taught at less than 10% of all schools (DfE and National Statistics, 2012).

6.2.6 Wider Context

The importance of educating the general populace about the earth sciences has already been identified. The US National Science Foundation's Earth Science Literacy initiative has produced a document outlining their nine "Big Ideas" in earth sciences (Earth Science Literacy Initiative, 2010). The first Big Idea put forward is that "*Earth scientists use repeatable observations and testable ideas to understand and explain our planet*". Explaining to the general public how scientists arrive at their results is one of the most difficult things to do. The methods and principles we as scientists take for granted are often not apparent to the general public. This problem is complicated by the fact at some point opposing views will be presented that could both be based in scientific fact. Explaining this to the layperson will often result in confusion as they expect one single outcome, whereas the reality is often more subtle.

6.3 Geoscience Communication for Radioactive Waste Disposal

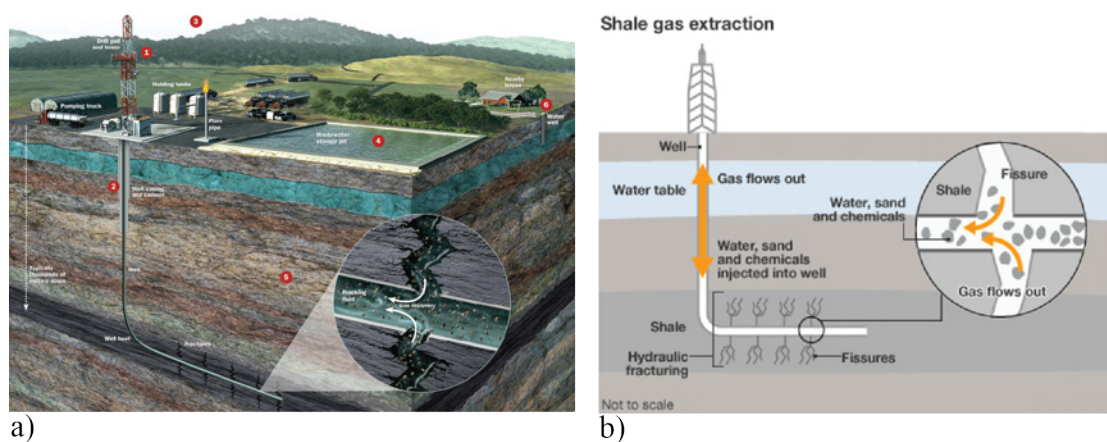


Figure 6.2: Visualisation of fracking during shale gas exploration and extraction from (a) ScienceNews.org and (b) BBC News website

As discussed, the association of geology with natural disasters such as earthquakes, volcanic eruptions and tsunamis provides a suitably interesting basis for the numerous television programmes with a geological theme. These are typically presented by scientists and are often very popular with the viewing public. It is often difficult to generate the same kind of interest in contentious infrastructure projects connected with the subsurface, yet these typically share a common theme to the popular programmes. Indeed, it is highly unlikely that a programme promoting any major infrastructure projects would be aired on a national network, unless it provided a balanced argument. This means companies will have to present their cases against strong, but not necessary legitimate, opposition. This will probably only meet with limited success, compared with the outreach to the communities that will make much more of a difference. With the UK having backtracked from the 1990's Nirex investigations to the point where it is still searching for potentially suitable locations for a deep geological disposal facility for

its higher-level radioactive waste, the most contentious current onshore subsurface projects in the UK are probably those associated with exploration and extraction of shale gas from deep, methane-bearing mudstones. In ‘fracking’ as it is known, a lack of knowledge, and media articles littered with inaccuracies and misreporting breed distrust even of the exploration process. Technically, so long as all the safety and regulatory requirements are adhered to and the exploration and extraction processes are followed correctly, shale gas extraction should be safe. Compared to the deep disposal of radioactive waste, fracking is relatively simple, so, if the process cannot be shown to be safe even though it is only in the exploration stages, then what chance does deep geological disposal have?

For example Figure 6.2 shows two visualisations of the shale gas extraction process, a) from ScienceNews.org and b) from the BBC News website. The latter provides a simplified view to show the salient features including a well head with cartoon drilling rig, the water table that the borehole is (in this case) drilled through, and the directional (horizontal) part of the borehole within the shale horizon where the hydraulic fracturing (the ‘fracking’) takes place. Through the additional use of an inset, providing a magnified view, the image conveys the fracking process that occurs at depth, but the attempt to connect this with a recognisable surface feature such as the drilling rig sets the details in a wholly inaccurate context that the inexperienced layperson would (quite rightly) be alarmed by. A typical drilling rig is roughly 6 m tall, which means that in this image the borehole would be around 12 m deep to the point when it deviates from the vertical, and around 1 m wide. The shale horizon is also around 12 m deep whilst the water table lies at about 2 m below the surface. In reality, shale gas horizons may be as deep as 3,000 m (3 km) with water tables typically deeper than 200 m, whilst boreholes are usually no

more than 0.4 m in diameter. All context is therefore lost and the layperson imagines gas being extracted from a few metres below his house, contaminating drinking water on its way up. Additionally, the simplification removes nearly all the important geological detail, instead relying on cartoon fractures.

The image Figure 6.2 (a) might look far better in its depiction of realism: after all, the rendering of surface features appears to be far more accurate in terms of dwellings placed in a landscape along with the drill-site, and the subsurface looks far more realistic. However, it makes the same errors in terms of context, with a borehole no more than say 20 m deep and a water table around 3–4 m below the surface, and thus may lead the viewer to conclude that the shale gas horizons and the water table are much closer to their own environment than they really are.

Even the small label in the image on the left, that indicates that depths may be typically thousands of metres does not really convey the realism, and, whilst the “not to scale” label in the image on the right is important, it is lost by the impact of the simplicity of the diagram. Similarly to the image on the right, no relevant geological complexities are conveyed, and information that could be of use to the lay person is replaced with simplicity displayed in an inaccurate contextual framework. Context and relevant complex information are therefore of vital importance to images used to convey the geoscience of contentious subsurface projects, if lay people are to absorb correct information in order to assess it in terms of their daily lives.

6.3.1 International Examples of Geoscience Communication in Deep Geological Disposal

Internationally, there is a preference for communicating geoscience related to geological radioactive waste disposal via websites, visitors' centres and underground tourist trips. Context and geological complexity in particular, can be conveyed through visitors' centres and underground tourist trips, where the hands-on nature allows visitors to experience the geology first hand. For instance, the French nuclear waste management organisation ANDRA (Agence nationale pour la gestion des déchets radioactifs) opened a visitors centre 'l'Espace technologique' (ANDRA, 2016b) in the Meuse/Haute-Marne department (near the Bure site) in June 2009, where permanent and temporary, special exhibitions and demonstrations of canister emplacement can be viewed. To complement l'Espace technologique Centre, ANDRA also opened another facility "Découvrez le Laboratoire souterrain/Visites des installations de surface" nearby, where visitors can gain an understanding of the activities at the Bure underground laboratory. Mock-ups of the galleries can be visited and a tour of surface facilities is also included.

In Sweden, the visitor centre at SKB's Äspö Hard Rock Laboratory (HRL) (Figure 6.3) is built 'in many ways resembles the final repository' (SKB, 2016), with the geology viewable in the tunnel itself, and explained in the visitors' centre.

In Switzerland, visitor centres are associated with both Grimsel and Mont Terri Underground Laboratories and pre-booked group visits are organised through Nagra or Swisstopo. Visitor numbers in 2012 were forecast to be about 4,550 (Mont Terri) and 1,500 (Grimsel) (Heinz Sager, Nagra, pers. comm to J M West). Virtual tours and videos of Grimsel can also be downloaded from the website,

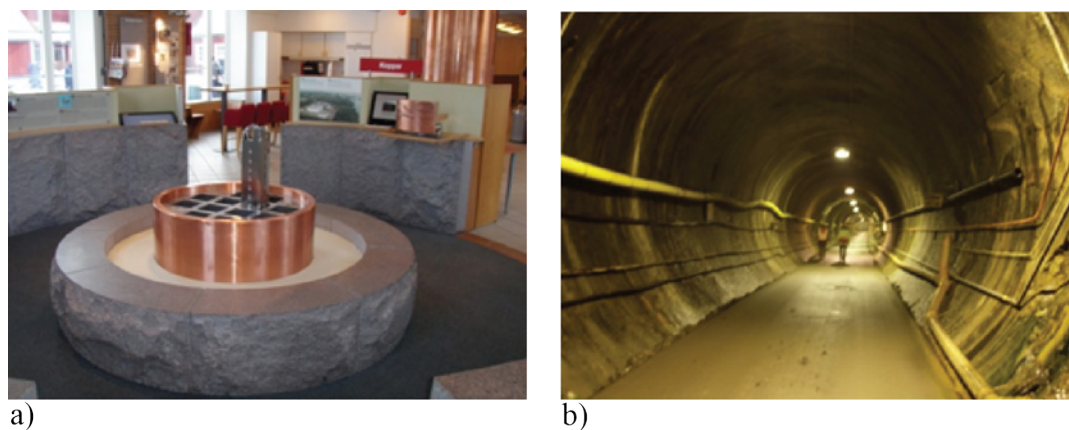


Figure 6.3: SKB's Äspö Visitor Centre (a) and tunnel into Hard Rock Laboratory (b) (images courtesy of R P Shaw and R Cuss).

whilst the underground tours allow visitors to see the geology first hand. There are a number of other initiatives such as documentary movies such as “Into Eternity”, a documentary released detailing activities at Onkalo in Finland and their efforts to dispose of the country’s nuclear waste.

Europe as a whole has been active, particularly in the area of gauging public opinion. For instance, the ‘Eurobarometer’ have been used by a wide range of users to assist with decision making at EU and member state levels. A Eurobarometer survey in 2005 sampled 25,000 European citizens and found that 75% of citizens did not feel well informed on nuclear waste issues, and 80% did not realise there are varying degrees of danger associated with radioactive waste, rather that the risk is consistent across waste forms (Skarlatidou et al., 2012).

In summary, the numerous underground tours and visitors’ centres are probably a very good basis for communicating complex geoscience and demonstrating it in both the context of an underground excavation, and of surface facilities. However, the UK, without a visitors’ centre or a dedicated underground tour, what has the UK done and what could it do to aid in communication of complex geoscience associated with GDF development? The UK does have an underground research

laboratory, but although this is located in rock that is representative of the evaporite geological setting for deep geological disposal, it currently contains little in the way of related research projects that could be shown to the public, and (as part of a working potash mine) is not open to the public regardless, for safety reasons.

6.3.1.1 Previous Communication of Complex Geology in UK Programmes for Deep Geological Disposal

The UK has a long-running nuclear programme – both for energy generation and for defence. The onset of research into the geological disposal of high-level waste (HLW) in the late 1970s and early 1980s met with public opposition and, ultimately, with the cancellation of the programme in 1981. The approach to communication at this time was ‘paternalistic’ - essentially the message was that the scientific and political authorities ‘knew best’. No attempt was made to engage the public, other than via formal routes such as Public Inquiries.

To find the best evidence for the UK’s approach to geocommunication in the radioactive waste disposal, we need to go back to the Nirex Rock Characterisation Facility (RCF) project, and to reports and papers published relating to the initiative, in order to examine the communication of complex geoscience for deep radioactive waste disposal.

To understand the approach to geo-communication that Nirex utilised it is worth understanding the context in which it was applied. Nirex itself was established in 1992 and tasked with developing a solution for the disposal of low-level and intermediate-level (LLW and ILW) waste. At that time a similar approach to the public as described above, was maintained. The site selection procedure was

secretive, possibly reflecting the political needs of the time. The resulting potential repository sites were simply announced, and so public reaction was immediate and strongly negative. By the end of the 1980s, confidence-building activities had commenced, including public meetings, local offices at potential sites and newsletters. However, the site selection process remained non-transparent and, when the deep site selection programme was started, the public remained broadly opposed.

To address this, in 1987, Nirex began a major public consultation exercise involving the distribution of around 50,000 copies of a discussion document entitled “The Way Forward” (Nirex, 1987) which asked the public to comment on a range of issues. As a public consultation, this initiative was considered a success, but there was little or no indication of how Nirex would take on board and act upon the views put forward by the public. The key public concerns that emerged in that consultation were:

- Repository safety was paramount, with safe waste transport coming second
- Monitoring and retrieval were considered important
- Negative impacts on local communities and industries

The analysis of the consultation process had only just been published when Nirex announced in 1989 that it intended to investigate two sites: Dounreay and Sellafield. The local communities near Dounreay and Sellafield supported investigations in their area, but there was no real evidence of the sites selection process being influenced by views expressed in the earlier public consultation.

By 1991, Nirex had decided to focus its efforts on the Longlands Farm area, to the south of the Sellafield nuclear plant, and, apparently without a great deal of

scientific justification, aimed to construct an underground rock characterisation facility (RCF) at the Longlands Farm site. The latter was typically referred to in most Nirex literature as ‘Sellafield’, but the location of the RCF was to be at Longlands Farm which is about 2 km south of the Sellafield nuclear site. Nirex’s public communication activities became highly targeted, with local offices, mobile exhibitions and production of information materials. However, the local authority, fearful that approval of the RCF would lead automatically to a repository if the geological conditions of the host rock proved to be suitable, refused planning approval and in the public inquiry which followed, the lack of transparency in site selection was a key factor in the appeal refusal.

In the 1970s and 1980s, communication efforts had been minimal, with a ‘top-down’ approach of announcing the selected site to the public via the media. This invariably led to opposition and failure as the general public do not react well to being patronised and told what is best for them. In the early 1990s, Nirex developed a, theoretically, more effective communication strategy with good consultative mechanisms, but failed to adequately implement any of the feedback received to the selection process. Again, this led to increased opposition.

The rejection of the RCF proposal in 1996 was a watershed moment in UK radioactive waste management policy. It led to a fundamental re-assessment of how to communicate to stakeholders. It resulted in the establishment in 2007 of the Radioactive Waste Management Directorate (RWMD) within the Nuclear Decommissioning Authority (NDA). At the same time, the government announced its ‘Managing Radioactive Waste Safely’ policy (Defra et al., 2008) which placed ‘voluntarism’ at the heart of its site selection strategy and promoted rigorous consultation via wider public engagement activities.

As a consequence of this announcement, and because most of the UK's radioactive waste is already at Sellafield, Allerdale Borough Council, Copeland Borough Council and Cumbria County Council approached the UK Government about the search for a site because, wherever a site is chosen, the waste will have to be transported through Cumbria affecting local people. The Councils established the West Cumbria Managing Radioactive Waste Safely (MRWS) Partnership (2016) so that community interests were involved in discussions. A variety of groups were also members of the Partnership including Trade Unions, National Farmers Union, Chambers of Commerce and the Lake District National Park as well as other interested local Councils. Government provided funding to cover the Partnership's work. The Partnership had an advisory role to the founding Councils and had run a public consultation obtaining views on issues that were relevant in West Cumbria taking part in the search for a repository site. Leaflets, 'advertorials' in the local press, consultation DVDs and community events were used to obtain views in this consultation process. Information displays on the issues involved were presented at events and Partnership members, representatives from DECC, the NDA, regulatory bodies and an independent geologist were also present to answer questions. This consultation took 3 years and the resulting report, completed in March 2012, helped inform the three Councils on whether to take part in the search for a repository site. The West Cumbria MRWS Partnership has been a unique experience in the UK because it has enabled government, industry councils and other interested parties to contribute to the consultation exercise in an open manner. It is also worth noting that Government funding has meant that the consultation exercise was properly resourced. However, on 30th January 2013, whilst Copeland and Allerdale Borough Councils voted to proceed to the next

stage of the MRWS process, Cumbria County Council voted against. At that time, the UK Government said it will not proceed against the wishes of the County Council and so the process in West Cumbria ended.

The MRWS process was so short in duration and so focused on screening out those areas where the rock volume was definitely not appropriate for a geological disposal facility (due to immediate presence of extractable resources, or aquifers), that very little complex geoscience was actually communicated by scientists connected with the process, leaving the job to either the media (where it was either incorrect, dumbed down or sensationalised), or to NIMBY-ists (“Not In My Back Yard”) who, typically with an axe to grind, removed much scientific fact from their arguments. There was more of an attempt to show what a facility could look like if it was built in the area to try and get the message across that the facility would have minimal visual impact on the region and to inform people what the vaults would look like. Figure 6.4 shows a good example of how information can evolve from what is effectively a cartoon, with bright colours and no quantitative information (Figure 6.4a), a much more informative technical drawing, including information as to the scale of the facility and the relatively small scale of the surface facilities (Figure 6.4 b). It should be pointed out that the drawing are not scale, it simply gives an idea as to what it would look like in a more informative manner. Very little geological information was conveyed during the MRWS process, so as noted earlier, for examples of geocommunication it is to the Nirex project that we must turn.

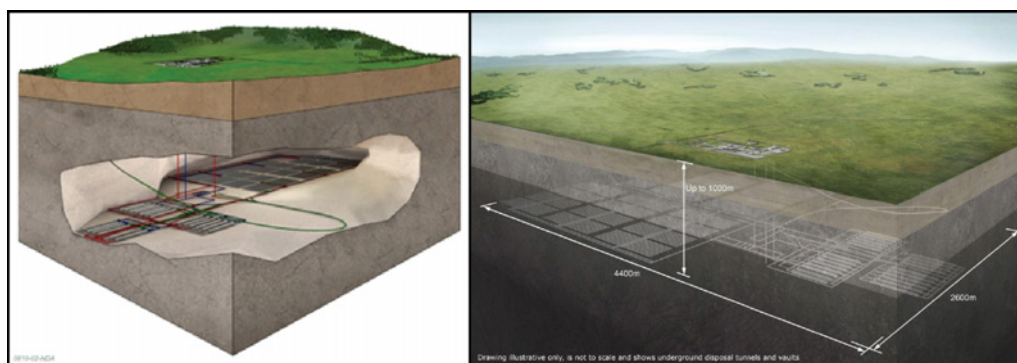


Figure 6.4: Two 3D renderings of the deep geological disposal concept: a) cartoon concept with cutaway (NDA, 2008) and b) semi-transparent visualisation (DECC, 2014).

6.4 Using Geoscience Outputs for

Geocommunication: Traditional Versus New

Presenting the complex problem of radioactive waste disposal requires a thorough and innovative approach that is relatable to the interested stakeholders. Conveying the complexity of the subsurface and also explaining any inherent uncertainty is something that exists in all subsurface infrastructure projects, and is important as it allows stakeholders to assess risk. Traditional methods of conveying information about complex geology include diagrams, annotated photographs gathered during fieldwork, annotated borehole logs, and (more recently) interpretations of geophysical information. Currently however, information technology developments have provided software and hardware media platforms that enable raw data to be presented alongside interpretations and models in 3D and in 4D (i.e. through time). Alongside new presentational media platforms, geological digital data capture instrumentation and geological modelling and geographical information systems software applications have developed considerably over the last twenty years to a point where all three facets of geological interpretation can be integrated with presentational media applications, such that raw data, geological models,

maps, visualisations can be presented to all levels of stakeholder without any difficulty. This is important as integrating everything enables concepts and models to be presented alongside raw data, and alongside familiar features such as surface buildings, thus allowing information to be accurately put into context such that everything is to scale unlike the images in Figure 6.5.

6.4.1 Traditional Geological Data Capture and Modelling as Geocommunication Platforms

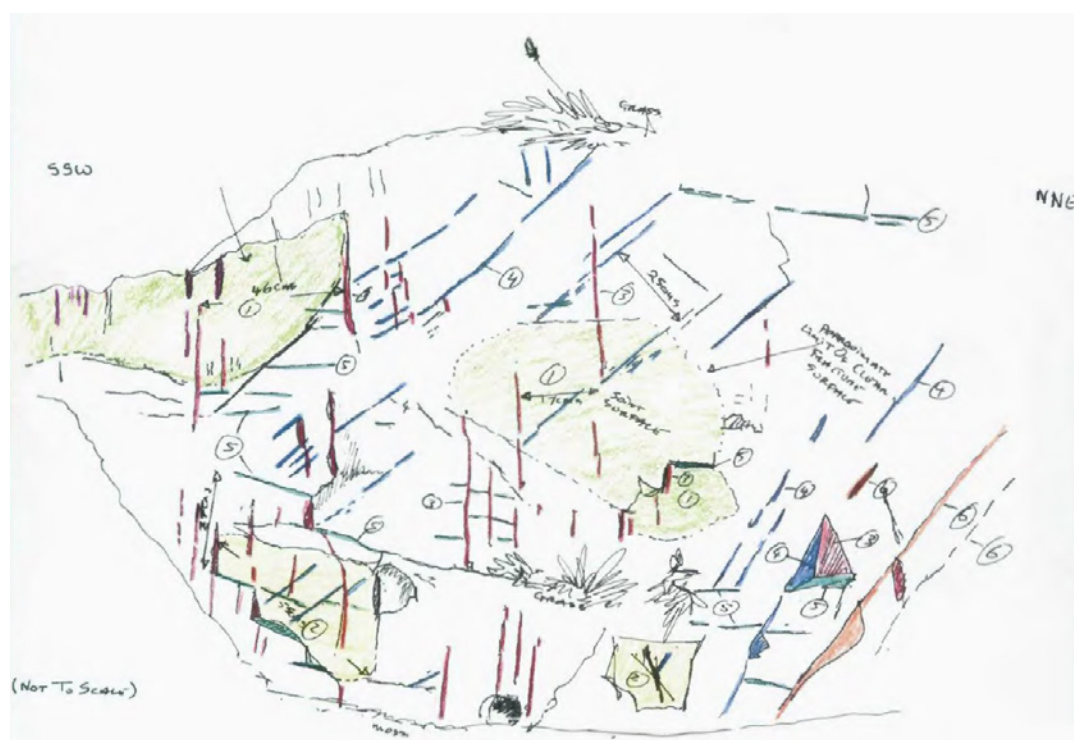


Figure 6.5: Field sketch of outcrop of Lower Palaeozoic volcanoclastic basement in the Bleng Valley, Cumbria, showing two sets of fractures and faults (Barnes et al, 2002).

Field sketches and annotated photos were the main method of reporting Nirex data. Figure 6.5 shows a detailed field sketch of an outcrop drawn during Nirex field work in the Bleng Valley in West Cumbria (Barnes et al., 2002). Whilst as a field sketch, the quality is excellent, with all the features required of a field sketch,

and the information it provides would certainly have been very useful to the Nirex investigations, there are a number of factors that illustrate its limited potential for incorporation into the styles of investigations today, and indeed render it unlikely to be incorporated into current media platforms. For instance, the diagram is a 2D representation of a 3D surface, one that is almost certainly highly irregular, with numerous 3D features that would be almost impossible to capture in any detail on a field sketch (so it is likely that not all features are captured) and certainly not in 3D. It is also “not to scale” which means an increase in the uncertainty of the placement and geometry of every feature presented on the diagram. These are not shortcomings in the ability of the geologist, on the contrary, but they are shortcomings in the technology available at the time.

Some useful features are captured in by the geologist in Figure 6.5: for instance, fracture sets with different orientations are shown in two colours. However, capturing 3D details such as dip and strike of all the fracture planes are just not possible in a field sketch. The field sketch provides a useful source of information but cannot provide the basis for construction of 3D models and cannot be shown in the same visualisation as those models, thus meaning the contextual links are not present from the start.

Information gathered from outcrop and from analysis of borehole core (which essentially represent outcrops) is often used in deep geological disposal facility development, as the basis for, or to inform, other forms of 3D and 4D models such as hydrogeological models. These in turn are utilised in performance assessments which form part of the safety cases that will be required for a GDF. For some years, field information has been incorporated into numerical models which can be used to represent a generic geological setting, or even an actual location (assuming

of course, relevant factors such as depth, pressure, temperature, geochemistry and stress-field information). However, in the 1990s field data was simply not of a high enough resolution to incorporate directly into numerical models.

Instead, conceptualizations were created, from which information was fed into numerical models. The better conceptualizations were those created with some indication of the 3D nature of the features. For example Figure 6.6 a) shows a 3D conceptualisation of fractures within the Borrowdale Volcanic Group using core data from boreholes drilled in the Nirex RCF area, and seismic interpretation.

Whilst there is much detail, the technology of the time means the conceptualisation is hand-drawn, and whilst there is a scale, the hand-drawn nature of the conceptualisation means any uncertainty cannot be quantified.

Further conceptualisation is provided in Figure 6.6 b), which, whilst of interest to hydrogeologists in presenting the concepts actually increases uncertainty to a point where there would be little point in building any performance assessment / safety case numerical models. Figure 6.6 c) is a simplification of the concepts presented in the previous images. From a geoscience communication point of view, as they stand these conceptualizations are probably only suitable for the technical expert.

Whilst the scale provides an idea of size, the lack of context means lay people would have difficulty understanding their meaning, whilst the unquantifiable uncertainty means that even if the meaning was clear the amount of risk that the concepts might imply could not be judged, least of all by a lay person.

Additionally, the lack of connection of the conceptualisations to the RCF itself would only have served to increase these issues.

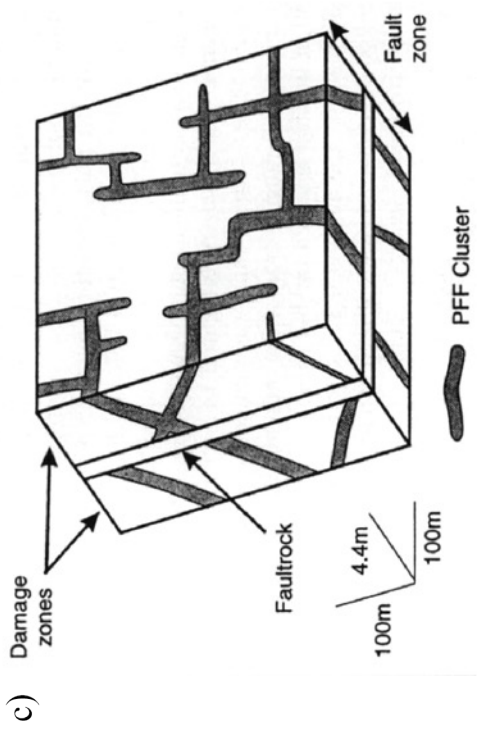
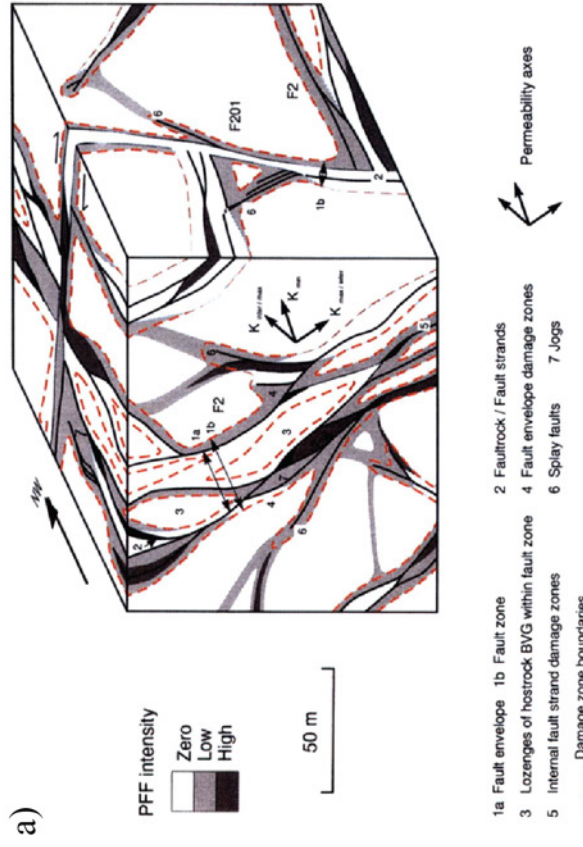
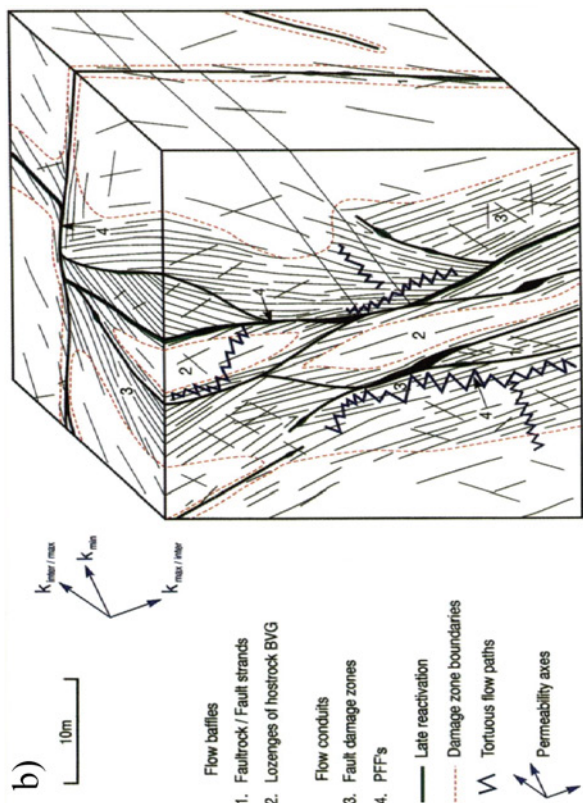


Figure 6.6: Previous fracture network visualisation derived from Nirex data: a) Conceptualization of fault structure in the Borrowdale Volcanic Group based on integration of borehole intersections and seismic interpretation during the Nirex RCF studies, showing interpreted distributions of Potential Flowing Features, b) Further conceptualization of fault structure and plumbing in the Borrowdale Volcanic Group, c) Borrowdale Volcanic Group fault model showing distribution of Potential Flowing Feature clusters (Gutmanis et al, 1998).

Whilst it was almost impossible, in the 1990s, to integrate field and borehole core observations into true 3D models as opposed to hand-drawn conceptualisations, geophysical data was certainly at a more advanced stage when it came to the creation of 3D models and visualisations and the Nirex studies certainly took advantage of this as Figure 6.7 illustrates.

These are excellent models considering the restrictions associated with the then available 3D geological modelling software, and provide very good information for the geological expert. However, they have limited use when it comes to geocommunication to lay stakeholders. For instance, Figure 6.7 a) and b) provide a lot of useful geological information, and a) is supported by map coordinates and a vertical scale (which b) is not), but the context that is so useful to a lay person is lost by the non-inclusion of surface features such as towns, villages, 3D topography, coastlines etc. Any indication of sources of data such as geophysical information is not present, probably due to 3D modelling software restrictions of the time. To a lay person, not being able to see any data sources may decrease confidence in the model itself, and thus increase the risk. It would be relatively simple to understand what the 3D models in a) and b) attempt to convey, but the structure contour map shown in Figure 6.7 c) is likely to be virtually impossible to assess by a lay person, particularly connected with geological disposal of radioactive waste. It falls into a similar trap of failing to provide any context with

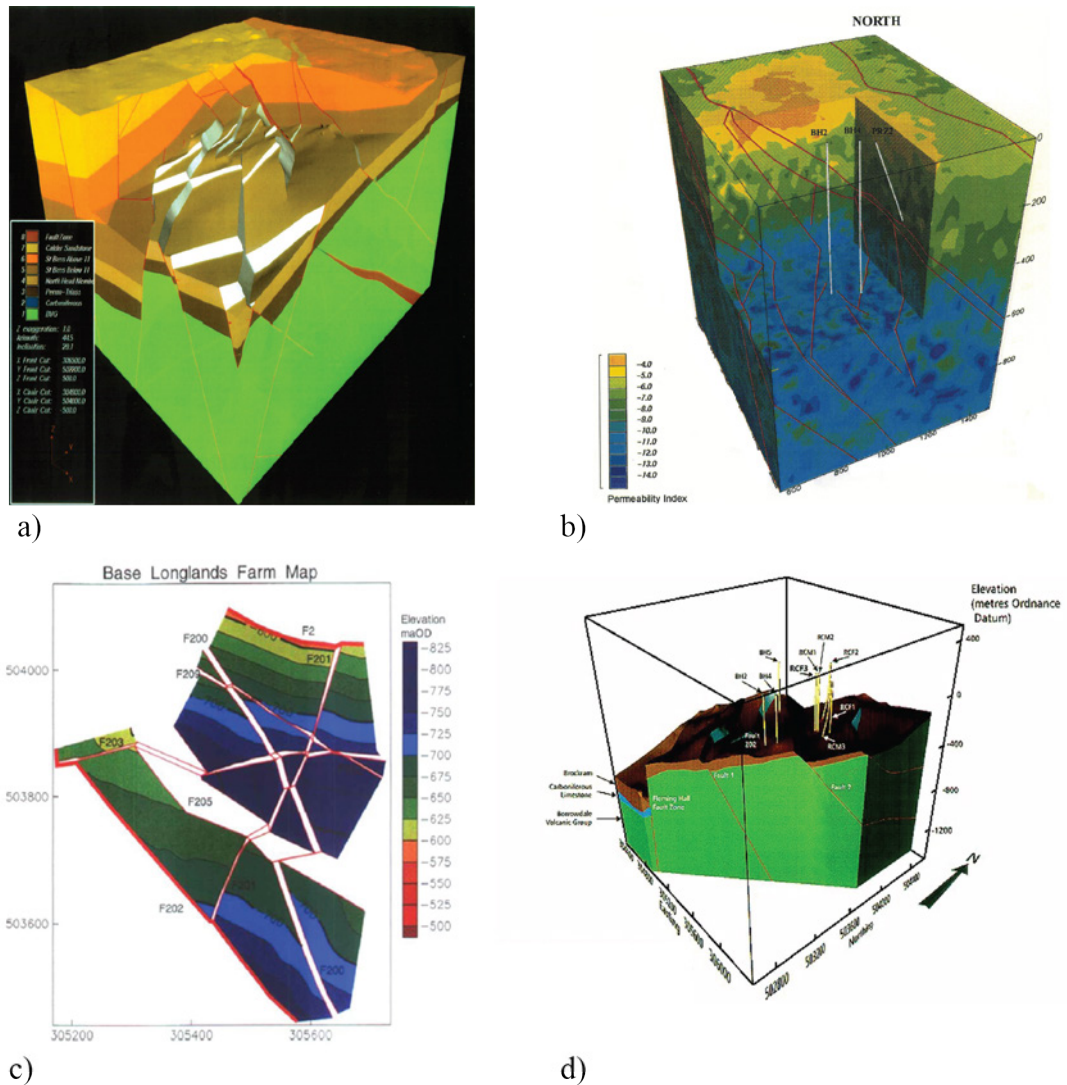


Figure 6.7: Output from 3D geological modelling undertaken during the Nirex studies in the Longlands Farm area of West Cumbria: a) a 3D block model with all post-Permian strata removed, b) 3D block model with cutaway down to base of St Bees Sandstone Formation (Triassic Sherwood Sandstone Group), c) structure contour map for an unspecified Triassic unit surface, d) 3D model of permeability in the Longlands Farm area of West Cumbria.

the project in hand, and would therefore be of little use as a geocommunication tool. Similarly, Figure 6.7 d) provides a 3D visualisation of permeability index. Here the lack of context again would be an issue, but the likelihood of a lay person even understanding what permeability is, never mind what a 3D model of it means, means it is also of very limited use as a geocommunication tool.

To summarise, it is no wonder that, notwithstanding the use of state of the art geological modelling software, there were great difficulties with conveying geological understanding to lay persons during the Nirex project. The complete lack of connection between data, to model and conceptualisation, and thus to uncertainty and risk, and the almost complete disregard of context only served to compound the issues associated with geocommunication, and probably contributed a great deal to the halt of the Nirex project.

Much development in software tools and digital data capture instruments has occurred since the 1990s however, meaning it is now possible to use raw data as direct input into 3D models. This enables a visible linkage from raw data to 3D model and 3D visualisation, allows data and 3D models to all be put into context with features of relevance to lay people, and communication of any of these features in new, state of the art media presentation platforms.

6.4.2 Digital Geological Data Capture and Modelling as Geocommunication Platforms

The world is awash with new technology, from software and hardware designed specifically as presentational media platforms, through to applications and hardware that, whilst not specifically designed for the job, are highly suitable for use in geocommunication. But how can these be utilised?

One technology which is growing in popularity is Virtual Reality (VR). The new wave of VR technologies include Oculus Rift, PlayStation VR, HTC Vive (in conjunction with Valve Corporation and Steam) and even the low cost Google Cardboard: a unit that is simply folded cardboard viewfinder and a smartphone and can cost only \$23.95. These units are still in their infancy, but they have huge potential. A number of geoscience organisations (e.g. the British Geological Survey) are utilising VR in both geoscience interpretation and in stakeholder engagement, with issues such as integrating geoscience software into VR software being rapidly overcome.

Another technology which is also already reasonably well established is Augmented Reality (AR). AR is different to virtual reality in that VR environments are wholly computer-generated, whereas AR environments utilise real-world imaging (such as live video recordings on a smartphone) and supplement them with computer generated information. Given the popularity of smartphones this could be a shorter-term, cheaper solution as the technology is proven compared to VR and the majority of people now own smartphones and would be able to participate. This could be used during presentations or during tours of outcrops that could be arranged for interested parties. It can also be used as part of a media campaign where leaflets or small booklets are used to disseminate information and augmented reality can be used to provide contextual 3D information. The British Geological Survey has proved AR with their iGeology 3D mobile phone app, which allows landscape to be viewed with a semi-transparent 3D overlay of the geology. Looking specifically at these technologies in the context of this paper, they would be perfect for community outreach as part of a geological disposal of radioactive waste programme. Instead of a presentation with 2D images of rocks, GDF plans

and blocks of text, the process could become an interactive tour. The public could be shown around the outcrops used to collect the data with interactive annotations explaining the rock type, fracturing, etc. Then they could receive a tour of what the GDF will look like inside, say following a waste package through each stage of the disposal process with information and explanations at each stage.

The highly visual nature of the presentations can be used to not only impress the public, but also be used to present complicated geologic data in an easily understandable manner. Rather than providing graphs, formulae and block geological models, the 3D visualisations with data overlain can provide a way of understanding what the data actually mean, as opposed to the more abstract concepts presented by the other media.

In order to achieve their aim of conveying complex geology however, these presentations need to be populated with suitable 3D data sets in the form of either raw 3D data (gathered for example from excavations, geological outcrops), 3D geophysical data, or modelled 3D data.

As described above, whilst photographs and diagrams are useful, without any 3D context or georeferencing they are little use in an integrated 3D/4D presentational set up. For this we must turn to the latest developments in 3D digital data capture, 3D geophysics and 3D geological modelling to allow us to integrate all forms of data into a context-rich highly visual presentational platform that will allow us to show any level of complexity, and above all to demonstrate risk alongside uncertainty to any stakeholder group.

6.4.2.1 Digital Data Capture and Geocommunication

The use of digital approaches to capturing geological data has grown tremendously in the last decade. This includes terrestrial or airborne laser scanning (lidar), photogrammetry and satellite imaging as data sources to visualise complex datasets and interpretations (Bellian, 2005; Fabuel-Perez et al., 2010; Hodgetts, 2013; Howell et al., 2014; Seers and Hodgetts, 2013; Wilson et al., 2009a). The general public, especially the younger generation, are technologically adept and many of the datasets collected resemble computer graphics. This type of data is more relatable to the general public than data in published reports and graphs. It is more likely to generate interest and conversations about the topic to hopefully keep people engaged in the process, rather than them losing interest and missing out on key information. The siting process is scheduled to take 20 years (DECC, 2014) and it is vital that a community's interest and support is maintained.

Investigations and their reports will take months or years to complete and it is important that progress is fed back on regular intervals to keep the communities informed and not allow speculation and gossip to fill the void.

This process is more than simply a flashy outreach tool. It can be used a way to instil a measure of confidence, through transparent, easy to understand presentation of the real life data used to inform their decisions. This is effectively raw data with interpretations transposed onto it that is presented to the public. Experimental data does not really lend itself to this (a graph is a graph!) so this is a unique method of data presentation.

This kind of outreach will work well with the outreach techniques already in use in Europe. Although the technologies discussed here can be used as a mobile presentation tool, they can be employed in a much more effective manner when at

a fixed installation at a visitor's centre or similar setup. Interactive exhibits can be much more complex as they will not need to be mobile.

Alongside presentations, movies and interactive websites can be produced as a way to provide more detailed information that is accessible on the internet. Videos and interactive information sources can be downloaded at the user's convenience. This can be used to spark interest in the programme and encourage further research online and attempt to inform the public of where to look for further information from reputable sources. There can be links to more detailed reports and other data sources.

This process of regaining public trust and community outreach needs to begin as soon as possible. The challenge posed is a unique one however. The timescales involved in this process mean that the process will cross generations. The younger generations will need to be engaged as much as the older ones. In general, the younger generation are much more familiar with VR/AR and other similar techniques thanks to video gaming.

That is not to say presentations will only appeal to the younger generation, but the datasets are highly visual in nature and the photorealism of the datasets collected (as shown in Figure 6.5) can be used to reinforce the conclusions presented.

6.4.2.2 3D Interpretation and Analysis, 3D Modelling and Geocommunication



Figure 6.8: 3D photomosaic combined with 3D lidar scan of Hodge Close Quarry (NY 31685 01694). Rocks are part of the Seathwaite Fell Sandstone Formation, Borrowdale Volcanic Group

The 3D image in Figure 6.8 can be rotated in the software, and is very high resolution (2.5 cm point spacing) thus meaning that once captured, the dataset can be used as an analogue potentially without the need to return, which is particularly useful if access to the location is restricted. If we compare Figure 6.8 to Figure 6.5, even though there is no interpretation in the former, it obviously represents a the huge step forwards in the way data can be presented now. But 3D digital data capture allows us to do much more in terms of interpretation and modelling, and conveying each step to stakeholders in such a way that context is preserved throughout.

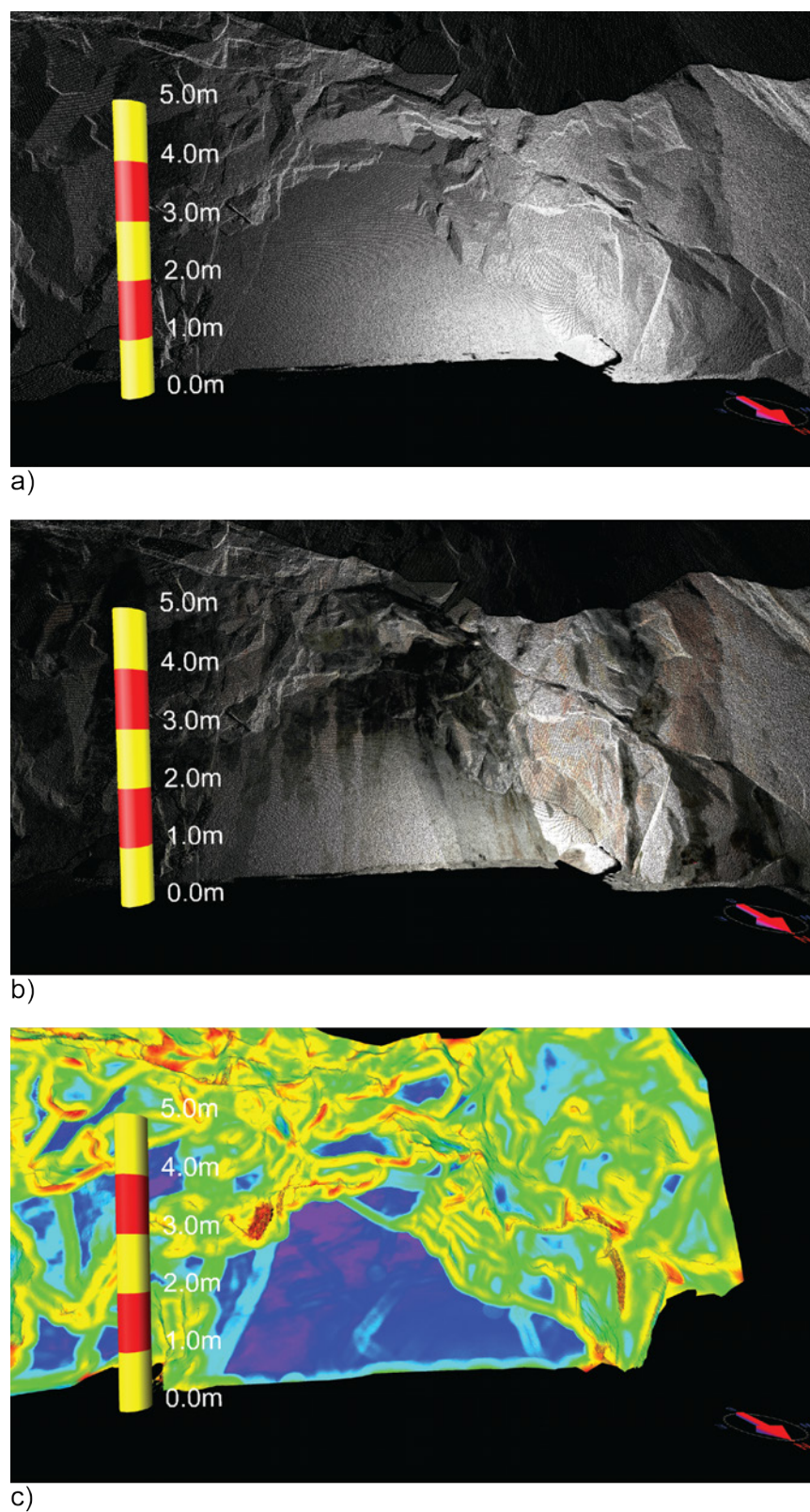


Figure 6.9: High resolution digital data capture of subsurface exposures of slate from the Seathwaite Fell Sandstone Member within Rydal Cave (part of the Borrowdale Volcanic Group): (a) low-resolution image of raw 3D point cloud, (b) rendered 3D surface, (c) analysis of planar surfaces during fracture identification.

Analysis steps convey the raw 3D point cloud data (Figure 6.9 a), a 3D surface render (Figure 6.9 b) and a colour-map image showing coplanarity, or measure of how flat a surface is, developed during analysis of fracture planes (Figure 6.9 c). In terms of faulting and fractures, actually visualising those fractures on the outcrops sampled is a much more powerful way to present data. It should not be forgotten that not only does data have to be presented in a convincing manner; it should also be interesting and visually appealing. This is even more important as a common complaint of academic presentations is that they can be dull, even to people who have a good level of technical knowledge in the field. This problem is amplified when presenting to stakeholders, who are only attending the presentation to allay fears they have. They will have no interest in rock fractures, but a need to understand them. Presenting 3D data is an excellent way to provide the information required to make an informed decision in an engaging manner.

Figure 6.10 illustrates how 3D data could be presented to stakeholders. 6.10 a) is a 2D photograph of the field location (in this case Rydal Cave, near Grasmere, Cumbria). The outcrop (in this case, an excavated cavern) was scanned using the a Riegl Z420i lidar shown in 6.10 b). 6.10 c) is a point-cloud visualised within 3D software. The results of structural analysis of faults and fractures can be shown alongside the lidar data, 6.10 d) and e). These can then be directly linked within the 3D visualisations to 3D fracture analysis stereonet. The red arrow in Figure 6.10 shows the clear link from complex structural analysis back to reality which is often missing in previous studies, yet all the intermediate workflow actions are visible.

Presenting a stereonet on its own would be of little use to a lay person, but showing it within the context of the workflow tasks and the original data at the

very least illustrates where the conclusions one can draw from it have originated – thus providing confidence for the stakeholder to assess the risk and uncertainty associated with those conclusions. For instance the images in Figures 6.6 and 6.7 have no link back to reality. Concepts such as potential flowing features are so abstract that they would be impossible to interpret by a lay person. Although it has a scale, it doesn't look real, and this is important. Similarly, presenting stereonet data as a standalone image would be all but meaningless to the lay person. The stakeholders want to know how the results of studies will affect them. This means explaining it to them in a clear manner, with some real world context. Another benefit of integrating original data, interpretation, modelling outputs and conceptualisations is that specific audiences can be targeted according to their technical requirements. For instance a lay audience comprising school children could be presented with non-technical summaries that nevertheless highlight the science being used, whilst an adult lay-audience could be presented with more technical information answering particular questions relating to context, such as location, risk and uncertainty. Similarly, an expert audience could be targeted with the full technical and scientific understanding.

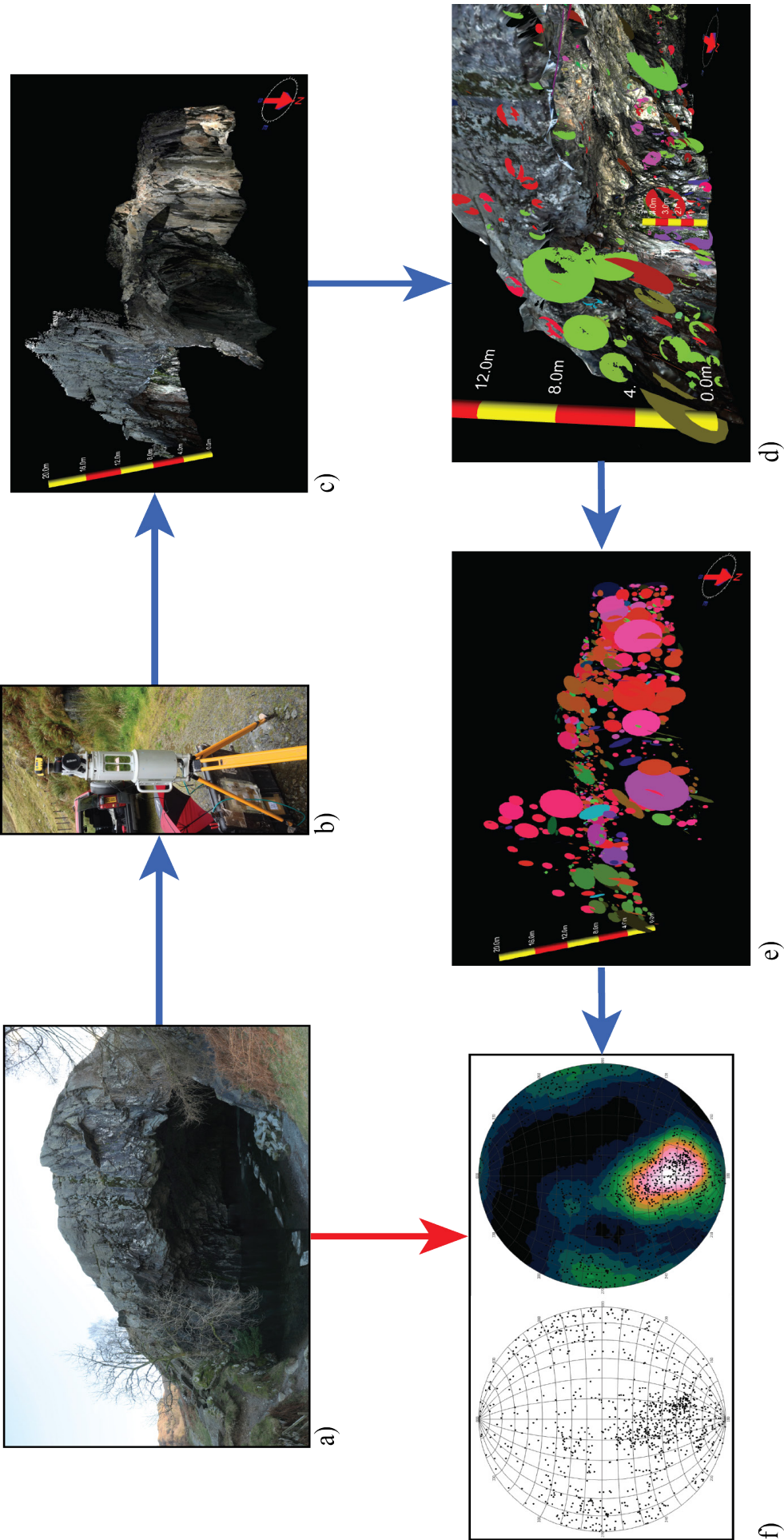


Figure 6.10: Summary workflow (blue arrows) generated by this research at Rydal Cave, near Grasmere, Cumbria: a) outcrop photograph of Rydal Cave, (b) Riegl Z-420i laser scanner used to acquire data, c) photo-realistic 3D point cloud visualisation with scale to give real world information, d) 3D fractures identified with associated dip and dip direction and displacement added to the stereonet, e) visualisation of all the 3D fracture analyses alone, (f) Resulting 3D stereonet fracture analysis developed directly from outcrop data. Previous studies only show the outcrop to stereonet process (red arrows) which is less informative and unintuitive.

6.5 Conclusions

Geoscientific communication in the UK has often fallen short of the mark, especially in terms of putting the scientific case forwards for nuclear waste disposal. Whether it be a legacy of mistrust or the industry not adequately addressing public concern, no project has yet managed to get local communities on their side in a meaningful way. Repairing or gaining this trust will be a difficult exercise, given the failings of the past. Projects need to have proactive campaigns of public engagement. They need to have preliminary information to present and must address any concerns raised, or that could be raised (within reason). They must have a robust engagement strategy and be up front and honest. 3D visualisation and modelling should form a strong part of this (if appropriate) and all presentations must be pitched at levels appropriate to the audience.

There will obviously be project specific challenges that would have to be part of any strategy. For example, underground characterisation would have to feature heavily in the outreach as this has been a key concern since the RCF plans were rejected in 1997. Most literature notes that all data presented really must be related back to the real world situation from which it was interpreted or observed.

This will make datasets relatable to the general public, and can aid in both explanation and acceptance of the information being put across.

Here we demonstrate that the utilisation of an integrated workflow of high resolution digital geological data capture, 3D interpretation, 3D modelling can be used as the basis for the highly visual communication of even the most complex geology during programmes for geological disposal of radioactive waste. In particular, using these methods also addresses the requirements for the use of innovative visualisation techniques such as virtual reality and augmented reality, increasing the potential of all the techniques as communication tools in such programmes.

Chapter 7: Best Practice for Host
Rock Characterisation of a GDF:
Synthesis

Chapter 7

Best Practice for Host Rock

Characterisation of a GDF: Synthesis

7.1 Introduction

This project was set up to investigate potential improvements to the site characterisation processes used when examining suitable geological settings for a GDF. It aimed to improve on existing techniques and evaluate whether these new methods are suitable for implementation in future studies. Improving the existing geological understanding of the chosen study area was also a main aim of the project.

The approach defined during this study marks a step change in the characterisation of GDF host-rocks within a higher-strength geological setting during GDF siting activities, and emphasizes the need for proper characterisation of the higher-strength geological setting in general, prior to undertaking those activities. The approach is robust and shows the benefits of modernising data collection, interpretation and implementation.

However a number of issues, challenges and problems were encountered during this research, especially with respect to regional scale geological modelling and fluid flow modelling, that raise some interesting and perhaps more fundamental questions about deep geological disposal as a higher-radioactive waste management concept. These are discussed in this Chapter.

In particular, discussion is provided on the fact that this study suggests that there may need to be a significant shift in attitudes that should be adopted towards geological disposal of radioactive waste.

7.2 Project Evolution

When this project was conceived, it was thought that geological and fluid flow modelling in an analogue host rock would be possible and the project could concentrate on the behaviour of fluids in the subsurface. As the project progressed, it became clear that the pre-existing data necessary to condition the model was not readily available and the uncertainty in the subsurface was so great that only a highly simplified model could be generated, which would be unsuitable for fluid modelling. Instead, the project evolved into an investigation and evaluation of how novel and existing techniques and software are suited to analysing a potential GDF analogue setting such as the BVG.

7.3 Discussion of Approaches

7.3.1 Geological Approaches

In this project digital outcrop data from four localities spread throughout the BVG exposure were analysed as part of a process to illustrate how digital methods could form an integral part of site selection processes for a GDF.

Overall, the project has succeeded in this aim, and this thesis illustrates improvements to site selection, characterisation and modelling, and shows improvements to any stakeholder communication process. In particular, the project highlights a novel method for collection of data from locations providing outcrop analogues to the higher-strength geological setting. It is suggested though, that the methods utilised have proved to be situation dependent and should therefore not be viewed as a complete replacement for existing, traditional methods, but as part of a workflow that complements and advances existing methods.

We have shown that digital data collection methodologies, namely Lidar and photogrammetry alongside computational modelling approaches, could be utilised in any future GDF characterisation studies. The techniques allow large amounts of data to be collected quickly, and detailed predictions to be made regarding parameters such as fracture characteristics and geological unit boundaries and contacts. The success of the techniques indicate that a move towards this method of data collection at an outcrop scale would be prudent. Whilst the use of airborne techniques such as gravity, lidar and magnetism surveys are commonplace to determine large scale structure in projects such as this, there is more scope for performing digital surveys manually on a smaller scale. These include TLS, UAV (or drone) surveying (e.g. Bemis et al, 2014) or even smaller devices that can

attach to an iPad, such as the Structure Sensor from Occipital: an infra-red emitter/detector unit that utilises the iPad's onboard camera to produce real time renderings of the surrounding environment (Occipital, 2016).

This project investigated the capabilities of terrestrial lidar and utilised it in a different manner to similar surveys of sandstone outcrops used as analogues for deep, unexposed hydrocarbon reservoirs. In the latter, the survey targets were often large, continuous outcrops, from which one lidar dataset could be acquired. These included canyons (Wilson et al., 2009b), amphitheatre-style (Burnham and Hodgetts, in prep) or simply large outcrops (Burnham et al., in prep). However the outcrops surveyed here provided spatially distant data sets, that could not be physically correlated.

The appearance of the data (i.e. the generation of photorealistic models) was also relatively unimportant. As long as the data was spatially referenced correctly then full coverage was not required at each outcrop. Other projects (e.g. Burnham and Hodgetts, in prep.) required photorealistic data of the entire outcrop to map properties such as geobodies that are not visible on intensity-coded point cloud data.

It was originally envisaged that the use of lidar might provide a large amount of digital fracture data from a number of outcrops. This was achieved, but not as fully as expected, due in part to the nature of the outcrops, and current technology limitations. Collection of lidar data from outcrops within the study area proved challenging, especially the ability to collect good quality datasets. High resolution lidar instruments may be small, but their accompanying equipment such as battery packs, tripods and stands are cumbersome and heavy (the total equipment weighs around 50 kg), precluding access to some of the more inaccessible outcrops both on

the surface and in subsurface excavations. For the nuclear industry, safety is of paramount importance, and the equipment could not be transported easily to potential scanning locations such as Pavey Ark in Langdale, without affecting safety of the users. Thus a number of locations could not safely be attempted. Another real issue in the study area was the prevalence of inclement weather conditions, meaning many potential field days were cancelled due to rain, or study areas were compromised by flooding. Unfortunately this is likely to be the case in many of the higher-strength outcrop analogues in the UK, especially in and around the Lake District.

These issues could be avoided in the future as newer, and better suited instruments come on stream. For example the recently released Riegl VZ-6000, which incorporates DGPS, a 5 MP camera, touchscreen controls and an 80 GB on board solid stated drive to store data (Riegl, 2015). The unit is IPV 64 certified, meaning is it protected from total dust ingress and water spray or rain (IEC 60529, 2001) and the base unit is 1.5 kg lighter than the Z420i TLS used in this survey at 14.5 kg. This means the unit is far more portable and able to withstand inclement weather. Another option is drone-based photogrammetric or lidar surveys (e.g. Bemis et al, 2014). The technique still in it's infancy, but one that would be useful in acquiring data from remote areas such as Cumbria where steep rugged terrain proved unsuitable for deployment of the TLS used in this study.

The lidar coverage was not as comprehensive as it could have been. As discussed, a study in the Nukhul half-graben in Suez, Egypt (Wilson et al., 2009a, 2009b), comprised a 9 km²continuous dataset with 4 billion data points and 5,000 registered photographs, whereas this project in total comprised of 82 million points

and 161 photographs and only occupied 6.44 km³. With more time and making use of the considerations above, this data set could be extended in the future.

As a means of providing fracture data suitable for input into GDF-depth fluid-flow models, the effectiveness of lidar scanning data proved to have limitations based on the scale of fluid flow model being attempted, and its strain on the computational hardware. Discontinuity data can be collected from mm to decimetre scale (potentially up to 100 m) depending on the chosen resolution of the survey (e.g. terrestrial or airborne lidar), showing direct application and to site-scale fluid flow models. However, this level of detail cannot be mapped on a regional scale model, unless the project has access to a large computational hub and a large timescale over which to run simulations. During attempts at regional-scale modelling (e.g. on the scale of a GDF), it was discovered that the computing power required to simulate flow along fractures below the 100m scale would be greater than what was available. This means that smaller fractures, which contribute significantly to fluid flow through the region, would have to be ignored, increasing uncertainty in such a model.

The workflow developed during this study proved better suited to creation of smaller scale geological models based on the data obtained from TLS, including fracture data down to 10's of metres. DFNs created from these data would result in <100 m scale geological and thus fluid flow models of host-geology local to a GDF once a site has been chosen. These can then be up-scaled into full GDF geosphere models. Similarly, deterministic models based on small-scale data upscaled into regional-sized models can be used and implemented as part of performance assessments within the development of safety cases when looking at geological setting studies during site selection stages.

7.3.2 Utilising Digital Data from Outcrop Analogues to Improve Efficiency of GDF Site Characterisation

With the volunteerism approach to GDF site selection (whereby communities can register interest in hosting the GDF with only limited investigations into the area's geology), understanding the regional hydrogeological regime will be vital from a regulatory and safety case point of view. This will ensure that radioactive waste does not impact on the surrounding environment through (for example) contaminants leaching into groundwater. One of the traditional methods of doing this is to drill boreholes to gather information about potential host rock and to undertake groundwater monitoring studies to input into hydrogeological understanding.

However, there is a requirement to limit intrusion of host rock whilst obtaining as much relevant subsurface data as possible. Boreholes can become fluid migration pathways that lead directly to the surface if improperly abandoned (Avci, 1994), or even if they are resealed properly as they provide an existing weakness in the geology. This requirement led to the idea of testing the feasibility of utilising detailed studies of outcrop analogues for GDF geological settings and GDF host rocks to contribute to a reduction in intrusive investigations such as boreholes. Boreholes are often relied upon to provide vital fracture and subsurface information. However the connectivity information gathered from borehole logging and geophysical down-hole scans is often poor. It was thus hoped to show that outcrop analogue lidar data in conjunction with traditional field information could be used to reduce the number of boreholes that would otherwise be required to be drilled in a potential GDF location.

This has proven to be partially true. Porosity and permeability analyses and also fracture network characterisation can be extracted from digital outcrop analogue studies and provide a much larger geostatistical database to work with. The 2.5D nature of the digital outcrop models is a vast improvement on the 1D information generated by boreholes.

The uncertainty in the modelling associated with correlation between survey areas is reduced and goes some way to assessing the spatial variability in a deterministic and quantitative manner, something which is difficult with boreholes. There are limitations to be considered. The digital techniques used in this study are not able to predict subsurface geological unit contacts and cannot provide any fluid properties for the dynamic modelling, such as salinity, hydraulic head, etc. The fluid properties are determined either from existing or new boreholes in a specific GDF location, or from boreholes in GDF-depth higher-strength geological setting analogues.

The uncertainties required when using depth parameter analogues as inputs in the modelling of fracture-driven fluid flow in rocks of high heterogeneity such as the BVG, are numerous and wide-ranging because the lateral variation in the subsurface is so great. However, these data are still of vital importance when the alternative is data obtained from traditional field locations, or no data at all.

Initially, searching for a suitable GDF location, siting the GDF and then undertaking characterisation as part of the site investigation will be a challenging task if the investigations take place in a complicated geological setting. The process will become gradually more focussed as it moves forward. The ideal scenario is that areas with a simple geology and low hydraulic conductivity are identified and then investigated, in line with the current successful projects being

undertaken in Finland, Sweden and Switzerland (Chapter 2). However, with the UK Government's policy of communities volunteering to host a GDF, sites which will have to be investigated could prove to have complex geology and/or hydraulic properties, as the BVG analogue analysed here demonstrates. These will require a more detailed investigation to understand and predict their behaviour.

7.3.3 Approach to Stakeholder Engagement

The digital methods discussed in this project and their application to stakeholder engagement (Chapter 6) are shown to have great value in providing tangible, easy to understand information to stakeholders, yet still maintaining a level of technical detail that allows informed discussion to take place.

No project will succeed without the backing of local communities that will be impacted upon by the building of a GDF. This was identified as a major influencing factor in the Finnish disposal investigations (Gibney, 2015). Population density differences between the UK and Finland mean that there is increased emphasis on a successful public engagement process. England and Wales have an average population density of 371 people per km² with England having a population density of 407 people per km² and Wales having 148 people per km² (Office for National Statistics, 2012). The population density of Finland is only 18 people per km² (The World Bank, 2015). This shows over an order of magnitude difference between the densities in England and Wales and the densities in Finland. As well as this, unlike Finland, sparsely inhabited wildernesses do not exist in England and Wales. Any GDF sited in the UK is likely to impact upon a significant population of people. Therefore not only must data be collected and analysed in a robust manner, those data and the results of analysis must be

presented to the general public in a clear, persuasive and informative manner. As discussed in Chapter 6 this includes the presentation of different levels of scientific evidence to a public audience possessing a wide range of understanding.

Even before a GDF site is chosen, there must be a focused campaign outlining how the work eventually leading to deep disposal will be undertaken, including its methodology, its outputs, conclusions, impacts and benefits. In addition, it is important that methods of how these data are to be presented to interested parties are explored in depth to ensure consensus on the best, most effective ways of doing this.

Support for the UK nuclear programmes is concentrated (unsurprisingly) around existing nuclear sites, especially Sellafield. The reactors (and Sellafield) often store a majority of the waste on site to avoid transporting hazardous material around the country. Therefore it is not an unreasonable suggestion that any potential GDF site investigations will be located in or around these sites. This is not to say that the benefits of transporting the nuclear waste to a suitable site in a lower strength or evaporitic setting is impossible, it is just more unlikely than use of a site near to existing nuclear infrastructure. The benefits of transporting hazardous waste to an area of better geological suitability, could outweigh the risks of burying the waste in unsuitable geology.

7.4 Deep Disposal Concept in the UK

It is important to place this work into the wider context of nuclear waste disposal to fully understand its implications. This study shows that the BVG, as an analogue for the higher strength geological setting, demonstrates that the setting itself at GDF depths is likely to be complex. Indeed, even taking into account the

use of the engineered, multibarrier concept (that might allow a GDF to be constructed within in complex geology) the higher strength setting may actually be so complex that, even with the techniques described in this thesis, it simply could not be characterised to a suitable level to be able to demonstrate complete confidence in containment of disposed waste. Due to factors such as pressure, temperature, hydrogeology, stress field etc., rocks at depth will always be different to those at the surface and only an underground laboratory or rock characterisation facility would be able to provide enough evidence to determine whether a site is suitable or not.

If we examine the site geology under consideration in the three European countries discussed, the site geologies are much simpler and therefore easier to predict.

Whilst still relying on proxy measurements and prediction, the uncertainty in these areas is much reduced and data can be applied to distant areas.

Whilst this works in simple geological settings, it is an unworkable approach in a host rock analogue with the complexity exhibited by the BVG. This view was put forwards in the Friends of the Earth Submissions to the planning authorities to counter Nirex's evidence in 1996 (Friends of the Earth, 1996a, 1996b, 1996c). In this, Dr. Peter Kokelaar stated that it would not be possible to characterise the BVG by extrapolation:

"... with any certainty in volumes (i.e. distances) of more than tens of metres."

(Peter Kokelaar, Page 210, Friends of the Earth, 1996a). Even utilising modern digital data collection methods, it was not possible to overcome this problem.

Whilst the data collected were an improvement on the Nirex data, they are no more transferable to other sites within a potential host rock. This will be a major limiting factor in any future investigation within a complex host rock in a

crystalline basement setting that exhibits the level of complexity of the BVG. Any underground rock laboratory will need to be located within a suitable distance to the GDF, so that results obtained by underground experiments would be applicable to a repository safety case.

This is the fundamental problem that this project has highlighted. There are many problems modelling structurally complex, heterogeneous areas. In an attempt to address these concerns, the UK government plans that engineered barriers will be used to mitigate against any uncertainty generated by complex host rock settings. For these engineered barriers to be effective, the facility must be created using materials that will last 1 million years to satisfy the safety case (Shaw et al., 2012). The oldest human structure is the Göbekli Tepe in Turkey which is thought to be around 11,000 years old (Curry, 2008). This structure cannot be thought of as a complete building. Indeed, archaeological evidence has been used previously to argue for the durability of materials in the NDA's generic Disposal System Safety Case (NDA, 2010). Roman nails and cement and Egyptian glassware were used to illustrate how materials can survive over hostile environments. The timescales involved, however, were only around 1,000 years, and whilst it is true they have held up rather well, these have not been exposed to nuclear waste and the materials here will have to survive potentially two orders of magnitude longer than this. A further complication is that after the operational life of the facility, (~ 100 years) the facility will be sealed. This means that, unlike with other buildings, there will be no way to maintain the integrity of the barriers. Any uncertainty in the barrier lifespan will directly affect any hydrogeological modelling. When modelling the geological (and therefore hydrological) evolution of the site, it is important to understand at what point in the site's lifespan there could be potential release of

radionuclides into the geosphere. The point at which it is released could affect the migration vectors, especially if the modelling realisation involves some sort of stress realignment, possibly due to glaciation, for example.

Groundwater migration velocity must be slow enough to limit the spread of the radionuclides. The UK currently assumes the SKB KBS-3V design as the method to dispose of the HLW as part of the generic Disposal System Safety Case (NDA, 2010). If this is indeed adopted, then the waste that is held in the spent fuel canisters will need to migrate through around 40 cm, that is to say through 35cm of low permeability bentonite rings and 5 cm of bentonite pellets (NDA, 2014).

Any further than this and they will reach the surrounding geosphere. If we assume a hydraulic conductivity value of $4.7 \times 10^{-14} \text{ ms}^{-1}$ for the clay, then the time taken for the radionuclides that have breached their containment to interact with the host rock will be around 270,000 years. This is obviously an over simplification, but it gives a rough idea of the timescales involved.

7.4.1 External Factors

Geological phenomena such as glaciations (and associated lithospheric flexure due to loading and unloading, e.g. Grollmund and Zoback (2000) and Pelletier (2004)) could lead to a reorganisation of the stress field in the repository site, and potentially the generation of new flowing features. Isostatic rebound can lead to an increase in seismicity due to crustal flexure (Brandes et al., 2015), which, if large enough, could lead to a breach in the repository.

Currently, the modelling approaches required to predict the effect of an event such as a glaciation (or even the likelihood of a glacial event occurring) do not exist in a form that could be used as part of this site selection process. Instead, it relies

upon looking at previous glaciations and how they have affected the UK. The effect of glaciation-induced seismicity in the UK cannot be studied using this approach as earthquakes are rarely preserved in the geological record and reliable data will not exist.

Another consideration that has both a scientific and societal impact is climate change. Not only will that have an effect in terms of the likelihood and magnitude of climatic changes (i.e glaciations), it shows that needs driven research does not always yield results.

Scientifically, long term climatic modelling is not robust enough to provide location specific information. Whilst broad predictions can be made as to the general trends in the Earth's climate (e.g. Moss et al., 2010)), it is not yet possible to predict, say, whether the UK will become totally glaciated as a result. This affects the robustness of the safety case and it can be argued that if bodies such as the IPCC (International Panel on Climate Change) and other organisations cannot push forwards with climate modelling then there is no guarantee the nuclear industry will do any better. There is a considerable need to provide robust modelling results and predictions, yet the progress is faltering. There is no guarantee that additional pressure exerted by the nuclear industry will stimulate discoveries. Pressure from climate change deniers can affect modelling especially at government level, and can limit funding to these areas.

7.4.2 Computational Considerations

It is also worth addressing the advances in modelling approaches. It is not only the improvements in processor (or CPU) speed that need to be taken into account.

Processor architecture has changed over the last two decades, with concepts like

Intel's™ Hyper-Threading technology which was released in 2002 that allows a processor speed boost (Intel, 2016). There is also the relatively new field of General-Purpose computing on Graphics Processing Units (GPGPU) which is the utilisation of the GPU to perform complex parallel operations faster than on a CPU. They have a high memory access rate using DDR5 memory. The GPU's can be linked and used in parallel to further increase the computing power. An example of this is NVIDIA™'s CUDA parallel computing architecture for use on their GPU's (NVIDIA, 2016). They are designed for floating point operations which are suited to mathematical calculation, and indeed give rise to the difference between how CPU and GPU speeds are documented (MIPS: Millions of Instructions Per Second and FLOPS: FLoating Point Operations Per Second, respectively). Computers can now operate at speeds in the terahertz and petaflop (10^{15} operations per second) range.

It should not be assumed, however, that increasing computational power will always be a steady upwards progression. Moore's Law (Moore, 1975) states that:

“the number of transistors in a dense integrated circuit doubles approximately every two years.”

and transistor number is directly related to the computational power of the unit, This law is the premise by which many technology companies operate. In recent times, it is thought that Law has begun to break down and computational power is beginning to plateau, with Intel moving the goalpost from two to two and a half years (Clark, 2015).

Focussing on the software used in this project, VRGS has been coded specifically to take advantage of parallel computing on newer CPU's, whereas Petrel was ported to the newer CPU architecture as it is an older program. As a result, Petrel

is not optimised to run on a parallel processor and as a result inefficiently utilises the computing power available. The Line Tracing software described in (Seers and Hodgetts, in press) is designed to perform calculations on the GPU. Therefore even with an increase in computational power, it may not be possible to build a fully functional model down to the scale required over the area required.

7.4.3 Previous Assessment of Site Characterisation

Workflows

Shaw et al (2011) summarise the processes involved in the creation of site descriptive models from nuclear projects around the world, and review software and hardware requirements. They conclude that current, off the shelf software programs and methodologies are capable of handling site investigation processes. Whilst this may be true in the context of that report, the authors do omit a number of complicating factors.

The complexity of the potential host rocks is completely ignored. The report extols the level of detail and effort Nirex placed into characterising the PRZ, but this was what was required to characterise the site. The BUSC (Basement Under Sedimentary Cover) setting of the Nirex investigations was described as complex due to the differing lithologies (sandstone over crystalline basement) but this is not the only source of complexity. It could be argued that this is not even the most important source of complexity in the region.

As discussed, the BVG itself is extremely complex, both lithologically and structurally. The conclusion that current software would be able to model a host rock as complex as the BVG should definitely be reconsidered. Whilst reference is made to geologies being less complex in other investigations (i.e. Finland), the

potential for complexity to render techniques and software unsuitable is ignored in Shaw et al, (2011).

The latter note that Nirex applied existing hydrocarbon techniques and software to characterise the PRZ. This project has shown that whilst this is true in geologically simple, sedimentary systems, it is much less effective in complex geological settings. Fracture characterisation in the study was also modelled using borehole analyses (image and wireline logs). Picking fractures from a 1D survey method greatly raises the level of uncertainty in the data. Whilst outcrop studies were performed, these were limited to large scale faults such as the Lake District Boundary fault Zone (Akhurst et al., 1998) and some limited geological mapping and fracture studies. Given that the main potential flowing features in the model were to be discontinuities in the rock (i.e. faults and fractures), these should be characterised using a more robust and modern approach. Fracture modelling within the hydrocarbon industry is generally stochastic and the models are populated from well logs and outcrop analogues (if available). They are often information poor and understanding develops as the field matures and more production and well data become available. This is an unacceptable approach for the nuclear industry as the fracture networks need to be characterised before construction of the GDF can begin.

The use of boreholes in a complex area such as the one studied here, has also been shown to be of reduced value. Even though in the report it is stated that:

“... logging of the cores in detail... allowed correlation of these units between boreholes and the interpretation of faults.”

(Page 26, Shaw et al, 2011). This formed part of the Friends of the Earth challenge to the RCF proposal (Friends of the Earth, 1996a, 1996b, 1996c) when

the planning application was submitted. To some extent this has been confirmed by this project in that that the level of heterogeneity within a host rock as complex as the BVG, correlation between boreholes for units that can vary in thickness over very short lateral distances. This means it is incorrect to say that if Unit A is in borehole X and borehole Y, then the unit is continuous between the two and should be modelled as such. It could pinch out and reappear, even over short distances between boreholes.

The conclusions of Shaw et al (2011) seem somewhat premature in that they have presumed that any geological setting will be able to be modelled using current techniques, without actually knowing what the site specific conditions or challenges are. The premise that current programmes in other countries mean that any UK siting process will be able to go ahead can be considered a valid opinion. However this only holds true as long as the geology in a UK site is no more complex than in Finland or Sweden.

7.4.4 Public Engagement

As discussed in Chapter 6 convincing the public to allow a siting process to begin and continue through to completion is a substantial consideration when siting a GDF. The novel workflow from digital data collection through to 3D modelling presented in this thesis, can form an excellent basis for visualisation as part of a coherent communication strategy.

However, this will only work for the presentation of 3D models where the linkages to the original data can be visualised. The technique becomes more difficult to implement when attempting to communicate models of future scenarios to public stakeholders, where the extrapolation of those forward models from the original

datasets needs to be demonstrated. The scientific community would be more accepting of the idea of technical advances allowing successful modelling when required. However, not only would public stakeholders be more sceptical, but using new technology whilst not demonstrating links to the original data can generate gaps in understanding, presenting opportunities for attack by those opposed to disposal in an area, to which the industry would struggle to respond.

In the NDA/RWMD document, 'The NDA's Research and Development Strategy to Underpin Geological Disposal of the United Kingdom's Higher-activity Radioactive Wastes' (2009), it states that the research is "needs-driven". This means where a technological shortfall is identified, work will be tendered to bring up the technical readiness level of the technology (Nuclear Decommissioning Authority, 2014).

The issue is that this attitude appears incompatible with the precedents set previously by the nuclear industry. The level of technical understanding and readiness required to construct a nuclear power plant is substantial. This project has shown that, for complex systems a great deal more work is needed to bring the technology to a point where it is ready to be implemented and even then it is not certain that it would be up to an appropriate readiness level once waste is emplaced.

Undoubtedly, there will be technological progress in the time between this thesis publication and the site investigation process beginning. We look back at the Nirex datasets, the investigation techniques and modelling approaches appear rather rudimentary compared to modern day techniques and approaches, for example, 3D seismic surveying is now a commonly employed technique and advances in

directional drilling and borehole characterisations allow greater subsurface understanding. However the level of this progress is impossible to predict.

7.5 Best Practice Methodology

The initial geological screening approach that RWM has implemented is an excellent starting point for a GDF, which should rule areas out based on their geology. This was the starting point for all current GDF projects and should be the same for the UK. The UK has been using the research and experience gained by foreign projects to shape their own disposal designs so there is no reason why geological exclusion criteria should not also be adopted. This will give a clear message to communities that the Government has faith in the geology, rather than sending an ambiguous message that further investigations are required and that it may or may not be suitable, which casts doubt. We feel that this will make stakeholder engagement easier.

As shown by this project, careful consideration must be given to excluding areas that have complex geology. Whilst engineered barriers could be used to retard radionuclide migration, this is irrelevant if the geology is too complicated to characterise; a fundamental part of the safety case.

Once an area has been selected the process can move forward, allowing the regulatory bodies to present evidence already in their possession with which to bring to interested stakeholders. More detailed, staged investigations can then be undertaken in areas that wish to proceed. This will utilise modern, high resolution digital surveying methods such as the ones outlined in this project. Outcrop studies must form part of any study, the extent to which would be limited by the

amount of exposure of the target geology in the area. Where there is limited exposure, outcrop analogues examined in this project could be utilised.

Figure 7.1 shows an idealised site selection workflow for a GDF. The orange asterisks indicate where the information should be presented to stakeholders, where feedback and concerns should be addressed and fed back into the process.

Independence and transparency of the data when it is presented to stakeholders is key. The project will not succeed without the backing of this group.

The geology selected should be as simple and homogeneous as possible; prolonging this century-long process by selecting a complex host geology is counter-intuitive.

This will not only make it easier to model, but should be part of a more pragmatic approach overall. Nuclear waste disposal is an immensely complex undertaking so it would be more efficient to select the simplest geology possible to expedite the process.

7.6 Conclusions

7.6.1 Objectives

It is worth revisiting the objectives set out at the beginning of the project to determine whether they have been met by the project:

1. Identification of a geological setting for a GDF which will be studied, including a specific onshore analogue and definition of the study area.
 - Successfully completed - We have successfully identified the BVG as a suitable analogue of the host site for a GDF.
2. Collection of a low-resolution regional dataset from the Borrowdale Volcanic Group which is the chosen analogue for the higher strength geological setting

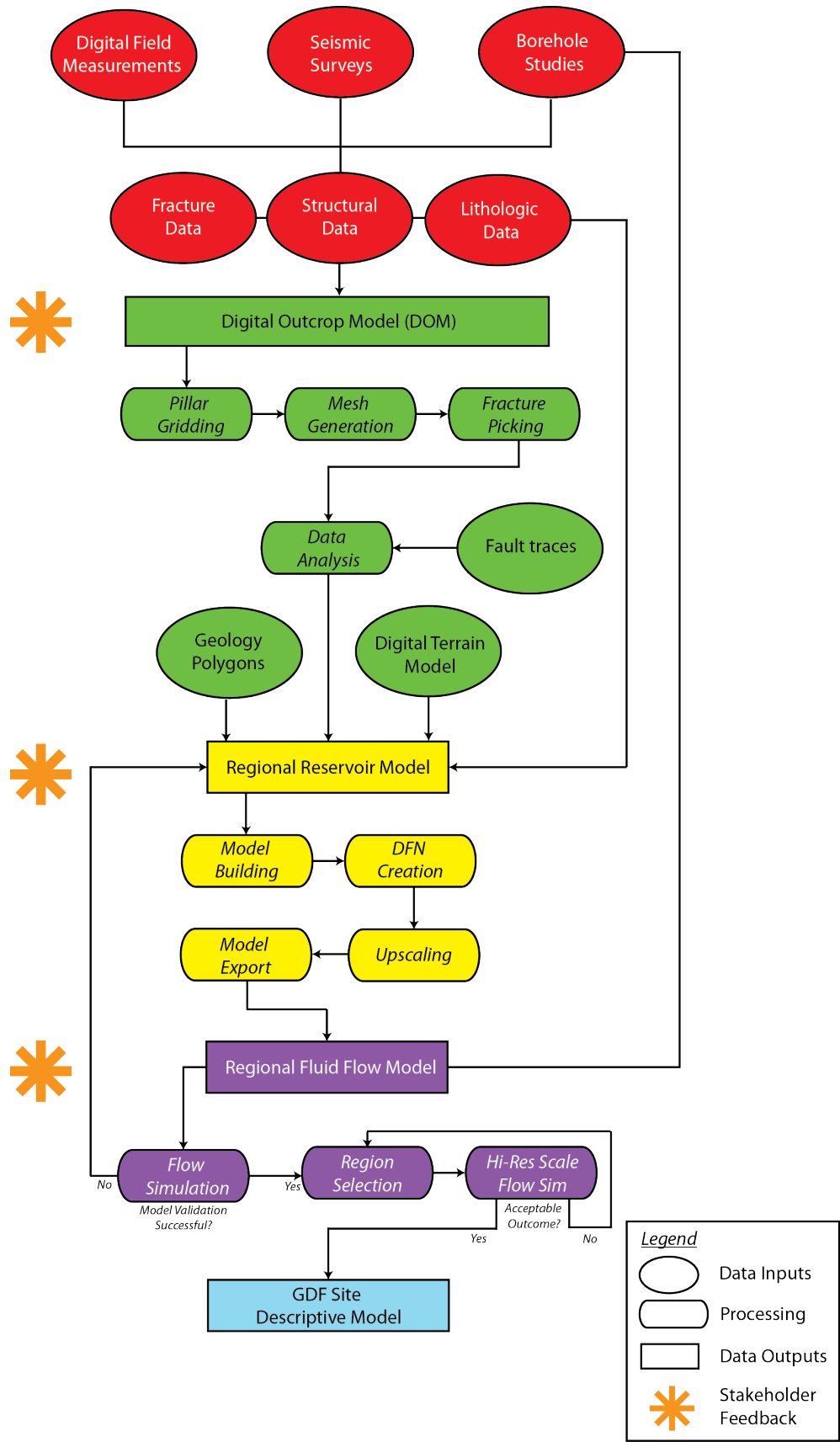


Figure 7.1: Idealised workflow to produce a site descriptive model for nuclear waste disposal.

This has been revised and refined from Figure 1.1 as this project has progressed.

for a GDF. This comprises published and unpublished existing data, including geophysical, borehole and field data (e.g. geological maps) and regional field data.

- Partially successful - Data was collected that formed the basis of the geological model in the form of geological polygons, a DTM and fault traces. Existing studies were used but not for a large scale model. Most of the existing data was not available or of limited use to the project.
3. Application of high-resolution data from selected surface and subsurface field locations within the study area, using 3D lidar, high-resolution 3D digital photogrammetry and traditional field data collection techniques.
- Successfully completed - lidar and photogrammetric surveys were collected at 4 locations around the study area and allowed a regional picture for the fracture statistics to be determined and modelled at outcrop scale.
4. Creation of low resolution, regional 3D structural understanding of the BVG.
- Partially successful - the beginnings of a model were created. but even at low-resolution, the model was not statistically valid due to the high levels of uncertainty due to a paucity of data. It was possible to generate a low resolution structural model for the area which could form the basis for a future geological model.
5. Creation of detailed 3D brittle deformation structure (fracture) models for each high-resolution field location using datasets collected.

- Mostly successful - Using the digital datasets and the statistics extracted from them, it was possible to generate a small, outcrop-scale DFN in PetrelTM for the Hardknott Pass dataset. If photogrammetric surveys had been performed at the remaining sites then DFNs could have been generated for each locality, but due to time constraints, the Hardknott Pass dataset was used as a proof of concept only.
6. Creation of 3D regional fracture network model for the BVG, integrating data collected and stochastic modelling.
- Unsuccessful - The data coverage was too sparse and not sufficient to create a regional geocellular model. This means there was no structure within which to generate the fracture network.
7. Creation of a test fracture network at an outcrop scale.
- Successful - we have the data obtained from the digital outcrop modelling to build a small scale model of the Hardknott Pass outcrop using novel photogrammetric techniques to improve the accuracy of the method.
8. Investigate how this data can be used as part of a wider effort to engage and inform relevant stakeholders.
- Successfully completed - The digital datasets and modelling approaches are an excellent method of stakeholder engagement and should form an integral part of any future GDF site investigation process.

The study illustrated that the complexity of the geology surrounding a GDF location in the higher-strength geological setting may have a considerable,

inhibitory effect on the success of site investigations for such a GDF.

Unfortunately, there is no quantifiable measure of complexity that could be used to rule areas in or out, so common sense would need to be employed.

Any modelling approach will require a measure of statistical or stochastic processing to generate any usable data. It is not possible to produce a deterministic site descriptive model. No methods exist currently that can successfully characterise a large geological volume in this way.

This means simplicity is the site investigation geologist's main ally. Simple geology is easier to predict with much reduced uncertainty and means that more faith can be placed in the modelling outputs. Theoretically, it should also be easier to provide data as proof to interested stakeholders and raise confidence that the repository is safe. Complex geology (such as the analogue used in this study) is much more difficult to characterise, even to the point where it could be classified "uncharacterisable" and, consequently, is a much harder sell to interested stakeholders.

This project has gone some way to highlight how new methods of data collection and presentation can be utilised to successfully solve the 60 year conundrum of radioactive waste disposal in the UK, and how attitudes must be rethought in order to move the process forwards.

7.7 Future Work

This study has highlighted numerous shortcomings to the methodologies used to approach the process of site selection for a GDF. It shows that digital techniques must be more widely utilised and replace older, more inefficient approaches. This

could include further work in fracture characterisation methodologies and a move towards larger-scale deterministic modelling approaches.

In order for the process to move forwards successfully, there must be an emphasis on focussed work in geologically simple regions and not just simply “working with what we are given”. The use of modern, digital approaches will only be successful in areas that are amenable to them and that can be modelled. In line with this, further consideration should be given to project specific software development in line with modern advances in technology and not just retrofitting older programs.

What is clear is that all these advances must form part of a robust, comprehensive and transparent public engagement process. This is absolutely vital if any future process is to succeed. Novel technologies and presentation methods must be investigated and implemented to grab the attention of the public and hold it long enough to convey the information necessary to make an informed decision.

Chapter 8

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