Radioactive Waste Management

Technical Note no. 24600903

Geological Disposal

National Geological Screening - Detailed Technical Instructions and Protocols

March 2016

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Executive Summary

RWM is carrying out national geological screening as set out in the 2014 White Paper – Implementing Geological Disposal. We have developed national geological screening guidance (referred to as the Guidance) which is to be applied using the specialist expertise of the British Geological Survey. The Guidance identifies five geological topics which are relevant to meeting the Safety Requirements for a Geological Disposal Facility (GDF) and sets out the sources of information which it is appropriate to use to apply the Guidance at a national scale.

RWM has worked with the BGS to develop the Detailed Technical Instructions and Protocols presented here. These are the specific instructions to the BGS on how to apply the Guidance in a uniform and transparent manner. This document provides sufficient technical detail to achieve this. It is not intended to be accessible to a non-technical audience.

BGS will produce Technical Information Reports and maps for the 13 regions identified in the Guidance. These will provide the geological basis for RWM to develop regional narratives and maps describing the key characteristics of the geological environment and their relevance to safety. The narratives will be written for a non-specialist audience.

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1 Introduction

RWM has been asked by UK Government to undertake national geological screening as one of three initial actions set out in the 2014 White Paper – Implementing Geological Disposal. We have developed draft national geological screening guidance (hereafter referred to as the Guidance) which has been considered by an Independent Review Panel (IRP) established by the Geological Society and presented for public consultation between the 8th September and the 4th December 2015.

The national geological screening exercise is a preparatory step to the siting process for a geological disposal facility which brings together high level geological information relevant to the geological disposal facility safety cases. More detailed local information will be considered as part of the discussions with communities during the siting process.

RWM has worked with the British Geological Survey (BGS) to develop the Detailed Technical Instructions in parallel with the consultation as the level of detail in the draft Guidance was considered appropriate for public consultation. Amendments to the Guidance in response to the public consultation are reflected in these final instructions.

1.1 Purpose of report

This report presents instructions and protocols for the production of the Technical Information Reports and supporting maps. It is a technical instruction to the BGS on how to apply the Guidance and provides sufficient technical detail to achieve this. It is not intended to be accessible to a non-technical audience.

The BGS deliverables will be a series of Technical Information Reports and production maps for each region. These will provide the geological basis for RWM to develop brief narratives and map outputs describing the key characteristics of the geological environment and their relevance to safety in a way that will be accessible to a non-technical audience.

1.1.1 Detailed Technical Instructions

The Guidance identifies a number of long-term safety requirements and the geological attributes that are relevant to meeting them. These attributes fall into five geological topics:

- Rock Type
  - Distribution of potential host rock types (higher strength rocks, lower strength sedimentary rocks, evaporite rocks) at the depths of a GDF
  - Properties of rock formations that surround the host rocks
- Rock Structure
  - Locations of highly folded zones
  - Locations of major faults
- Groundwater
  - Presence of aquifers
  - Presence of geological features and rock types which may indicate separation of shallow and deep groundwater systems
  - Locations of features likely to permit rapid flow of deep groundwater to near-surface environments
  - Groundwater age and chemical composition
- Natural Processes
  - Distribution and patterns of seismicity
  - Extent of past glaciations

- Resources
    - Locations of existing deep mines
    - Locations of intensely deep-drilled areas
    - Potential for future exploration or exploitation of resources.

RWM has worked together with BGS to develop a Detailed Technical Instruction for each of these topic areas explaining how the outputs will be produced. The Detailed Technical Instructions define in detail how the Guidance will be applied. While the Detailed Technical Instructions provide sufficient detail to capture the technical work process, they retain some flexibility to allow practical changes to be made during application. Each Detailed Technical Instruction includes the following:

- A step-by-step description of the activities which will be undertaken to collate and present the data and information to produce each output
- Details of any assumptions or proposed expert judgements which will be used to produce the outputs

A summary of the supporting information and metadata which will be produced to provide the audit trail linking the data and information sources to the final presentations used within the outputs.

A Geological Data and Information Technical Note that provides the details of the datasets and information needed to apply the Guidance has been produced by BGS to support the Detailed Technical Instructions.

The Detailed Technical Instructions for each of the five geological topics are presented in Sections 2 through 6 of this document.

1.1.2 Protocols

The Protocols are the agreed set of rules, methodologies and vocabularies that apply across the topic areas and outputs, and which require a consistency of approach to be applied, demonstrated and communicated.

There are five Protocols which are presented in Section 7 of this document. They comprise:

- Data
    - Existing Data
    - Approach to Metadata
    - Approach to Data Collation
    - Road Map to Supporting Information
- Expert Judgement and Uncertainty
    - Approach to Expert Judgement
    - Approach to Uncertainty
- Language and Vocabularies
    - Terminology
    - Nomenclature
    - Assumptions
    - Acronyms
- NGS datum and spatial limits
    - NGS datum for depth
    - Offshore limits
    - Overlaps between regions
- Outputs

- Technical Information Reports and NGS Narratives
- Map Formats and Conventions

1.1.3 NGS datum

In areas of high topographic relief, maps produced using depths of 200 m and 1000 m below ground level will indicate volumes of potentially suitable host rocks below hills and mountains. Although these rocks would be located at greater than 200 m below ground level, a GDF constructed in them could be penetrated in the future by a horizontal or gently inclined tunnel (e.g. an aqueduct or transport tunnel) excavated into a nearby hillside.

To address this safety consideration, an alternative datum for depth is described in the NGS datum Protocol in Section 7.4. This is brought to the reader’s attention at this early stage as it is a key part of the approach in all the Detailed Technical Instructions.

1.2 References

DECC, Implementing Geological Disposal. A Framework for the long-term management of higher activity radioactive waste, July 2014.

RWM, Implementing Geological Disposal: Providing Information on Geology - National Geological Screening Guidance, March 2016.

2 Detailed Technical Instruction: Rock Type

2.1 Introduction

The Rock Type Detailed Technical Instruction sets out how data and information on the topic of rock type will be assembled and presented. For the rock type topic the following outputs for each of the 13 regions have been specified in the Guidance:

- maps at 1:625,000 scale showing the 'distribution of potential host rocks at 200-1000 m depth (separate maps for the distribution of each of the three generic host rock types)' together with 'summary regional maps of areas beneath which at least one potential host rock may be present'
- an illustrative geological column showing the sequence of rocks present in the region; a description of potential host rocks, their depths and remaining uncertainties in properties and/or location
- a description of rock formations surrounding potential host rocks with properties that may contribute to safety

For the purposes of screening, the surrounding rocks that are expected to contribute to the Geological Disposal Facility (GDF) safety case will be combined with the host rock types and herein termed 'Rock Types of Interest'.

The Rock Type Detailed Technical Instruction sets out a step-by-step methodology of how geological information of the 13 regions of England, Wales and Northern Ireland will be assembled and presented as part of the national geological screening exercise. Specifically the Detailed Technical Instruction sets outs the methodology required to identify Rock Types of Interest; extract these from existing BGS 3D geological information to illustrate their extent in the depth range of interest and to output these as ArcGIS shape files. It does not include development of these polygons into published maps. The specification for production maps is described in Section 7.5.2 (NGS Protocols). This process will also provide the information that will be used to underpin the rock type component of the Technical Information Report that will be compiled for each region and used by RWM as the basis for the outputs.

The Rock Type Detailed Technical Instruction has the following structure:

- definitions and assumptions - contextual information describing the overarching premise, assumptions and relevant definitions that underpin the production of Rock Type outputs (Section 2.2)
- data and information sources - overview of the information to be used in the Rock Type Detailed Technical Instruction with reference to the Geological Data and Information Technical Note (Section 2.3)
- topic process and workflow - overview of the Rock Type process followed by a step-by-step description of the Rock Type workflow (Section 2.4)
- relationship with other Instructions and Protocols - a brief note on the relationship between the Rock Type Detailed Technical Instruction, the other Detailed Technical Instructions prepared for the national geological screening exercise, and the Protocols (Section 2.5)
- references - a list of references cited in this Rock Type Detailed Technical Instruction (Section 2.6)

2.2 Definitions and assumptions

Following the Guidance, potentially suitable host rock types will be considered in three broad types, classified as higher strength rocks, lower strength sedimentary rocks and evaporite rocks:

- higher strength rocks, which may be igneous, metamorphic or older sedimentary rocks, have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass
- lower strength sedimentary rocks are fine-grained sedimentary rocks with a high content of clay minerals that provides their low permeability and are mechanically weak, so that open fractures cannot be sustained. They will be interlayered with other sedimentary rock types
- evaporite rocks have formed as ancient seas and lakes evaporated and often contain bodies of halite that provide a suitably dry environment and are weak and creep easily so that open cracks cannot be sustained

2.2.1 Rock Types of Interest

The rock types assigned to the Rock Types of Interest categories will be common geological materials described in the BGS Rock Classification Scheme (Gillespie & Styles, 1999; Hallsworth & Knox, 1999; Robertson 1999), classified on the basis of their physical properties, using lithological descriptors employed on the BGS Engineering Geology Map of the UK (Dearman *et al.,* 2011).

The criteria for assigning a lithology category recognised in the Rock Classification Scheme to a Rock Type of Interest have been discussed in depth at meetings between RWM and BGS in order to ensure that all potential Rock Types of Interest are captured effectively. The rock types (as recognised in the BGS Rock Classification Scheme) assigned to the Rock Type of Interest categories are summarised in Table 1 and will be as follows:

HSR: These rocks have a low porosity (including fracture porosity) and low permeability, and form homogeneous bodies (i.e. without major interbeds or other bodies with significantly different physical properties) on an appropriate scale to accommodate a GDF. The permeability of all or part of an HSR body at depth is unlikely to be known without detailed investigations, and so all potentially suitable bodies will be included and the likely uncertainty discussed. Many potential HSR (based on laboratory scale properties) do not occur in sufficiently large bodies to accommodate a GDF, but for others, large uniform bodies are available. For a mapped rock type to qualify as an HSR, at least 80% of the mapped unit must be made up of the specific rock type of interest. For rocks of sedimentary origin, rock types which form individual beds that are unlikely to be thick enough to house a GDF while still providing containment or which have complex (faulted or folded) geometries, were judged unlikely to be suitable and have not been included for screening. It is noted however that where such potential HSR occurs beneath a cover of impermeable LSSR or evaporite, the area will have been identified under those RTIs. The rock types listed in Table 1 as potential HSR include both granite and other intrusive igneous rocks, slates of sedimentary or volcanic origin and medium to high grade metamorphic rocks.

LSSR: LSSR have a high clay content, and correspond to the clay and mudstone categories in the BGS Rock Classification Scheme. The mudstone category also includes older compacted and metamorphosed mudstones which do not meet the definition of LSSR given in the guidance, and expert judgement will be needed to identify LSSR among the rock units identified as containing mudstone in the BGS classification. Units of LSSR must be continuous laterally on a scale of tens of kilometres, but there is no minimum thickness because laterally extensive layers of LSSR may provide containment to a GDF in underlying host rocks. In order to ensure that only laterally extensive units of clay or mudstone are included, the mapped units must contain at least 50% clay or mudstone to qualify as LSSR.

Evaporites: The distinct Evaporite safety case is based on halite (rock salt) as the host rock. At a national scale it is only practicable for the Rock Type topic to identify sedimentary units deposited in an evaporitic environment and hence likely to contain bodies of halite. Presently-known halite bodies are however included under the Resources topic. Evaporite formations may also contain units of other rock types of interest.

Table 1 Rock Types of Interest

Generic Host Rock Type	Rock Type of Interest
Evaporite	Rock Salt
LSSR	Clay
	Mudstone
HSR	Very Low Grade Metamudstone
	Extrusive Igneous Rock
	Intrusive Igneous Rock
	Metamorphic Rock

The rock types listed in Table 1 will be identified in geological units that underlie England, Wales and Northern Ireland. It is explicitly assumed that geological units are sufficiently homogeneous to display the characteristics of interest. In reality, most lithologies are known to vary over the extent of a geological unit and this has been allowed for in the detailed guidelines presented above. This approach is considered pragmatic and proportionate for a national scale screening exercise.

The Rock Types of Interest are mapped onto an extract from the BGS digital dataset, termed UK3D. In order to ensure the separation between the source material and the screening-specific platform, this extract will be saved, and referred to as NGS3D. It should be understood that UK3D is itself an interpretation and that there are implicit assumptions, relating to surface mapping as well as projecting geological formations in the subsurface, inherent in its development.

The geological lithostratigraphic units that are represented are described in an editable table of attributes. Where this is ordered in stratigraphic order of superposition, it is referred to as the Generalised Vertical Section (GVS). Identifying Rock Types of Interest utilises a process of interrogating the attribution table to UK3D. The particular attribution, termed LEX_RCS code, relates the lithostratigraphic unit present in the BGS lexicon of named rock units (LEX) to a lithology code based on the BGS Rock Classification Scheme (RCS) and is illustrated in the GVS. The LEX ('or Lexicon') component is used to indicate a stratigraphic unit (e.g. Kimmeridge Clay Formation = KC). Definitions of these units are available from the BGS Lexicon of Named Rock Units at http://www.bgs.ac.uk/lexicon/. As UK3D is based upon the geological units presented by 625K DigMap V5, many GVS and corresponding cross-section units are composites comprising more than one formation.

The RCS component relates to the principal lithologies (rock types) present within the named stratigraphic unit (in the case of KC it is MDST, the code used for mudstone). The definitions of the codes are provided in the BGS RCS database search http://www.bgs.ac.uk/bgsrcs/searchrcs.html. Many of these RCS codes are composite lithologies which are recorded in the BGS Dictionary DIC_ROCK_SIGMA.

RWM screening guidance sets the depth relevant to the underground facilities of a GDF at 200 m to 1000 m below the NGS datum and defines this as the depth range across which to represent the distribution of Rock Types of Interest.

2.3 Data and information sources

2.3.1 3D geological model

Rock type screening is based principally on the UK3D tool and supporting datasets.

UK3D is a national resolution geological model of the UK consisting of a network, or 'fence diagram' of interconnected cross-sections showing the stratigraphy and structure of the bedrock to depths of 1.5 - 6km. The model was first developed for England, Wales and subsequently Scotland (as GB3D) and improved in various phases with funding from the Environment Agency of England and Wales, NERC and NDA/RWM. The latest version, UK3D v2015 is due for publication in February 2016 and includes cross-sections for Northern Ireland, constructed with funding from RWM. UK3D v2015 is one of the principal sources of existing information to be used by the National Geological Screening. BGS will continue in the future to augment UK3D with new information as part of its ongoing National Geological Model programme.

The UK3D model comprises a network of digital geological cross-sections constructed by geologists using Geological Surveying and Investigation in 3D (GSI3D) software. The model is informed by a number of spatial geological datasets that are contained within the GSI3D project. These are described in the supporting Geological Data and Information Technical Note. Together this network of cross-sections and underpinning data make up the principal information set and workspace for developing the 'rock type' topic screening output.

The GVS represents a summary of the geological succession displayed in the model, which comprises 445 lithostratigraphic units incorporated at the 1:625,000 resolution. The dataset for UK3D and a Metadata Report will be available from the BGS website when published in February 2016.

2.3.2 Principal information sources

The principal information sources which have been used to construct UK3D are:

- DiGMapGB-50
- the BGS Lexicon of Named Rock Units
- BGS 1:50,000 series (paper maps)
- regional subsurface memoirs
- regional guides
- BGS Sheet Memoirs, Sheet Explanations and Sheet Description
- BGS Offshore Memoirs
- legacy BGS 3D Regional Models

Many of these principal information sources incorporate interpretations of and references to datasets and peer reviewed publications. Seismic data in particular have been extensively utilised in the production of the various geological models which have supported the fence diagrams that comprise UK3D.

Other sources of information, such as additional borehole records from the Single Onshore Borehole Index (SOBI) will only be consulted where there is a specific identified need.

All of the sources of information listed above will be described in a supporting Geological Data and Information Technical Note. The UK3D dataset has a comprehensive metadata record also described in the Geological Data and Information Technical Note.

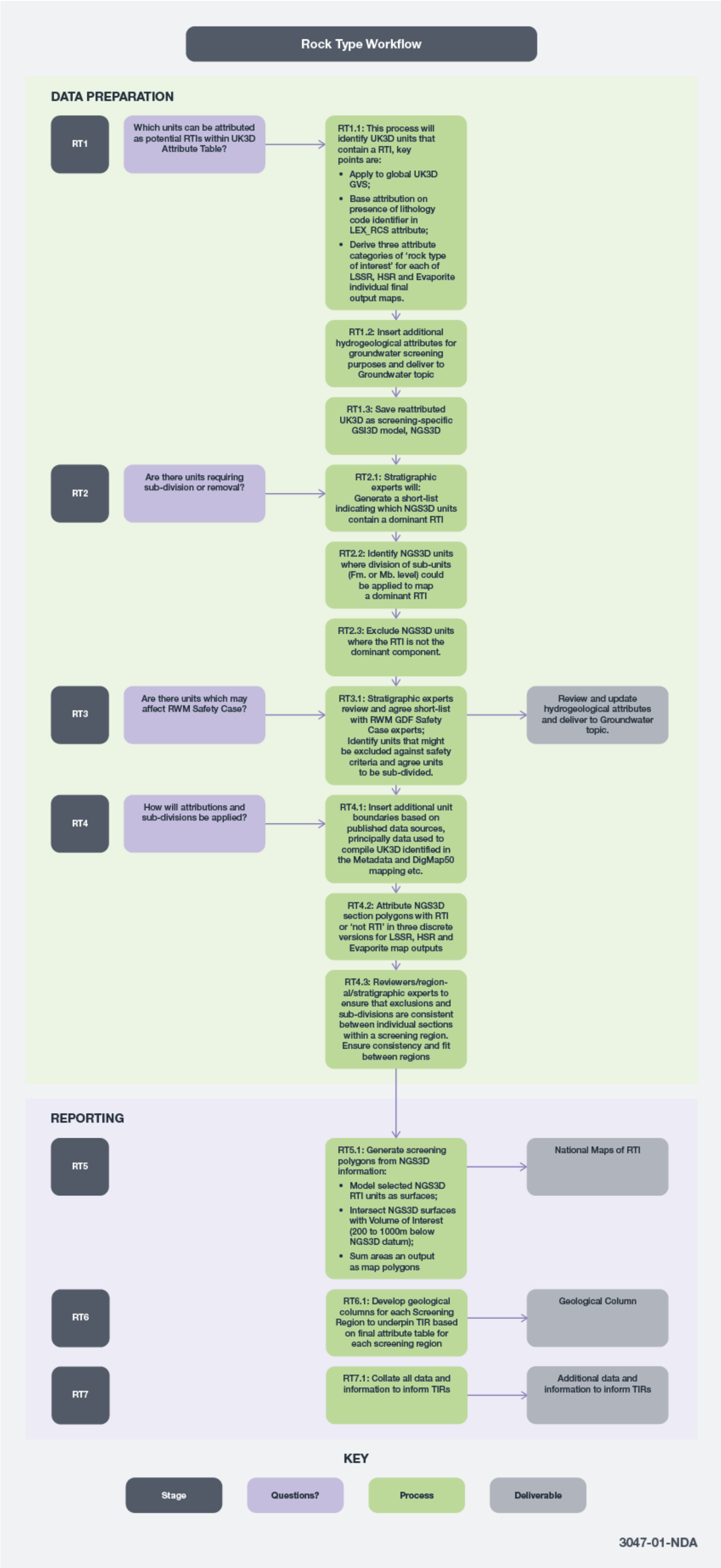
2.4 Detailed Technical Instruction workflow

2.4.1 Workflow overview

The Rock Type Detailed Technical Instruction workflow describes the methodology to be used to create the national maps and geological columns for the rock type component of the Technical Information Reports. These will form the basis for the geological description of the potential host rocks and surrounding rock formations. The workflow is organised in a series of ordered, linked steps RT1 to RT7 (Figure 1). Each step comprises an action or actions to be undertaken using specific supporting data and information.

Figure 1 is a schematic illustration of the Rock Type Detailed Technical Instruction workflow showing how Rock Types of Interest will be mapped between 200 m and 1000 m below the NGS datum. The workflow itself is further detailed in Table 2 Section 2.4.2 below.

Figure 1 Schematic Illustration of Rock Type Detailed Technical Instruction



As each Rock Type Detailed Technical Instruction workflow action step is undertaken the results will be captured as detailed metadata. This will inform the Technical Information Reports produced for each region. The report should include notes of which information sources provide the evidence for specific statements. Where appropriate, if the information has been derived from visual sources, such as digital maps or geological sections, then, if needed, a screen-grab of the source image can be included to substantiate and illustrate key statements described.

2.4.2 Detailed workflow description

Table 2 Rock Type Detailed Technical Instruction Workflow

Step	Description of activity
Data Preparation	
RT1 Which units can be attributed as potential RTIs within UK3D Attribute Table?	
RT1.1	This process will interrogate the table of attributions of UK3D for England, Wales and Northern Ireland to identify the presence of a lithology equating to a Rock Type of Interest within each lithostratigraphic unit represented in the model. In this process, all the UK3D units that contain a RCS code signifying a Rock Type of Interest as a sole or composite component will be identified in the GVS. Three additional columns will be inserted into the table of attributions for identifying Rock Types of Interest for LSSR, HSR and Evaporite models (Table 1). For each LEX_RCS entry, these will be completed as either 'Rock Type of Interest' or 'not a Rock Type of Interest' depending on the presence of absence of a relevant lithology in the RCS component of the LEX_RCS attribution code (See Appendix 1).
RT1.2	At this stage, additional attribution columns will be added to identify key hydrogeological features that will inform the groundwater screening topic, namely NGS3D units which make up part of a 'principal aquifer' or can be classified as 'unproductive strata' (defined by Groundwater Detailed Technical Instruction). This information will be used for developing the screening outputs relevant to groundwater and will cross-over into the Groundwater topic at this point.
RT1.3	The version of UK3D with new attributions added will be saved as NGS3D in order to separate the primary information from that customised for national geological screening purposes.
RT2 Are there units requiring sub-division or removal?	
RT2.1 – RT2.3	Stratigraphic experts (selected in accordance with the Expert Judgement Protocol in Section 7.2.1) will review each region-specific GVS. Experts will use their own knowledge, expert consultees and published sources of information, such as BGS maps and memoirs, to identify NGS3D units or sub-units where the Rock Type of Interest is the dominant lithology. NGS3D units that do not contain a dominant Rock Type of Interest will then be excluded from the short-list in the NGS3D attribution table. For the purposes of Geological Screening, for an LSSR lithology or Evaporite to be the dominant Rock Type of Interest it should comprise at least 50 % of the NGS3D unit or component stratigraphic sub-unit, and form laterally continuous layers over a scale of at least a 5 km radius, estimated to be consistent with the likely extent required as a host or lower permeability overlying rock for a GDF safety case. It should be noted that, as a constraint from the primary survey data from which UK3D is derived, it is expected that NGS3D sub-units will be at least 10 m thick. For an HSR lithology to be the dominant Rock Type of Interest it should comprise at least 80% of the

Step	Description of activity
	NGS3D unit or sub-unit, which is estimated as the proportion likely to provide a sufficient thickness of the Rock Type of Interest, in many of the relevant NG3D units, to provide a GDF host volume. Where there is insufficient information within the BGS published information to determine the detailed criteria for whether a Rock Type of Interest is dominant in an NG3D unit, the default position will be to retain that NGS3D unit in the short-list. Our approach to identifying dominant lithology within an NGS3D unit will be to: a) filter NGS3D units and their sub-units, also listed in the BGS Lexicon, on the basis of the 'dominant' or 'major component' recorded in BGS Lexicon of named rocks b) review short-listed units against RWM specific criteria above The methodology for determining 'dominant' or 'major components' from the BGS Lexicon is described and tested in Appendix 2. A review of sub-units will provide a check of the completeness of the short-list and facilitate the identification of select units to be sub-divided in NGS3D, proportionate to national screening. The units or sub-units containing a dominant Rock Type of Interest based on searching the BGS Lexicon, will be researched from published BGS material such as geological memoirs or sheet explanation series to identify whether they meet the detailed criteria. Any units, where there is explicit information, that do not meet the criteria will be excluded from the short-list. Similarly, because the BGS Lexicon of named rock units is incomplete, those for which there is no entry for 'major' or 'dominant' rock type will be determined on the basis of research from published BGS sources. The results of this phase of rationalisation will be recorded as an updated short-list in three additional columns in the attribution table indicating 'Rock Type of Interest' or 'not a Rock Type of Interest' for LSSR post-review_1, HSR post-review_1, and Evaporite post-review_1.
RT3 Are there units which may affect RWM Safety Case?	
RT3	In order to confirm the short-listed selection of Rock Types of Interest BGS Stratigraphic experts will review and agree with RWM safety case experts. If needed, this review process will include workshops for Screening Regions. This process will test and challenge the short-list as well as identify further NGS3D units that could be excluded on the basis of specific GDF safety-case criteria identified by RWM experts. At this stage BGS and RWM experts will also ensure that the final short-list is proportionate to national screening and consistent with the accuracy and precision of the original datasets. The results of this review will be recorded in additional columns in the GVS indicating 'Rock Type of Interest' or 'not a Rock Type of Interest' for LSSR post-review_2, HSR post-review_2, and Evaporite post-review_2. Additional sub-units to be modelled will also be inserted in their stratigraphic position into the GVS. At this stage the hydrogeological attributions of 'principal aquifer' and 'unproductive strata' will be updated to reflect the GVS short-list and the detailed requirement of the Groundwater topic and cross-over into that workflow.

Step	Description of activity
RT4 How will attributions and sub-divisions be applied?	
RT4.1	Any subdivisions agreed and identified in the short-listed attribution table will be applied to NGS3D sections. Additional unit boundaries will be developed following UK3D methods. This will comprise: a) inserting surface geological map boundaries for additional sub-units extracted from appropriate BGS digital geological mapping (DigMapUK 50); b) projecting the bases of additional sub-units into the subsurface, constrained principally by boreholes and other subsurface information that have already been used to develop UK3D, but also consulting other published BGS information if required; and c) updating associated metadata. The methodology and testing for this process are described in Appendix 2.
RT4.2	The NGS3D sections, including any new sub-units, will be attributed with 'Rock Type of Interest' or 'not Rock Type of Interest' from short-list attribution tables for each of the three intended output versions, LSSR, HSR and Evaporite.
RT4.3	Review and approval of NGS3D customised fence diagram. This step provides the essential Quality Assurance (QA) of the attributed model between BGS reviewers, regional and stratigraphic experts. BGS stratigraphic experts will ensure that inserted sub-units and reattribution is consistent between individual cross-sections.
Reporting	
RT5	Once the NGS3D sections are approved, this step applies the process needed to develop NGS3D units as map polygons (see Protocol, Section 7.5.2) illustrating the extent of Rock Types of Interest between 200 m and 1000 m beneath the NGS datum. The GSI3D section lines representing the bases of units attributed as Rock Types of Interest are exported as polylines into SKUA-GOCAD geological modelling software. Model surfaces are interpolated. These are imported back into GSI3D and the tops of units identified. The detailed methodology for this process is presented in Appendix 3. The top and base surfaces are exported into ArcGIS software as ASCII grids. Surface representing the 200 m and 1000 m below NGS datum (Protocol, 7.4.1), defining the Volume of Interest (VOI) are also imported into ArcGIS. These two datasets are intersected using the ArcGIS Raster Calculator and output as shape files representing the aerial extent of each Rock Type of Interest attributed unit in the VOI. This process and associated testing are described in detail in Appendix 3. Individual units for LSSR, HSR and Evaporite are summed to define a 'combined Rock Types of Interest' polygon for each category that is inserted into an appropriate ArcGIS map layout as a Production Map. The distribution of Evaporites will be provided to the Resources workflow to inform the generation of text regarding gas storage potential (see Section 6.4.5.2)
RT6	Develop a unique GVS for each Screening Region (based on methodology in Appendix 1). Based on the GVS for each Screening Region, a diagrammatic geological succession will be produced that illustrates the stratigraphic succession present in the regional GVS, as well as key screening attributions of Rock Types of Interest for each of LSSR, HSR and Evaporite, and NGS3D units that are classified as a principal aquifer rocks or unproductive strata.
RT7	For each region a Technical Information Report will be written by the Regional expert that describes the potential host rocks and other Rock Types of Interest in the context of the overall geological succession for that region.

Step	Description of activity
	Each report will include a commentary that describes the lithology of the Rock Types of Interest and an account of their distribution and thickness variation as well as additional high level information that may influence GDF safety (example of weathering in granites). The report content will be informed by the production maps and diagrammatic geological successions and will be consistent in format with existing regional geological summaries which can be viewed at http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html.

2.5 Relationship with other Detailed Technical Instructions and the NGS Protocols

The Rock Type Detailed Technical Instruction does not depend on the outputs of the other Detailed Technical Instructions. However, other Detailed Technical Instruction's explicitly depend on its outputs, namely Groundwater and Resources, as well as the NGS Protocols (Section 7.0).

The Groundwater Detailed Technical Instruction requires input from the Rock Type Detailed Technical Instruction in the form of:

- information regarding the Rock Types of Interest, specifically their annotation in the UK3D GVS and sections (i.e. GW2.1))
- information regarding Principal Aquifers and Unproductive Strata, i.e. their annotation in the UK3D GVS and sections (i.e. GW2.2 and GW2.3)
- brief lithological descriptions of the rock types of interest (i.e. GW6)
- maps of the distribution of the rock types of interest (i.e. GW1)

The Resources Detailed Technical Instruction requires the outputs from Rock Type against which to check that the commodities defined by areas of deep mining are compatible with the geology as defined by rock type and to inform the consideration of gas storage potential in salt. If any differences are noted this information will be fed back, retrospectively, into the Rock Type and Resources Detailed Technical Instructions.

The Rock Type Detailed Technical Instruction is to be undertaken in the context of the NGS Protocols outlined in Section 7), and, as already noted above, a number of assumptions specific to the Rock Type Detailed Technical Instruction, consistent with the NGS Protocols, have been identified. In addition, the Rock Type Detailed Technical Instruction explicitly requires the use of:

- existing data (Section 7.1.1)
- approach to metadata (Section 7.1.2)
- nomenclature (Section 7.3.2)
- NGS datum for depth (Section 7.4.1)
- approach to expert judgement (Section 7.2.1)
- maps formats and conventions (Section 7.5.2)
- Technical Information Report and NGS Narratives(Section 7.5.1)
- terminology (Section 7.3.1)

2.6 References

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3 Detailed Technical Instruction: Rock Structure

3.1 Introduction

This Detailed Technical Instruction sets out how data and information on the topic of rock structure will be assembled and presented. For the rock structure topic the following outputs for each of the 13 regions have been specified in the Guidance:

- explanation of the nature of the structures within the region that are relevant to safety, these will be major faults and fault zones and areas of folded rocks with complex properties
- regional maps of the distribution of the structures described in the narrative.

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This Detailed Technical Instruction sets out a step-by-step description of how information related to Rock Structure in England, Wales and Northern Ireland will be assembled and presented for National Geological Screening. To do this the Rock Structure Detailed Technical Instruction has the following structure:

- definitions and assumptions - describes the definitions and assumptions (including use of expert judgements) used to specify how the outputs are produced (Section 3.2)
- data and information sources - details the data sources available for the study (Section 3.3)
- topic process and workflow - provides an overview of the Rock Structure process, a step-by-step methodology for the analysis and interpretation of the data and a description of the required outputs of maps and the Technical Information Reports (Section 3.4)
- relationship with other Instructions and Protocols - describes the relationship with other Detailed Technical Instructions and the NGS Protocols (Section 3.5)
- references - presents a short list of references (Section 3.6).

3.2 Definitions and assumptions

3.2.1 Definitions

In order to develop the Detailed Technical Instruction the following attributes identified in the Guidance are defined:

- location of major faults
- location of highly folded zones

3.2.1.1 Major faults

For the purpose of this Detailed Technical Instruction, major faults are defined as those that give rise to the juxtaposition of different rock types and/or changes in rock properties within fault zones which may impact on the behaviour of groundwater at GDF depths. It was judged that faults with a vertical throw of at least 200m would be proportionate with the national scale screening outputs since these would be most likely to have significant fracture networks and/or fault rocks and would have sufficient displacement to juxtapose rock of contrasting physical properties at the GDF scale. However, faults that do not meet the 200m criterion, but are still considered significant, at the 1:625,000 scale of screening by the regional expert, will also be mapped and discussed in the Technical Information Report compiled for each region. It is recognised that many locally important minor faults would not meet this criterion and would be more appropriately mapped during regional or local geological characterisation stages.

3.2.1.2 Locations of highly folded zones

Areas of folded rocks are considered to be important in a heterogeneous body of rock, such as interlayered sandstone and mudstone, where the rock mass has complex properties and fold limbs dip at steep angles, potentially resulting in complex pathways for deep groundwater. Where folding occurs in relatively homogeneous rock there is little change in the bulk physical properties and therefore there is less impact on fluid pathways. Hence, for this Detailed Technical Instruction, the folded rocks category will identify areas where anomalously steep dips are recorded in a heterogeneous rock mass of strongly contrasting physical properties. Their location will be indicated on the map in general terms and the nature of the folding will be discussed in the Technical Information Report compiled for each region.

3.2.2 Assumptions

Faulting in the UK is pervasive and therefore it is not practical to identify all faults and fault zones. Although any faulting can result in an area being difficult to characterise and could influence groundwater movement, it is assumed that minor faulting will be characterised in detail at the GDF siting stage and therefore only major faults, as defined above, are to be identified during national screening.

The majority of faults shown on BGS geological maps have been interpreted from surface information, while knowledge of faulting at depth is typically limited to areas of resource exploration where significant subsurface investigation has taken place. Faults shown on BGS geological maps are largely based on interpretation of topographic features that define stratigraphic offset and are not mapped purely on the basis of observation of fault rock distribution. Hence, in areas where the bedrock is concealed by superficial deposits, the stratigraphic units are thick and homogeneous, or there is limited subsurface data, faulting is likely to be under-represented (Aldiss, 2013). It is assumed in this workflow that, where faulting is not represented on current data sources (Section 3.3), the presence of any faulting will be determined at the GDF siting stage.

Where there is no subsurface data to constrain surface faults at depth it is assumed in this workflow that the faults are vertical and extend through the GDF screening depth range of 200 m to 1000 m. Where faults are known to terminate within the GDF screening depth range, this will be recorded and shown on the map.

3.3 Data and information sources

3.3.1 3D geological model

UK3D V2015 is described in Section 2.3.1. For the Rock Structure topic only an enhanced version of UK3D V2015 will be used. The enhanced version of UK3D V2015 includes explicit fault objects, where UK3D V2015 modelled faults as offsets in the stratigraphy. The enhanced version of UK3D V2015 used in this Detailed Technical Instruction also includes minor revision of the positions of some stratigraphic boundaries in UK3D in the vicinity of faults.

As part of its ongoing NERC-funded programme to further develop the National Geological Model, BGS commenced work in June 2015 to migrate GB3D from GSI3d to Groundhog and to augment the cross-sections in England Wales and Scotland with these fault objects. The enhanced version of UK3D for England, Wales and Northern Ireland is currently being checked and an interim version of the signed off fault data will be ready for Rock Structure topic by mid-March 2016. Work on the insertion of faults in UK3D for Scotland is in progress. The work will be completed by early autumn 2016, at which time it will released on the BGS website as the next full version of UK3D (UK3D v2016).

3.3.2 Principal information sources

There are a number of data sources used for this study. These are publicly available and are national datasets. The principal information sources identified in the Guidance include:

- Tectonic Map of Britain, Ireland and adjacent areas (1:1,500,000) (Pharaoh, 1996) - Tectonic data comprising main tectonostratigraphic sequence packages, from Archaean to Quaternary; magmatic rocks; structures attributed to the principal tectonic episodes (orogeny, extensional rifting and basin inversion) affecting Britain and Ireland and their offshore areas
- Map 2: Contours on the top of the Pre-Permian Surface of the United Kingdom (South) (1:1,000,000) (British Geological Survey, 1985) - Contour map of the base Permian including faults
- BGS 1:50,000 series (paper maps) - These provide a consistent series of surface maps across the UK. They include cross-sections which may be useful in identifying major faults and folds in the subsurface
- DiGMapGB-625 and DiGMapGB-50 - These are digital maps covering the UK at a scale of 1:625,000 and 1:50,000 scale respectively. They contain digital lines for faults

3.3.3 Other information sources

Additionally selected BGS published maps, memoirs and regional guides will be consulted as required and may include:

- regional subsurface memoirs
    - structure and stratigraphy of use particularly for information on the deeper concealed geology of regions of the UK and their evolution through time
- regional guides
    - overview of the geology of the individual regions of the United Kingdom
- BGS Sheet Memoirs, Sheet Explanations and Sheet Description
    - detailed reports for each 1:50,000 scale map sheet containing detailed information of the structure and subsurface geology of the map sheet which will be used to justify fault names and detailed information related to the geology
- BGS Offshore Memoirs
    - overview of the offshore geology around the coast of the UK
- Seismic Atlas of southern Britain
    - summary of important structural features in England and Wales

3.4 Detailed Technical Instruction workflow

3.4.1 Workflow overview

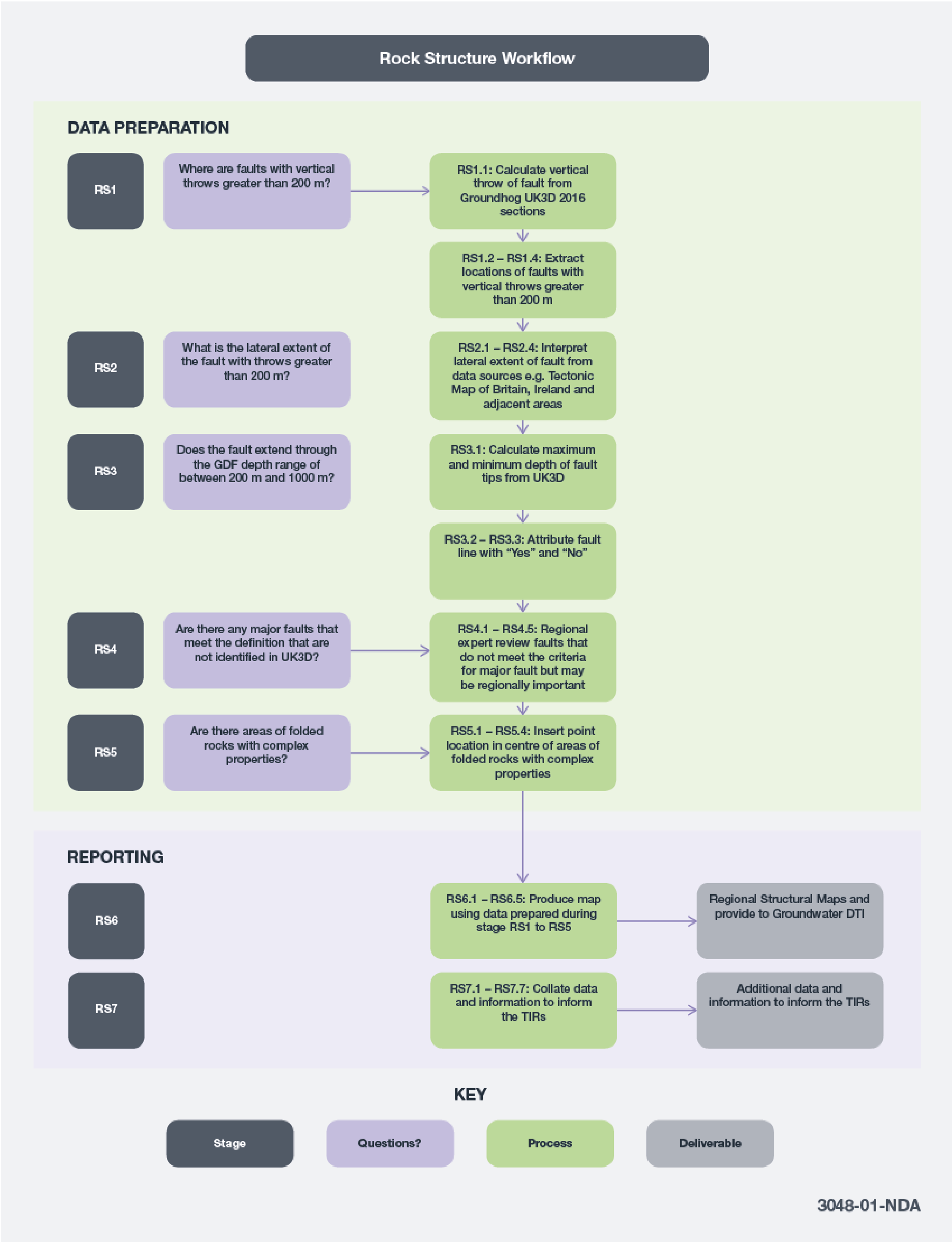
Using the data sources outlined above, Technical Information Reports and maps will be produced following the workflow outlined below to demonstrate the understanding of the major faults and areas of folded rocks with complex properties in each of the 13 regions as defined in the Guidance.

The workflow follows as a series of stages (Figure 2) which are described in detail in Tables 3 and 4 in Section 3.4.2. The workflow can be divided into two sections: data preparation; and reporting. The data preparation section consists of stages Rock Structure Step 1 (RS1) to RS5. These stages collate the data to produce a series of mapped major faults and point locations for areas of folded rocks with complex properties which will be discussed in detail in the Technical Information Reports. Metadata will be collected during the implementation to record any expert judgment decisions that were made.

Stages RS7 and RS8 describe the specifications and processes required to develop the outputs as defined in the Guidance. This will include a description of the rock structures of the region as displayed on the accompanying map of major faults and locations of areas of folded rocks with complex properties which was produced during stages RS1 to RS5.

Reviews will be undertaken during the data preparation stage and the reporting stage to ensure consistency and accuracy across all regions.

Figure 2 Schematic Illustration of Rock Structure Detailed Technical Instruction



3.4.2 Detailed workflow description

Table 3 Rock Structure Detailed Technical Instruction Workflow – Data Preparation

Step	Action and assumptions	Data and/or information sources
Data Preparation		
RS1 Where are major faults with vertical throw greater than 200 m?		
RS1.1	Using the enhanced version of UK3D V2015 in Groundhog software, vertical throws will be calculated for all faults. The level of detail and accuracy of UK3D sections are proportionate to the scale and level of information required at a national screening scale.	UK3D
RS1.2	Faults with vertical throws greater than 200 m will be extracted from UK3D. The vertical throw is a good representation of the fault displacement in section at a scale proportionate to a national screening program.	
RS1.3	Only the maximum vertical throw shown on the cross-section for each fault will be considered.	
RS1.4	These will be exported as points along the UK3D cross-sections with metadata including fault name, maximum offset, and stratigraphic unit with greatest offset.	
RS2 What are the lateral extents of the faults with vertical throws greater than 200 m?		
RS2.1	The points extracted from UK3D (RS1.4) will be superimposed on data sources to identify the lateral extent of the faults identified in the UK3D cross-sections.	Tectonic Map of Britain, Ireland and adjacent areas, Pre-Permian map of the United Kingdom (South) Map, DiGMapGB-625
RS2.2	The points extracted from UK3D, will be correlated with the lateral extent using DiGMapGB-625, Pre-Permian geology of the United Kingdom (South) map and the Tectonic Map of Britain, Ireland and adjacent areas. The data sources are accurate and consistent. If inconsistencies are apparent then this will be captured in comments in the metadata.	
RS2.3	Fault name, maximum vertical throw, and stratigraphic unit with greatest vertical throw will be captured in the metadata table for major faults.	UK3D, Memoirs, Regional Guides, Subsurface Memoirs, Tectonic Map of Britain, Ireland and adjacent areas, Offshore Memoirs
RS2.4	Data sources and comments on the faults will be captured in the metadata table associated with major faults and fault	

Step	Action and assumptions	Data and/or information sources
	zones. Additionally the consistency between the data sources will be discussed and comments made on the interpretation taken.	
RS3 Does the fault extend through the GDF depth range of between 200 m and 1000 m?		
RS3.1	Using UK3D, the maximum and minimum depth of the faults with vertical throws greater than 200 m will be extracted and recorded in the metadata.	UK3D, RS1
RS3.2	Based on UK3D, the user will identify those faults that either extend through or terminate within the GDF depth range.	
RS3.3	The fault lines developed in RS2 will be attributed with "Yes" or "No" to describe if the fault extends through the GDF depth range.	
RS4 Are there any major faults that meet the definition of major fault that are not identified in UK3D?		
RS4.1	If there are known major faults that are not identified in UK3D, the regional expert may use the their expert judgement and other data to include these faults within the map.	BGS published maps, Memoirs and Regional Guides
RS4.2	The lateral extent of these faults will be drawn.	Tectonic Map of Britain, Ireland and adjacent areas, Pre-Permian geology of the United Kingdom (South), DiGMap-625
RS4.3	Fault name, maximum vertical throw, and stratigraphic unit with greatest vertical throw will be captured in the metadata table for major faults.	
RS4.4	Data sources and comments on the faults will be captured in the metadata table associated with major faults and fault zones. Additionally the consistency between the data sources will be discussed and comments made on the interpretation taken.	
RS4.5	The fault lines developed in RS2 will be attributed with "Yes" or "No" to describe if the fault extends through the GDF depth range.	
RS5 Are there areas of folded rocks with complex properties?		
RS5.1	Based on the data sources the regional expert will identify areas of folded rocks with complex properties. These include subsurface areas within the GDF depth range of between 200 m and 1000 m.	UK3D, Tectonic Map of Britain, Ireland and adjacent areas, BGS published maps, memoirs and regional guides
RS5.2	These will be indicated on the map by a point or letter located approximately in the centre of the areas of folded rocks with complex properties and referred to in the accompanying Technical Information Report.	
RS5.3	Metadata table to be completed including an ID consisting of the Region Number followed by area number e.g. the third	

Step	Action and assumptions	Data and/or information sources
	area of folds in Region 10 would be "10.3".	
RS5.4	Metadata will be completed briefly commenting on the area of folded rocks and complex properties and giving any references.	

Table 4 Rock Structure Detailed Technical Instruction Workflow - Reporting

Step	Action and assumptions	Data and/or information sources
Reporting		
RS6 Regional Rock Structure Maps		
RS6.1	Maps for each region will be constructed based on the interpreted fault lines and folding identified in steps RS1 to 5.	**RS4** and **RS5**
RS6.2	These maps will be used by the Groundwater Detailed Technical Instruction steps GW3.2 and GW6.2.	
RS6.3	Solid lines will be used for faults that extend through the GDF depth range.	
RS6.4	Dashed lines will be used for faults that are truncated within the GDF depth range.	
RS6.5	Areas of folded rocks with complex properties will be displayed as a point or letter that will be referred to in the Technical Information Report.	
RS7 Rock Structure Technical Information Reports		
RS7.1	The Technical Information Report for each region will be written by the regional expert within BGS.	BGS published maps, memoirs and regional guides
RS7.2	The Technical Information Report will give a brief account of the structure of the region.	
RS7.3	The Technical Information Report will describe the large scale structures e.g. broad folds (Wealden Anticline) or blocks and basins e.g. Northumberland Basin, Alston Block (Waters *et al*. 2009).	
RS7.4	Describe the typical faulting of the region in general terms, e.g. minor faulting in the region is pervasive and typically trend E-W and N-S.	
RS7.5	Describe the extent and nature of the major faults identified on the supporting map for each region.	
RS7.6	Describe the extent and nature of areas of folded rocks with complex properties identified on the supporting map for each region.	

3.5 Relationship with other Detailed Technical Instructions and the NGS Protocols

The Rock Structure Detailed Technical Instruction does not depend on outputs from the four other Detailed Technical Instructions. However, the Groundwater Detailed Technical Instruction depends on outputs from the Rock Structure Detailed Technical Instruction, as well as the NGS Protocols (Section 7).

The Rock Structure Detailed Technical Instruction will provide the Groundwater Detailed Technical Instruction with maps of basin bounding faults, structural lineaments and folds with steeply dipping limbs (i.e. specifically RS6.2 will directly input into GW3.2 and GW6.2).

The Rock Structure Detailed Technical Instruction is to be undertaken in the context of the NGS Protocols (Section 7), and, as already noted above, a number of assumptions specific to the Rock Structure Detailed Technical Instruction, consistent with the NGS Protocols, have been identified. In addition, the Rock Structure Detailed Technical Instruction explicitly requires the use of the following protocols:

- existing data (Section 7.1.1): RS1.1, RS2.2
- approach to metadata (Section 7.1.2): RS1.4, RS2.3, RS2.4, RS4.3, RS5.4, RS5.5
- nomenclature (Section 7.3.2): RS1.4, RS2.3, RS4.3, RS5.4, RS5.5, RS7.1
- NGS datum for depth (Section 7.4.1): RS3.1, RS5.1
- approach to expert judgement (Section 7.2.1): RS4.1, RS5.1
- maps formats and conventions (Section 7.5.2): RS6.1
- Technical Information Reports and NGS Narratives (Section 7.5.1): RS7.1
- terminology (Section 7.3.1): RS7.1

3.6 References

Aldiss, D. T. 2013. Under-representation of faults on geological maps of the London region: reasons, consequences and solutions. *Proceedings of the Geologists Association*. 124, 929-945.

Waters, C. N., Waters, R. A., Barclay, W. J., and Davies, J. R., 2009. A lithostratigraphical framework for the Carboniferous successions of southern Great Britain (Onshore). British *Geological Survey Research Report*, RR/09/01.

4 Detailed Technical Instruction: Groundwater

4.1 Introduction

This Detailed Technical Instruction sets out how data and information on the topic of groundwater will be assembled and presented as part of the national geological screening exercise. For the groundwater topic, the following outputs for each of the 13 regions have been specified in the Guidance:

- an explanation of the known shallow and deep groundwater flow regimes and groundwater chemistry, salinity and age
- a discussion of the rock types and other geological features likely to influence groundwater movement and the interaction between deep and shallow groundwater in a region
- a map at 1:625,000 scale will be produced of areas showing locations of thermal springs (to be produced under this Detailed Technical Instruction)
- Maps at 1:625,000 scale will be produced showing locations of deep boreholes and mines (to be produced under the Resources Detailed Technical Instruction, see Section 6)

A number of features related to the movement and chemical composition of groundwater present in rocks from the surface down to a depth of around 1000 m have been identified as attributes in the Guidance. These are:

- the presence of aquifers
- the presence of geological features and rock types which may indicate separation of shallow and deep groundwater systems
- the locations of features likely to permit rapid flow of deep groundwater to near-surface environments
- the age and chemical composition of groundwater

This chapter sets out a step-by-step description of how groundwater-related information, with particular emphasis on groundwater characteristics pertinent to the safety case for a GDF in the interval of interest from 200 m to 1000 m, of 13 regions of England, Wales and Northern Ireland will be assembled and presented as part of the national geological screening exercise. It has the following structure:

- definitions and assumptions – definitions and assumptions used in the production of groundwater outputs (Section 4.2)
- data and information sources – overview of the information to be used in the Groundwater Detailed Technical Instruction with reference to the Geological Data and Information Technical Note (Section 4.3)
- topic process and workflow - overview of the Groundwater process, followed by a step-by-step description of the Groundwater workflow (Section 4.4)
- relationship with other Instructions and Protocols - a brief note on the relationship between the Groundwater Detailed Technical Instruction, the other Detailed Technical Instructions prepared for the national geological screening exercise, and the NGS Protocols set out in Section 7 (Section 4.5)
- references - a list of references cited in this Groundwater Detailed Technical Instruction (Section 4.6)

4.2 Definitions and assumptions

In order to produce the groundwater-related narrative for the Technical Information Reports, it is necessary to define the following hydrogeological terms: aquifers and groundwater, and to define a number of hydrogeological concepts, including: the depth of groundwater systems and features; groundwater flow; thermal springs; and hydrogeological separation.

Section 4.2.2 sets out the assumptions which will be used to support this Detailed Technical Instruction.

4.2.1 Definition of aquifers, groundwater and related terms

4.2.1.1 Aquifers

For the purposes of the Detailed Technical Instruction, aquifers are defined for England and Wales based on the Environment Agency designation and for Northern Ireland following the bedrock aquifer scheme for the Water Framework Directive of McConvey (2005).

The Environment Agency (EA) has designated aquifers in England and Wales consistent with the Water Framework Directive (European Union, 2000; Environment Agency, 2013). The EA consider 'aquifers' to be 'underground layers of water-bearing permeable rock or drift deposits from which groundwater can be extracted' (see http://apps.environment-agency.gov.uk/wiyby/117020.aspx). Aquifers were designated based on geological maps of the ground surface or rock head provided by the British Geological Survey at a scale of 1:50,000. This designation was for the purpose of producing Groundwater Vulnerability Maps, which indicated the vulnerability of groundwater to surface and near surface pollutants. The aquifer designations 'reflect the importance of aquifers in terms of groundwater as a resource (drinking water supply) but also their role in supporting surface water flows and wetland ecosystems' (see http://apps.environment-agency.gov.uk/wiyby/117020.aspx). The EA had responsibilities for Wales until handover to Natural Resources Wales in 2013; the same aquifer designations still apply in Wales.

The EA define a number of aquifer types and 'Unproductive Strata' as follows in Table 5.

Table 5 EA Definitions of Aquifers and Unproductive Strata

Aquifer / Strata type	Definition
Principal Aquifer	These are layers of rock or drift deposits that have high intergranular and/or fracture permeability - meaning they usually provide a high level of water storage. They may support water supply and/or river base flow on a strategic scale. In most cases, principal aquifers are aquifers previously designated as major aquifer.
Secondary Aquifer	These include a wide range of rock layers or drift deposits with an equally wide range of water permeability and storage. Secondary aquifers are subdivided into three types: Secondary A; Secondary B; and Secondary Undifferentiated.
Secondary A	Permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers. These are generally aquifers formerly classified as minor aquifers.
Secondary B	Predominantly lower permeability layers which may store and yield limited amounts of groundwater due to localised features such as fissures, thin permeable horizons and weathering. These are generally the water-bearing parts of the former non-aquifers.
Secondary Undifferentiated	Cases where it has not been possible to attribute either category A or B to a rock type. In most cases, this means that the layer in question has previously been designated as both minor and non-aquifer in different locations due to the variable characteristics of the rock type.
Unproductive Strata	These are rock layers or drift deposits with low permeability that have negligible significance for water supply or river base flow.

Because Secondary Aquifers are defined by the EA as aquifers with local rather than strategic importance, they will not be considered specifically in this Detailed Technical Instruction. However, if they have an important role in the hydrogeology of a particular region, reference may be made to them in step GW4, specifically step GW4.2 of the Groundwater workflow. They would be considered in more detailed assessments during any siting process.

Principal Aquifers need to be identified at an appropriate scale for the national geological screening exercise and are considered as coherent units of common lithostratigraphy on the basis of proximity in the stratigraphic column. For the purposes of the NGS, all the bedrock Principal Aquifers have been grouped into 19 units[1] as follows:

- Crag Group (except clay)
- Chalk Group
- Upper Greensand Group
- Lower Greensand Group (except mudstone and some Sandgate Formation)
- Sandringham Sand Formation
- Cromer Knoll Group
- Portland Group (Portland Stone Formation only)
- Corallian Group and Brantingham Formation (Yorkshire only)
- Great Oolite Group limestones (excluding Cornbrash Formation)
- Inferior Oolite Group limestones
- Bridport Sand Formation (except Down Cliff Clay Member)
- Blue Lias Formation and Mercia Mudstone Group marginal facies only
- Sherwood Sandstone Group
- Zechstein Group dolomites

  Permian sandstones (Dawlish Sandstone Formation sandstones, Rotliegendes Group, Appleby Group and Bridgnorth Sandstone Formation)
- Warwickshire Group (Ashow, Kenilworth Sandstone, Tile Hill Mudstone and parts of Salop (Allesley, Keresly and Whitacre members) formations)
- Fell Sandstone Formation sandstones
- Carboniferous Limestone Supergroup limestones and sandstones (includes Onecote Sandstones of Widmerpool Formation)
- Middle and Upper Devonian limestones

In Northern Ireland, bedrock aquifers are classified into six categories for the Water Framework Directive (European Union, 2000), based upon resource potential, productivity and flow type (McConvey, 2005). Six high potential productivity rocks (Table 6) were identified by McConvey (2005).

The high potential productivity formations for Northern Ireland in Table 7 are taken to be equivalent to the Principal Aquifers in England and Wales.

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[1] Note that as part of the BGS/EA iHydrogeology project (http://www.bgs.ac.uk/aquifers-shales/) BGS identified 11 Principal Aquifers. The iHydrogeology project, based on BGS' UK3D model and associated stratigraphic succession, had the purpose of producing maps of separation between aquifers and shales. Since only 11 of the 19 Principal Aquifer units listed above were represented in the UK3D model only those 11 Principal Aquifers were considered in that project. However, as the Groundwater DTI is not required to produce maps of Principal Aquifers, for this NGS exercise all 19 Principal Aquifers can be considered in the narratives.

Table 6 **Bedrock Aquifers Classification in Northern Ireland (from McConvey 2005)**

Aquifer Category	Symbol	Description
High productivity fracture flow	Bh (f)	High to moderate yields probable, however dependence on fracture flow makes poorer yields possible. Generally includes element of regional flow (kms).
High productivity fracture/intergranular flow	Bh (I-f)	High to moderate yields probable, however part dependence on fracture flow makes poorer yields possible. Dual porosity. Generally includes element of regional flow.
High productivity fracture flow with karstic element	Bh (f-k)	High to moderate yields probable, however dependence on fracture flow makes poorer yields possible. Evidence of karstic flow. Generally includes element of regional flow.
Moderate productivity fracture flow	Bm (f)	High to moderate yields possible in places however dependence on fracture flow makes poorer yields possible. Potential element of regional flow, but local flow significant.
Limited productivity fracture flow	Bl (f)	Moderate yields unusual. Low yields more common. Regional flow limited. Mainly shallow, local flow.
Poor productivity fracture flow	Bp (F)	Small supplies may be possible but strata rarely exploited. Negligible regional flow. Limited local flow.

Table 7 **High Potential Productivity Rock Formations in Northern Ireland (from McConvey, 2005)**

Formation	Potential productivity and flow type
Hibernian Greensand and Ulster White Limestone Formations	High productivity - fracture flow, with karst.
Sherwood Sandstone Formation	High productivity- fracture/intergranular flow.
Enler Group	High productivity- fracture/intergranular flow.
Dartry Limestone Formation	High productivity - fracture flow, with karst.
Knockmore Limestone Member and Ballyshannon Limestone Formation	High productivity - fracture flow, with karst.
Ballysteen, Ulster Canal, Cooldaragh and Fearnaght formations	High productivity - fracture flow, with karst.

4.2.1.2 Groundwater

This Detailed Technical Instruction will use the definition of 'groundwater' set out in the Water Framework Directive (European Union, 2000) as 'all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil'. Given this general, non-specific definition, groundwater will be present in both Principal Aquifers and other rock types. However, groundwater will vary significantly in quality and age, particularly with depth. For example, groundwater in aquifers in good hydraulic connection with the land surface are typically relatively young with their chemistry influenced by meteoric water (water derived from precipitation). Groundwater age and degree of mineralisation generally increase with depth and in relatively deep formations the chemistry of the groundwater may reflect connate water (waters associated with the deposition of the rocks).

4.2.1.3 Potentially confining layers and Unproductive Strata

Rocks with the potential to confine groundwater in underlying aquifers will generally be unproductive and of low permeability. Unproductive Strata, as defined by the EA (Table 5), are important rock types because they are low permeability beds that can potentially confine groundwater in underlying aquifers and hence potentially may separate groundwater systems within a region of interest (see also definition of hydraulic separation below). The workflow (Section 4.4) calls for information about or consideration of Unproductive Strata at various steps, and it is taken that throughout the workflow Unproductive Strata are synonymous with units that have the potential to provide separation between groundwater systems.

As with the Principal Aquifers, Unproductive Strata in England and Wales were originally defined by the EA at a scale of 1:50,000 (http://apps.environment-agency.gov.uk/wiyby/117020.aspx), so they need to be identified at the national-scale. Consequently, on the basis of common lithostratigraphy and proximity in the stratigraphic column, the following units, generally groups of formations, have been defined as Unproductive Strata:

- Bembridge Marls Formation
- Barton Clay Formation
- Thames Group
- Gault Formation
- Lias Group mudstones (excluding Charmouth Mudstone Formation)
- Weald Clay Formation and Atherfield Clay Formation
- West Walton, Ampthill and Kimmeridge Clay formations
- Kellaways and Oxford Clay formations
- Frome Clay and Fuller’s Earth formations
- Mercia Mudstone Group halite
- Cumbrian Coast Group halite and gypsum

There are other confining beds in England and Wales, not designated by the EA as Unproductive Strata, but as Secondary Aquifers, which may fall within the Rock Type Detailed Technical Instruction definition of Rock Types of Interest [Section 2.2]. These geological units include the following: the Lias Group; the Mercia Mudstone Group; and Permian mudstones. Where these units are potentially confining layers they will be classified as Rock Types of Interest.

In Northern Ireland, geological units that are classified as potential poor productivity rocks (Table 6) are taken to be equivalent to Unproductive Strata in England and Wales. These are as follows:

- Lough Neagh Group and Dunaghy Formation
- Waterloo Mudstone Group; the Penarth Group; and, the Mercia Mudstone Group (note these are contiguous geological units and will be treated as a single unit for the purposes of the Groundwater Detailed Technical Instruction)

Other confining beds located above high productivity aquifers in Northern Ireland are: the Palaeocene basalts and Belfast Group. Again, where these units do not fall within the classification of Rock Types of Interest they will still be considered.

4.2.1.4 Depth of features of groundwater systems

Table 2 in UKTAG (A partnership of the UK environment and conservation agencies) (2012), a report defining the extent of Groundwater Bodies (WFD management and reporting units), states that for 'highly productive aquifers', such as the bedrock Principal Aquifers, a maximum depth (of groundwater bodies) of 400 m should be assumed by default unless this can be altered using 'local information if available'. Consequently, in the absence of any other guidance, and by analogy, although groundwater can be present 400 m below ground level Principal Aquifers will be assumed to be only present down to 400 m below ground level. Note that the three-dimensional extent of aquifers would be further defined during the siting process, taking into account local information. Given this definition, it is necessary to make reference to the depth of the base of Principal Aquifers relative to ground level. Where this is the case, the depth of the base of Principal Aquifers will always be explicitly specified as 'metres below ground level' or (m bgl).

More generally, when making reference to groundwater, the position of features of the groundwater system will be described as either:

i. based on information about the absolute position of features of the groundwater system (e.g. 'in the north-west of the region the Chalk Principal Aquifer lies at least 200 m above the top of the Lias Clay' or 'based on geochemical evidence [include citation], the source of groundwater for the thermal springs is from a minimum of 4000 m); or

ii. in terms of the relative positions of specific rock types or units (e.g. 'across the region the Chalk always overlies both the Oxford Clay and the Lias Clay' or 'a groundwater flow system below the London Clay is characterised by higher total dissolved solids (TDS) and residence times typically >10,000 years [include citation]')

Depth-related terms will not be used in an ambiguous manner (e.g. the following references to depth would not be considered appropriate in the narrative: 'as evidenced by deep salinity data' or 'from deep-sourced springs'), and arbitrary terms such as deep/shallow and upper/lower should not be included in the description in the Regional Technical Information Reports arising from the workflow.

4.2.1.5 Groundwater flow and transport

There is a general paucity of nationally- and regional-consistent information related to groundwater flow and transport for most of the depth interval of interest, i.e. 200 to 1000 m (see the Guidance). Consequently, the use of any terminology related to groundwater flow and transport in the Groundwater Detailed Technical Instruction will be very limited, and if used will be based on citeable evidence. Statements of relative flow and transport characteristics should be avoided in the Groundwater Detailed Technical Instruction, and only used when they can be supported by citeable evidence.

4.2.1.6 Thermal springs

Thermal springs are taken to be an indication of flow of groundwater from depth since anomalous temperatures are generally only acquired from the higher ground temperatures that exist deeper within the earth, and it has been necessary to find a suitable simple, fit-for-purpose definition of thermal springs in this context. Groundwater that has risen from depth and is not in thermal equilibrium with groundwater at ambient temperature at the land surface will have an anomalously high temperature indicative of a 'deep-source' for the spring and hence will be considered 'thermal' in nature. Here 'thermal springs' (indicative of deep sources) are defined as those springs with groundwater temperatures >15 °C. This has been based on the following considerations.

- the lowest mean annual temperature at a depth of 1 m, corrected to sea level for a Meteorological Office weather station, in England, Wales and Northern Ireland, is 10.5°C, at Ulster University, Coleraine, in Northern Ireland (Busby, 2015)
- the lowest mean annual temperature at a depth of 1 m, uncorrected for elevation for a Meteorological weather station is 9°C at Shap, England (255 m above OD)(Busby, 2015)
- the mean geothermal gradient in the UK is 26.4°C/km (Downing and Gray, 1986), therefore an increase in temperature of 5.28°C can be expected at a depth of 200 m below ground level compared with in the soil, near surface

Based on these data, minimum spring water temperatures in the range 14.3 to 15.8°C could be inferred to be representative of groundwater flow from a depth of at least 200 m. Therefore a temperature of water discharged at surface of >15 °C has been chosen to be representative of thermal springs. This estimate is conservative and allows for the identification of all springs that might have a deep source. Mine water discharges at the surface at a temperature of >15 °C should also be included as thermal springs as these also indicate a deeper groundwater source.

The primary sources of information on thermal springs are:

- BGS Regional Guides
- Wells and Springs Memoir Series
- Water Supply Memoirs Series
- BGS/EA Baseline Report Series
- EA Groundwater Quality Reviews
- the UK memoir on the potential of geothermal energy

These sources typically contain summarised information with some associated quality assurance (detailed in the Geological Data and Information Technical Note and associated metadata catalogue). However, there is no comprehensive national catalogue of thermal springs and therefore the thermal springs information that will be compiled by the Groundwater Detailed Technical Instruction workflow is unlikely to be complete[2].

4.2.1.7 Hydraulic separation

For this Detailed Work Instruction hydraulic separation is defined as the separation of discrete bodies of groundwater by regionally extensive rocks of low permeability, such as Unproductive Strata. Evidence for hydraulic separation would be differences in regional groundwater heads and hydraulic gradients, as well as differences in groundwater age and groundwater quality across a low permeability formation. An example of hydraulic separation would be relatively fresh groundwater found in an aquifer in good hydraulic connection with the land surface separated from poor quality, highly mineralised relatively old groundwater found in an aquifer or Rock Type of Interest by a thick, plastic clay.

4.2.2 Assumptions

Section 7 (Protocols) describes how assumptions, both explicit and implicit, are managed within the Detailed Technical Instruction workflows, including the Groundwater workflow. The explicit assumptions specific to the Groundwater workflow, with the rationale and justifications explained in the previous section, are:

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[2] The EA's water quality database (WIMS) contains some information related to spring temperatures. However, there is evidence that the groundwater temperature measurements in the database may be systematically contaminated by ambient air temperatures (Watts et al., 2015).Consequently it will not be used as a source of information for spring temperatures but water chemistry data from WIMS and other data sources would be considered during more detailed assessments during the siting process.

- for the purposes of a national- scale screening exercise, 19 Principal Aquifers in England and Wales have been assumed to be hydrogeologically significant at Group level
- on the basis of common lithostratigraphy and proximity in the stratigraphic column, 11 units (generally groups of formations) identified by the EA as Unproductive Strata are assumed to be potentially confining rock units in England and Wales
- high potential productivity formations for Northern Ireland (McConvey, 2005) are assumed to be equivalent to Principal Aquifers in England and Wales
- in Northern Ireland, geological units that are classified as potential poor productivity rocks (McConvey, 2005) are assumed to be equivalent to the Unproductive Strata of England and Wales and hence are assumed to be potentially confining rock units
- although groundwater can be present below 400 m, Principal Aquifers are assumed to be present only down to 400 m below ground level
- thermal springs with groundwater temperatures >15°C are assumed to have a deep groundwater source

4.3 Data and information sources

4.3.1 Three-dimensional (3D) geological model

The UK3D model is described in Section 2.3.1 above. For the Groundwater topic the BGS UK3D 2015 geological model (GSI3D version) attributed with the EA Principal Aquifers and Unproductive Strata will be used. This will enable depth and spatial relationships between the Rock Types of Interest, Unproductive Strata and Principal Aquifers to be estimated.

4.3.2 Principal information sources

The principal information sources will be publically available national datasets, compilations and syntheses including:

- information gathered under Rock Type topic
    - regional GVS - produced by the Rock Type Detailed Technical Instruction and annotated with Rock Types of Interest, Principal Aquifers and Unproductive Strata (Section 2)
- information gathered under Rock Structure topic
    - structural maps - maps of basin bounding faults, major structural lineaments and folds with steeply dipping limbs output from the Rock Structure Detailed Technical Instruction (Section 3)
- information gathered under Resources topic
    - maps of high density borehole arrays - maps of arrays of boreholes with depths >200 m below NGS datum output from the Resources Detailed Technical Instruction (Section 6)
    - maps of mines - output from Resources Detailed Technical Instruction, maps of all mines and related excavations extending to depths > 100 m below NGS datum (Section 6)
- maps of the distribution of aquifers in England, Wales and Northern Ireland
    - EA Aquifer designation dataset (http://apps.environment-agency.gov.uk/wiyby/117020.aspx) including former extension to cover Wales
    - GSNI 1:250,000 bedrock and superficial aquifer classification/metadata (McConvey, 2005)
    - Hydrogeological map of UK and the Isle of Man (1:625,000) (digital/paper)

- Regional hydrogeological maps of the UK (paper and on-line at http://www.bgs.ac.uk/research/groundwater/datainfo/hydromaps/hydro_maps_scanviewer.html)

- BGS/EA baseline chemistry and dominant geochemical processes report series

4.3.3 Other information sources

A range of high-level, text-based summaries of hydrogeology will also be used as a source of information. The latter will include BGS memoir and report series and high-level overviews and data syntheses from the peer-reviewed literature. When selecting the peer-reviewed papers for use they will primarily be publications that provide information on the physical and hydrogeochemical properties and characteristics of rocks in the principal interval of interest, i.e. between 200 m to 1000 m, an interval for which information from other sources is limited. Articles that consist of assertions without links to supporting evidence will not be used. A summary of the main types of information used is presented below. Full details of each of these information sources, some of which are common to other Detailed Technical Instructions (for example the Regional Memoirs) can be found in the Geological Data and Information Technical Note and associated metadata catalogue. Where a single source of information only is used to make a statement in the groundwater Technical Information Reports this should be noted.

- regional subsurface memoirs
- regional guides, memoirs, sheet descriptions and explanations
- Engineering geology of British rocks and soils series
- Aquifer properties manuals
- Regional groundwater memoirs
- Wells and Springs and Water Supply series, Memoirs of the Geological Survey, England
- Water Resources Board Publications
- Hydrogeology of Northern Ireland
- Hydrogeology of Wales
- Geothermal Energy – the potential in the United Kingdom
- Hot Dry Rock geothermal reports, Cornwall.
- Catalogue of geothermal data for the land area of the United Kingdom
- Chalk groundwater in England and France: hydrogeochemistry and water quality
- Environment Agency Groundwater Quality Reviews.

Additional sources of information, such as EA data on source protection zones, more recent hydrogeological mapping associated with EA groundwater models and information held by the Drinking Water Inspectorate on private drinking water supplies, are not considered appropriate for the national screening exercise but would be considered during any siting process.

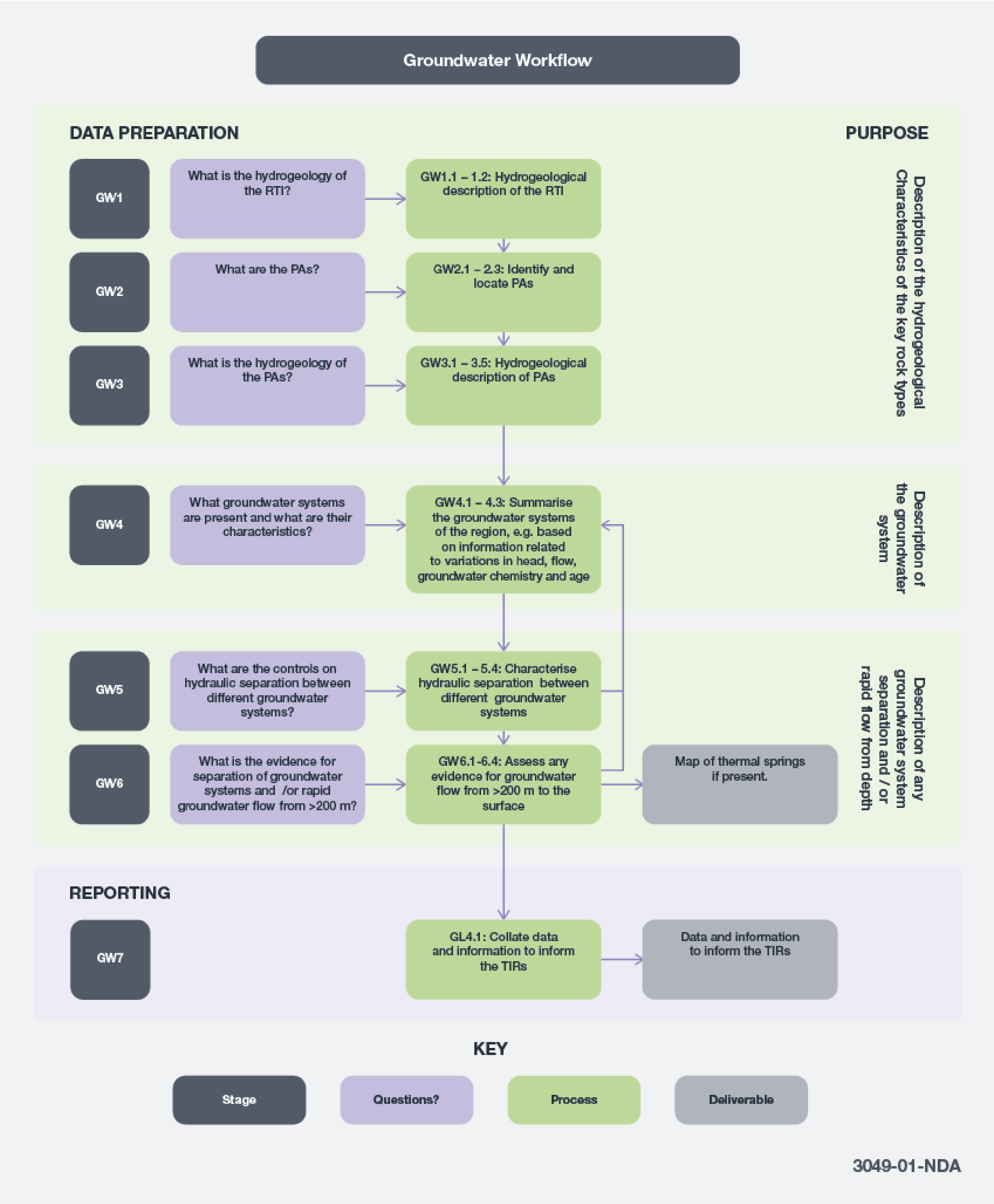
4.4 Detailed Technical Instruction workflow

4.4.1 Workflow overview

The structure of the workflow is based on the final form of the groundwater Technical Information Reports. As the main purpose of the groundwater Technical Information Report is to set out existing information about the hydrogeology that is relevant to the long-term safety case of a GDF, the main focus of the Detailed Technical Instruction will be on information related to the presence of hydrogeological features which may indicate hydraulic separation of shallow and deep groundwater systems (GW5), and locations of any features likely to permit rapid flow of deep groundwater to near-surface environments (GW6). However, to achieve this it is first necessary to provide hydrogeological information about rock types in the area (GW1 to GW3) and the overall groundwater systems (GW4).

Figure 3 is a schematic illustration of the Groundwater Detailed Technical Instruction workflow showing the three main elements and the high-level actions to be taken. The arrows show the order in which the components of the workflow should be undertaken. The workflow itself is given in detail in Table 8 in Section 4.4.2 below. Note that although broadly linear in structure (reflecting the linear nature of the resulting groundwater component of the Technical Information Reports), loops have been introduced into the workflow between high-level actions GW4, GW5 and GW6 to check for and ensure consistency.

Figure 3 Schematic illustration of the Groundwater Detailed Technical Instruction Workflow



4.4.2 Detailed workflow description

Table 8 Groundwater Detailed Technical Instruction Workflow

Step	Action	Data and / or information source
Hydrogeological description of key rock types in the region		
GW1. What is the hydrogeology of rock types and their immediate environment?		
GW1.1 What are the hydrogeological physical properties of the Rock Types of Interest that have significance for the hydrogeology of the region?	For each unit of Rock Types of Interest briefly describe the key hydrogeological physical properties of the Rock Type of Interest including permeability and flow type, porosity and storage characteristics (and any information about heterogeneity and anisotropy) that may be hydrogeologically significant at the regional scale. Go to **GW1.2**.	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs Engineering geology of the British rocks and soils series of memoirs List of key peer-reviewed publications Water Resources Board reports
GW1.2 What are the characteristics of the hydrogeochemistry of the groundwater associated with the Rock Types of Interest that have significance for the hydrogeology of the region?	For each Rock Type of Interest briefly describe the key characteristics of their hydrogeochemistry, including groundwater chemistry, age and temperature, which are significant at the regional scale. Go to **GW2.**	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs BGS/EA Baseline series Engineering geology of the British rocks and soils series List of key peer-reviewed publications Water Resources Board reports
GW2. What and where are the Principal Aquifers?		
GW2.1 Are there any Principal Aquifers present in the region?	Using the GVS for the region identify if any Principal Aquifers are present. If yes go to **GW2.2**. If no state that no Principal Aquifers are present in the region and then go to **GW4**.	Use the Regional GVS annotated by Rock Type of Interest, Principal Aquifer and Unproductive Strata (GVS annotation based on **RT3**), and the EA's Aquifer Designation Dataset (http://apps.environment-agency.gov.uk/wiyby/117020.aspx)
GW2.2 What are the Principal Aquifers present in the region?	Note the Principal Aquifers in stratigraphic order in the region. Go to **GW 2.3.**	Use the Regional GVS annotated by Rock Type of Interest, Principal Aquifers and Unproductive Strata (GVS annotation based on **RT3**), and the EA's Aquifer Designation Dataset (http://apps.environment-agency.gov.uk/wiyby/117020.aspx)

Step	Action	Data and / or information source
GW2.3 What is the geographical and depth distribution of Principal Aquifers in the region?	For each Principal Aquifer, briefly describe their geographical and depth distribution. Specifically identify if any geological formations that constitute Principal Aquifers are continuous below 400 m. If present, note which ones they are, and describe their geometry and extent. Go to **GW3**.	Use maps of Principal Aquifers and attributed sections of UK3D (produced by **RT4.2**)
GW3. What is the hydrogeology of the Principal Aquifers?		
GW3.1 What are the lithological characteristics of the Principal Aquifers that have potential significance for the regional hydrogeology?	For each Principal Aquifer very briefly describe the key lithological features that have potential significance for the regional hydrogeology. Go to **GW3.2**.	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals Hydrogeological maps Geothermal potential of the UK report Water Resources Board reports
GW3.2 What are the major structural features associated the Principal Aquifers that have significance for the regional hydrogeology of the unit?	Very briefly describe the key structural features (e.g. basin bounding faults, structural lineaments and folds with steeply dipping limbs) associated with the Principal Aquifers and their immediate environment. Check for consistency with **GW1.2**. Go to **GW3.3**.	Maps of basin bounding faults and structural lineaments (based on maps produced by **RS6.2**). Also information from the following sources: BGS Regional guides BGS Subsurface memoirs Water Resources Board reports
GW3.3 What are the hydrogeological physical properties of the Principal Aquifers that have regional significance?	For each Principal Aquifer very briefly describe the key hydrogeological physical properties, including permeability and flow type, porosity and storage characteristics (and any information about heterogeneity and anisotropy) that may be significant at the regional scale. Go to **GW3.4**.	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals Geothermal Potential of the UK report Hydrogeological maps Regional Hydrogeology Memoirs Hydrogeology of Northern Ireland Wells and springs and water supply memoirs Water Resources Board reports

Step	Action	Data and / or information source
GW3.4 What are the characteristics of the hydrogeochemistry of the Principal Aquifers that have regional significance?	For each Principal Aquifer, very briefly describe the key characteristics of their hydrogeochemistry, including groundwater chemistry, age and temperature that are significant at the regional scale. Go to **GW3.5**.	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs BGS/EA Baseline series EA Groundwater Quality Reviews Regional Hydrogeology Memoirs Hydrogeology of Northern Ireland Wells and springs and water supply memoir series Chalk groundwater in England and France (BGS report) Water Resources Board reports List of key peer-reviewed publications
GW3.5 What, if any, hydrogeological gradients (physical and hydrogeochemical) are present in any geological formations that constitute Principal Aquifers that are continuous from surface to below 400 m bgl?	For each geological formation that constitutes a Principal Aquifer and that is continuous from the surface to below 400 m bgl, describe any depth gradients in their physical properties (including permeability and storage characteristics) and hydrogeochemistry (including groundwater chemistry, age and temperature). Go to **GW4**.	Use information from the following sources: BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals BGS/EA Baseline series EA Groundwater Quality Reviews Regional Hydrogeology Memoirs Hydrogeology of Northern Ireland Chalk groundwater in England and France (BGS report) Water Resources Board reports List of key peer-reviewed publications

Step	Action	Data and / or information source
Description of the regional groundwater system(s)		
GW4. What are the groundwater systems of the region?		
GW4.1 What are the boundary conditions for the regional groundwater flow system?	Identify and briefly describe the following regional groundwater flow boundary conditions: constant head boundaries (e.g. coast and major rivers), areas of recharge and discharge (including to sea) and no flow boundaries (e.g. groundwater divides). The descriptions should be in the context of regional topography and spatial relationships with named rock types (e.g. Rock Type of Interest, Principal Aquifers and Unproductive Strata). Go to **GW4.2**.	Use information from the following sources: Hydrogeological maps Topography BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals BGS Baseline series Regional Hydrogeology Memoirs Hydrogeology of Northern Ireland Water Resources Board reports List of key peer-reviewed publications
GW4.2 What are the regional-scale groundwater flows?	Identify and briefly describe regional-scale groundwater flow using groundwater head distributions as primary evidence, supported by other evidence such as variations in groundwater chemistry and age. The descriptions should be in the context of spatial relationships with named rock types (e.g. Rock Type of Interest, Principal Aquifers and Unproductive Strata), and any regionally important Secondary Aquifers where appropriate, and mapped rock structure. Go to **GW4.3**.	Use information from the following sources: Hydrogeological maps BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals BGS/EA Baseline series Hydrogeology of Northern Ireland Geothermal Potential of the UK report Regional Hydrogeology Memoirs Wells and springs and water supply memoir series Water Resources Board reports List of key peer-reviewed publications

Step	Action	Data and / or information source
GW4.3 Is there any evidence that distinct groundwater flow systems can be distinguished within the regional scale flow system, geographically, and / or on the basis of depth?	Assess evidence for distinct groundwater flow systems either geographical and / or on the basis of depth, including evidence for connections between different Principal Aquifers Evidence to include step changes in heads, groundwater chemistry and / or age. Where identified the distinct flow systems should be related to the distribution of named rock types (e.g. Rock Type of Interest, Principal Aquifers and Unproductive Strata) and mapped rock structure. Go to **GW5**.	Use information from the following sources: Hydrogeological maps BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals BGS/EA Baseline series Hydrogeology of Northern Ireland Regional Hydrogeology Memoirs Water Resources Board reports List of key peer-reviewed publications
Groundwater system separation and/or rapid flow from depth		
GW5. What are the controls on hydraulic separation between different groundwater systems?		
GW5.1 Are there rock types that might separate the different groundwater systems?	Identify if any rock types are present that might separate different groundwater systems identified in **GW4.3**. If yes, go to **GW5.2**, if no, state that no such rock types are present in the region and then go to **GW5.3**.	Use the Regional GVS annotated with Rock Type of Interest, Principal Aquifers and Unproductive Strata (GVS annotation based on **RT3**) and the attributed sections of UK3D (produced by **RT4.2**)
GW5.2 What are the locations and characteristic features of rock types that might cause hydraulic separation between Rock Types of Interest and Principal Aquifers?	Describe the distribution of rock types that might cause hydraulic separation between Rock Types of Interest and Principal Aquifers. Describe their continuity and thickness across the region. Go to **GW4** to check for consistency with the regional hydrogeological description. If **GW5.2** and **GW4** are consistent, go to **GW5.3**.	Use the attributed sections of UK3D (produced by **RT4.2)**
GW5.3 Are there other geological features that might separate different groundwater systems and where are they located?	Are there other large-scale, regionally significant, geological features and structures, such as major unconformities that might separate different groundwater systems? If no, go to **GW5.5**. If yes, for each feature describe their location and depth then go to **GW5.4**.	Use the attributed sections of UK3D (produced by **RT4.2**).

Step	Action	Data and / or information source
GW5.4 What are the hydrogeological physical properties of the geological features identified in **GW5.3** that might cause them to separate different groundwater systems?	For each geological feature identified in **GW5.3**, describe their hydrogeological physical properties that might cause them to separate different groundwater systems. Go to **GW4** to check for consistency with the regional hydrogeological description. If **GW5.4** and **GW4** are consistent, go to **GW6**.	Use information from the following sources: Hydrogeological maps BGS Regional guides BGS Subsurface memoirs Aquifer Properties Manuals BGS/EA Baseline series Hydrogeology of Northern Ireland Geothermal Potential of the UK report Regional Hydrogeology Memoirs List of key peer-reviewed publications
GW6. What is the evidence for flow from >200 m to the surface and links between different groundwater systems?		
GW6.1 Are there any thermal springs that indicate rapid flow from depth to the near surface?	Identify any thermal springs. If springs are present construct GIS layer showing spring locations (including associated metadata detailing source of information, summarising spring temperature and discharge data as appropriate, and giving an assessment of data quality). Describe their location in relation to named rock types at the point of emergence and key characteristics, including groundwater temperature and flow rate. If no springs are present go to **GW6.3**. If thermal springs are present go to **GW6.2**.	Use information from the following sources: Regional guides Wells and Springs Memoir series Water supply memoir series BGS/EA Baseline series EA Groundwater Quality Reviews Geothermal potential of the UK Key peer-reviewed publications Geothermal energy – potential in the UK memoir
GW6.2 What are the geological pathways and hydrogeological context for the thermal springs?	Briefly describe evidence for geological pathways, such as basin-scale faults and zones of deformation, folds with steeply dipping limbs, unconformities or degree and nature of karstification, which may enable rapid flow of groundwater from depth. Go to **GW4.0** to check for consistency with the regional hydrogeological description. If **GW6.2** and **GW4** are consistent, go to **GW6.3**.	Use information from the following sources: Regional guides Wells and Springs Memoir series Water supply memoir series Maps of basin bounding faults and structural lineaments (based on maps produced by **RS6.2**) BGS/EA Baseline series EA Groundwater Quality Reviews Karst and Caves of Great Britain List of key peer-reviewed papers

Step	Action	Data and / or information source
GW6.3 Are there any anthropogenic features in the subsurface that could provide rapid flow from depth to the near surface?	Identify and summarise anthropogenic features and structures, such as deep boreholes (>200 m), mines and adits that could provide pathways for rapid flow from depth to the near surface and note their location. Go to **GW6.4**.	Maps of borehole arrays and maps of mines (produced by **RE5.2** and **RE7.4**)
GW6.4 What is the nature of the evidence for hydraulic connection between groundwater systems via anthropogenic features identified in **GW6.3**?	Summarise any evidence, such as anomalous changes in groundwater heads, groundwater quality and temperature, for hydraulic connection between groundwater systems via anthropogenic features identified in **GW6.3**. Go to **GW4.0** to check for consistency with the regional hydrogeological description. If **GW6.5** and **GW4.0** are consistent **END**.	Regional guides Wells and Springs Memoir series Water supply memoir series Maps of basin bounding faults and structural lineaments (based on maps produced by **RES5.2** and **RES9**) BGS/EA Baseline series EA Groundwater Quality Reviews Karst and Caves of Great Britain List of key peer-reviewed papers

4.5 Relationship with other Detailed Technical Instructions and the NGS Protocols

This Detailed Technical Instruction is explicitly dependent on three of the four other Detailed Technical Instructions, namely the Rock Type, Rock Structure and Resources Detailed Technical Instructions, as well as the NGS Protocols (Section 7.0).

The Groundwater Detailed Technical Instruction requires input from the Rock Type Detailed Technical Instruction in the form of:

- information regarding the Rock Types of Interest, i.e. their annotation in the UK3D GVS and sections (i.e. GW4)
- information regarding Principal Aquifers and Unproductive Strata, i.e. their annotation in the UK3D GVS and sections (i.e. GW2, GW3, GW4)
- sections showing the depth distribution of the Rock Types of Interest (i.e. GW3.0)

The Groundwater Detailed Technical Instruction requires input from the Rock Structure Detailed Technical Instruction in the form of maps of basin bounding faults, structural lineaments and folds with steeply dipping limbs (i.e. GW3, GW4, GW6).

The Groundwater Detailed Technical Instruction requires input from the Resources Detailed Technical Instruction in the form of maps of borehole arrays and of mines (i.e. GW6).

The Groundwater Detailed Technical Instruction is to be undertaken in the context of the NGS Protocols (Section 7), and, as already noted in Section 4.2 (above), a number of assumptions specific to the Groundwater Detailed Technical Instruction have been identified which are consistent with the NGS Protocols. In addition, the Groundwater Detailed Technical Instruction explicitly requires the use of topographic Digital Terrane Model (DTM) data (Protocol, Section 7.4.2).

4.6 References

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5 Detailed Technical Instruction: Natural Processes

5.1 Introduction

This Detailed Technical Instruction sets out how data and information on the topic of natural processes will be assembled and presented as part of the national geological screening exercise. For the natural processes topic the following outputs for each of the 13 regions have been specified in the Guidance:

- a national map showing the extent of past glaciation
- a national map of the distribution of recent seismicity
- interpretation of national information (on seismicity, uplift rate, erosion rate, and past ice cover during glaciations) in the context of the region

The Guidance identified the distribution and patterns of seismicity and the extent of past glaciations as attributes to provide information on natural processes. Furthermore, the Guidance notes that the explanation of the nature and distribution of natural processes that have the potential to affect safety will be qualitative.

This Detailed Technical Instruction sets out a step-by-step description of how information about natural processes, specifically glaciation, permafrost and seismicity, that may impact the safety of a GDF in England, Wales and Northern Ireland, will be assembled and presented as part of the national geological screening exercise. Sea-level change, driven by global (eustatic) and UK (isostatic) scales of glaciation, are considered where appropriate, within the glaciation and permafrost sections of the Natural Processes Detailed Technical Instruction.

The Natural Processes Detailed Technical Instruction is presented in three separate parts: glaciation (Section 5.2); permafrost (Section 5.3); and seismicity (Section 5.4). Each part has the following structure:

- definitions and assumptions – assumptions used to specify how the outputs are produced
- data and information sources – an overview of the data and information to be used
- topic process and workflow - an overview of the broad process and a step-by-step description of the Detailed Technical Instruction workflow and methodology
- relationship with other Instructions and Protocols - a brief note on the relationship with other Detailed Technical Instructions prepared for the national geological screening exercise, and the NGS Protocols
- references - a list of references cited

5.2 Glaciation

5.2.1 Definitions and assumptions

This section describes the definitions and assumptions that underpin the description of glaciation within the Technical Information Report for each region.

5.2.1.1 Definitions

Glaciation

A glaciation, often referred to as an 'Ice Age', occurs under a cold climate, when glaciers form in highland areas. When these cold climates exist for a prolonged period of time, glaciers can coalesce into larger ice sheets and extend into adjacent lowland areas. The impact of glaciation on the depth range of interest would be dependent upon topographic context including proximity to sea-level, the extent and frequency of glaciation, the proximity of an ice margin and the activity of a range of linked geological processes. These are evaluated below and several key assumptions are listed that will underpin the production of the Technical Information Report for each region.

Glaciations: extent and frequency

The extent and frequency of future glaciations, both globally and regionally, will dictate which areas of England, Wales and Northern Ireland may be susceptible to different scales of glaciation, sea-level change (i.e. eustatic and isostatic) and, in-turn, the different natural processes that may affect the depth range of interest and their level of impact (Shaw *et al*., 2012). Predicting the scale of glaciations that may affect the UK during the next million years is a significant challenge. Geological evidence obtained from the world's oceans demonstrates that numerous glaciations have occurred globally over the past 2.6 million years. These have acted to drive major eustatic fluctuations in global sea-level (up to 160 m) which in the UK has caused repeated emergence and drowning of coastal, shelf and shallow marine areas. In the UK itself, the geological record reveals that multiple phases of glaciation have occurred over the same time-interval. This record offers a crude analogue for the scale and frequency of possible future glaciations that may directly affect the UK over the next million years (Table 9).

Table 9 Classification of potential glaciations to affect the UK encompassing frequency and extent

Scale of Glaciation	Geological Analogue	Frequency of Glaciation	Extent of Glaciation
Continental	Anglian or Late Devensian	Low	High
Lowland	Other	Medium	Medium
Highland	Younger Dryas	High	Low

Continental-scale glaciation

'Continental-scale' glaciations correspond to those where more than half of the total UK land area was glaciated (Table 9). Only two known continental-scale glaciations have affected the UK over the past one million years and these correspond to the Anglian (c.480-430 ka) and Late Devensian glaciations (c.30-16 ka) (Shaw *et al*., 2012) (see Figure 4). Both resulted in the glaciation of upland areas, lowland areas of Northern Ireland, Wales and central and northern England, adjacent marine basins (e.g. the North Sea and Irish Sea), and some continental shelf areas. Continental-scale glaciations are classified as high-magnitude and low-frequency glaciations because they are large in spatial extent but geologically, are least frequent. For the purpose of this Detailed Technical Instruction the extent of the Anglian Glaciation is considered as the 'worst-case' extent for future glaciation. Currently available scientific information, based upon future climate predictions, indicates that a glaciation approaching this scale is unlikely to affect England, Wales and Northern Ireland during the next 170,000 years (Shaw *et al*., 2012).

Lowland and highland glaciations

An absence within Shaw *et al*. (2012) is the consideration of future glaciations which may be less extensive than the Late Devensian glaciation. However, because of their higher frequency and cumulative affects over multiple stages of glaciation, these may also affect the depth range of interest at a local scale. Evidence for smaller glaciations within the geological record is limited because the associated landforms and sediments are prone to removal or over-printing by subsequent glacial and non-glacial processes. Nevertheless, a growing body of geological evidence indicates that numerous (c.30+) glaciations that were smaller than the Anglian and Late Devensian have occurred in the UK over the past 2.6

million years (Lee *et al*., 2011, 2012; Thierens *et al*., 2012). The last of these glaciations occurred approximately 11,000 years ago during the Younger Dryas (Loch Lomond) Stadial (McDougall, 2001; Benn and Lukas, 2006; Bendle and Glasser, 2012). Geological evidence therefore demonstrates that over the past one million years, highland (and sometimes adjacent lowland areas) regions of northern and western UK have been glaciated repeatedly.

In light of this revised understanding of smaller glaciations, two further scales of glaciation are defined within the Detailed Technical Instruction. Firstly, 'lowland glaciation' occurs when ice from different highland source areas converge in adjacent lowlands. Geological evidence is lacking, but this scale of glaciation is considered to be moderate and variable in extent; it may occur on several occasions over the next million years. Secondly, a 'highland glaciation' scale, where glaciers are restricted principally to highland areas with individual corrie glaciers coalescing in major valleys. Geologically, these have low spatial-extent but have occurred most frequently in the past.

Glaciation-related mechanisms that may affect the depth range of interest

Shaw *et al*. (2012) identified several different mechanisms related to glaciation that should be considered relative to the depth range of interest, as outlined below:

- glacial over-deepening - these occur in many glaciated highland areas of England, Wales and Northern Ireland
- tunnel valleys - these are localised and steep-sided channels that are eroded into the substrate by fast-flowing meltwater streams beneath a glacier, they typically occur in lowland areas adjacent to the margins of glaciers
- isostatic rebound modifies the localised tectonic stress-field within the crust and can cause increased fracturing and the reactivation of some faults leading to earthquakes, highest areas of rebound occurs in areas where maximum thickness of ice have been removed
- glacier forebulge is uplift in front of an ice sheet in response to loading that may cause increased fracturing and some faults to become reactivated leading to earthquakes (Shaw *et al*., 2012), this could affect areas that have been glaciated and areas beyond the limits of glaciation
- saline groundwater ingress - glaciation modifies sea-level either regionally (by isostatic crustal adjustments) or globally (eustatic change) and this in-turn can alter temporal and spatial patterns of saline groundwater behaviour

5.2.1.2 Assumptions

A number of generic scale- and process-related assumptions can be made which will underpin the description in the Technical Information Report for each region.

Scale-related generic assumptions:

- based on geological evidence, highland areas of Wales, western and northern England and Northern Ireland are susceptible to being glaciated on multiple occasions over the next million years with glaciers occurring in plateau areas, corries and valleys
- based on geological evidence, lowland areas of northern England, Wales and Northern Ireland are susceptible to being glaciated on several occasions over the next million years
- based on geological evidence, lowland areas of central, southern and eastern England are susceptible to being glaciated once or twice over the next million years

- based on geological evidence, areas that lie beyond the Anglian (i.e. worst case) glacial limit are unlikely to be glaciated during the next million years except under exceptional circumstances

Process-related generic assumptions:

- glacial over-deepening is a process that is active predominantly within highland areas
- tunnel valleys develop beneath glaciers occupying lowland areas
- isostatic rebound will be greatest in areas of maximum ice thickness
- deep glacial erosion (either by ice or meltwater erosion) can lead to the development of highly-localised groundwater behaviour and chemistry
- based on published studies, a glacier forebulge can extend several hundred kilometres beyond a glacier margin
- increased fracturing, fault reactivation and earthquakes can affect groundwater behaviour and chemistry
- all regional areas that border a coastline may be affected by variations in saline groundwater behaviour

5.2.2 Data and information sources

5.2.2.1 Principal information source

The report Potential Natural Changes and Implications for a UK GDF (Shaw *et al*., 2012) and information referred to therein is the principal information source for the Glaciation workflow.

5.2.2.2 Other information sources

The UK glacial limits and shaded relief map is shown in Figure 4 below. This shows the principal limits of continental scale Quaternary glaciation within the UK – the Anglian (red) and Late Devensian (blue) (after Bowen *et al*., 1986; Clark *et al*., 2004) relative to the defined 13 region areas (white outline) and are superimposed upon a digital elevation model (Data Source 3) which shows topographic relief (dark areas = highland areas and lighter areas = lowland areas). The Digital Elevation Model (DEM) is sourced from EU Copernicus DEM for England, Wales and Northern Ireland. http://www.eea.europa.eu/data-and-maps/data/eu-dem#tab-original-data.

Other relevant published national scale peer-reviewed papers may also be used.

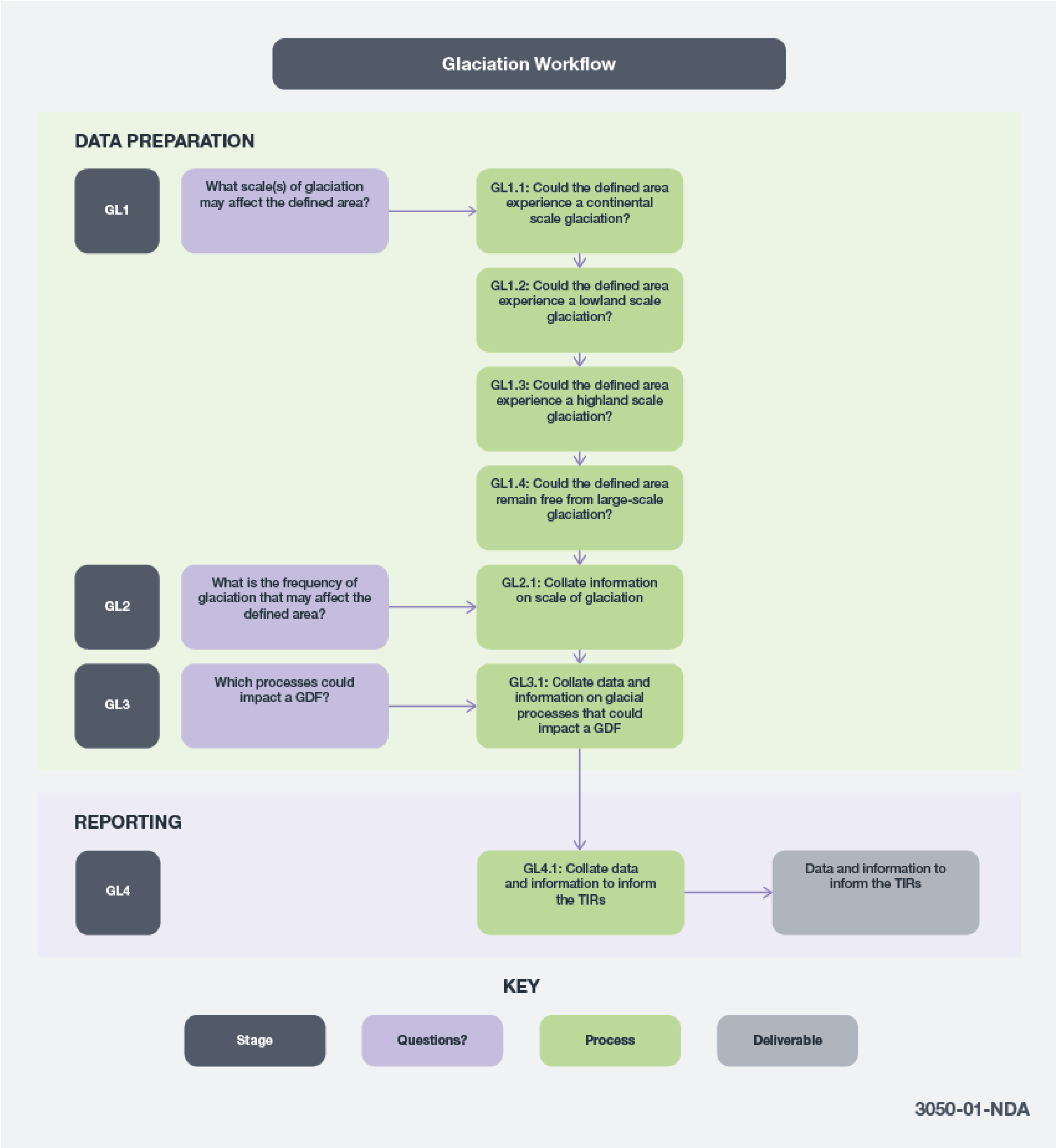
Figure 4 **Shaded relief terrain map of England, Wales and Northern Ireland, showing the limits of Quaternary glaciation (Anglian – red; and Late Devensian – blue).**

5.2.3 Workflow overview

The glaciation component of the Natural Processes Detailed Technical Instruction describes the methodology to be used to create the extent of glaciation map and inform the description of the future glaciation in the accompanying Technical Information Report. Using Figure 4 and the supporting information detailed above, regional descriptions of glaciation will be constructed for the Technical Information Reports following a defined workflow that guides the expert through a set of key information and decision gateways. At each stage of the workflow, metadata will be captured that records specific decisions made and the rationale behind them.

Figure 5 presents a schematic illustration of the workflow and Table 10 provides a more detailed description of each step.

Figure 5 Schematic Illustration of Glaciation Workflow



5.2.4 Detailed workflow

Table 10 Glaciation Workflow

Step	**Action**	**Data and / or information source**
Glaciation: scale, frequency and relevant geological processes		
GL1. What scale(s) of glaciation may affect the defined area?		
GL1.1. Is the defined area likely to be affected by a continental scale glaciation?	For the specified defined area, determine whether some or all is situated between the Late Devensian and Anglian ice limits.	Use Figure 4.
GL1.2. Is the defined area likely to be affected by a lowland scale glaciation?	For the specified defined area, determine whether some or all is situated between the Late Devensian ice limit and the edge of highland areas.	Use Figure 4.
GL1.3. Is the defined area likely to be affected by a highland scale glaciation?	For the specified defined area, determine whether some or all encompasses a highland area.	Use Figure 4.
GL1.4. Is the defined area unlikely to be affected by significant glaciation during the next million years?	For the specified defined area, determine whether some or all is situated beyond the maximum limit of glaciation (Anglian).	Use Figure 4.
GL2. What is the frequency of glaciation that may affect the defined area?		
GL2. How frequently is the specified defined area likely to be glaciated during the next million years?	Cross-reference the scale(s) of glaciation (G1) for the specified area with the frequency.	Cross-reference description for GL1.1-GL1.4 with **Error! Reference source not found.** 5.2.1 which defines the scale and frequency of glaciation and 'scale-related generic assumptions'.
GL3. What processes may be relevant to long-term GDF safety?		
GL3. What processes may be relevant to long-term GDF safety based upon the defined scale and frequency and glaciation?	Cross-reference the scale(s) (GL1) and frequency(s) of glaciation (GL2) for the specified area with processes that may be relevant to long-term GDF safety.	Cross-reference with 'process-related generic assumptions' and Shaw *et al*. (2012).
GL4. **Produce Technical Information Report**		

5.3 Permafrost

Permafrost is defined as ground that remains below the 0°C isotherm for two or more consecutive years (French, 2007; Hartikainen *et al*., 2010). Periglacial, by contrast, describes the geomorphological or geological processes that result from the action of ice growth (and decay) on natural and artificial materials. Significant thicknesses of permafrost can develop over decadal to centennial time-scales, provided that the ground surface is not insulated by overlying glacial ice.

The extent and thickness of permafrost during specific periglacial episodes is poorly-understood in the UK. To partly overcome this knowledge gap a regional-scale modelling exercise was undertaken to reconstruct past permafrost thickness and to predict its potential future thicknesses and development at 10 localities over the past 130,000 years and future 300,000 years (Busby *et al*., 2014). The modelling exercise estimated the development of at least 180 m of permafrost across all of the sites during a future cold climate (See Data Sources 5.3.2).

5.3.1 Assumptions

A number of generic assumptions are made which will underpin the description in the Technical Information Report for each region.

All areas of England, Wales and Northern Ireland will be subjected to permafrost development over the next million years but only some areas may be subject (at a lower frequency) to glaciation and glacial effects;

- the development of permafrost to a few hundred metres depth will occur in all areas of England, Wales and Northern Ireland under future cold climates regardless of glacier cover
- the development of permafrost can affect groundwater behaviour and chemistry
- in combination with glacial erosion, future development of permafrost may be to several hundred metres beneath the current ground surface

5.3.2 Data and information sources

The report Cold climate permafrost thicknesses (Busby *et al.,* 2014) and information referred to therein is the principal information source for the Permafrost workflow. This dataset records the modelled permafrost depths for 10 localities across the UK that may occur under a future cold climate.

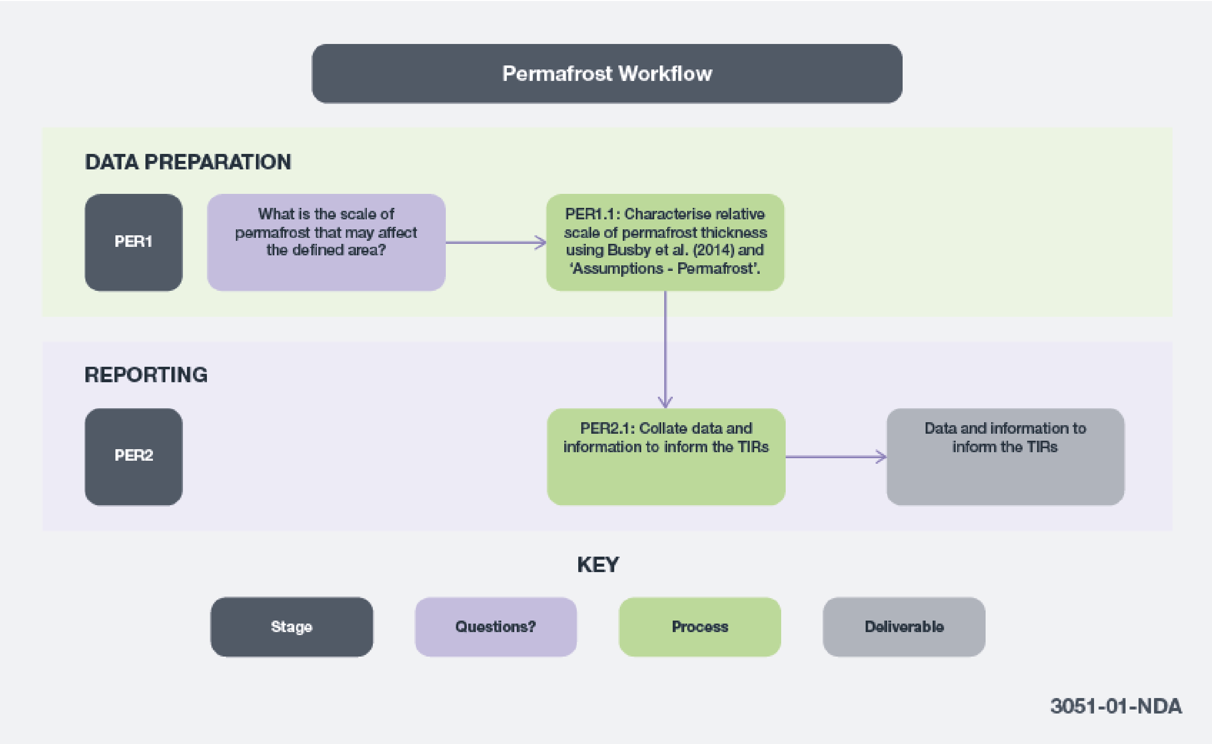
Other relevant published national scale peer-reviewed papers may also be used.

5.3.3 Workflow overview

Using the supporting information detailed above, regional descriptions for permafrost can be constructed for the Technical Information Reports that guides the writer through a set of key information and decision gateways. At each stage of the workflow, metadata is captured that records specific decisions made and the rationale behind them.

Figure 6 presents a schematic illustration of the workflow and Table 11 provides a more detailed description of each step.

Figure 6 Schematic Illustration of Permafrost Workflow



5.3.4 Detailed workflow

Table 11 Permafrost Workflow

Step	Action	Data and / or information source
Permafrost		
PER1. What is the scale of permafrost that may affect the defined area?		
PER1. What scale of permafrost may occur within the defined area?	Cross-reference defined area with cold climate permafrost thicknesses defined by Busby *et al*. (2014).	Cold climate permafrost thicknesses (Busby *et al* 2014).
PER2. Produce Technical Information Report		

5.4 Seismicity

5.4.1 Definitions and assumptions

The seismicity of an area relates to the relative frequency, magnitude and distribution of earthquakes. In order to produce the seismicity component of the Technical Information Report of a region, it is necessary to define a number of key earthquake related terms and definitions. Consequently, this section describes key concepts and terms that have been defined for use in the Seismicity Detailed Technical Instruction. They reflect concepts and existing definitions in the underlying information sources that are to be used in the Detailed Technical Instruction, as well as current usage of earthquake-related terms.

5.4.1.1 Definitions

Earthquakes

Earthquakes are the result of sudden movement along faults within the Earth that releases stored up elastic strain energy in the form of seismic waves that propagate through the Earth and cause the ground surface to shake. Such movement on the faults is generally a response to long-term deformation and build-up of stress, caused by processes such as plate tectonics. When this stress exceeds the static frictional stress that resists the motion of the rocks on either side of the fault, they slide or slip past each other along a rupture plane. The size of any earthquake depends on both the area of the fault that ruptures and also the amount of slip or displacement on the rupture plane. Larger rupture areas and displacements result in larger earthquakes.

Earthquake hypocentre

The hypocentre is the point within the Earth where an earthquake rupture starts. The epicentre is the point directly above it at the surface of the Earth. The hypocentre is also commonly termed the focus and usually specified in a Cartesian reference frame in terms of North-South, East-West and depth coordinates.

Earthquake magnitude

Earthquake magnitude is a measure of the amount of energy released during an earthquake. A number of different magnitude scales have been developed generally based on the amplitude of different parts of the observed record of ground motion, often in a particular frequency range, and with specific corrections for distance. However, the most standard and reliable measure of earthquake size is moment magnitude, Mw, (Hanks and Kanamori, 1979). This is based on the logarithm of the seismic moment, which in turn is related to both the area of the rupture and the displacement on the rupture. Since the magnitude scale is logarithmic, each whole number increase in magnitude represents a tenfold increase in measured amplitude and about 32 times the energy released.

Minimum magnitude of interest

This is defined as the lowest magnitude of earthquake considered in this study. Earthquakes below this magnitude are not considered relevant to the safety of the GDF. In probabilistic seismic hazard assessments the minimum magnitude is the smallest earthquake considered to be of engineering significance; for engineered structures such as dams and power stations, earthquakes less than magnitude 5.0 Mw are generally discounted. For other applications, a lower bound may be relevant. Earthquakes below this magnitude may provide useful information on the nature and distribution of earthquake activity. Their possible relevance to GDF infrastructure will be considered during the siting process.

Activity rate and recurrence

The relationship between the magnitude and number of earthquakes in a given region and time period generally takes an exponential form that is referred to as the Gutenberg-Richter law (Gutenberg and Richter, 1954), and is commonly expressed as

$$\log_{10} N = a - bM$$

where N is the number of earthquakes above a given magnitude M. The constant a, is a function of the total number of earthquakes in the sample and is known as the earthquake activity rate. This is commonly normalised over period of time, such as a year. The constant b gives the proportion of large events to small ones, and is commonly referred to as the recurrence parameter or b-value. In general, b-values are close to unity. This means that for each unit increase in magnitude, the number of earthquakes reduces tenfold.

Uncertainties in earthquake locations

An impulsive source of seismic energy can be thought of as a point source in time and space, defined by an origin time (t0) and hypocentre (x0, y0, z0), respectively. The travel time of a seismic wave propagating away from such a source will depend on the distance from the source and the velocity of the medium, and, in general, will increase with distance from the source. Measured arrival times at different points can be used to estimate the location of the seismic event. The problem of estimating source location from travel time data has been extensively studied in earthquake seismology and numerous algorithms of this type have been developed and are in widespread use. Given observations of arrival times at a number of points one can compute predicted travel times to the same points by assuming a reference velocity model. One can then try to minimise the difference between the observed and modelled travel times and estimate the best fitting location for the event. Although the travel-times are not linearly dependent on the earthquake location, the problem can be linearized by considering only small perturbations from an initial target location. Iterative, linearized methods are largely based on the method of Geiger (1912) and solve the problem using partial derivatives and matrix inversion. These usually converge rapidly unless the data are badly configured or the initial guess is very far away from the mathematically best solution.

Uncertainties in earthquake locations are dominated by three factors (Pavlis 1986): (1) measurement errors of seismic arrival times; (2) modelling errors of calculated travel times; and (3), nonlinearity of the earthquake location problem. Measurement errors may arise because it is difficult to clearly identify the arrival time of the seismic phase because the signal is small and cannot clearly be discriminated from the noise. Assuming that the measurement errors are normally distributed, confidence regions may be computed. The size of the confidence regions depends on the variance and is commonly computed using either the F-statistic (e.g. Flinn, 1965) or the χ^2 statistic (Evernden, 1969). Quality factors are used in addition to formal errors to assess location quality.

5.4.1.2 Assumptions

Stationarity

The earthquake frequency-magnitude distribution is stationary, i.e. it has statistical properties that do not change with time. As a result past earthquake activity is assumed to be a reasonable approximation of future possible activity. However, the possibility of renewed glaciation in the next million years means that estimates of the distribution and rates of regional seismicity are unlikely to remain the same as at present.

Catalogue completeness

The magnitude of completeness of the catalogue, defined as the lowest magnitude at which 100% of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989), varies strongly with time. For example, Musson (1996a) states that prior to 1700 only the largest earthquakes are known, whereas, from the 19th century on many smaller earthquakes are known. Table 12 shows the assumed magnitude of completeness for different periods of time in Britain as used by Musson and Sargeant (2008).

Table 12 Magnitude of completeness for different periods of time used for Britain by Musson and Sargeant (2008)

Magnitude	Date
3.0	1970
3.5	1850
4.0	1750
4.5	1700
5.0	1650
6.5	1000

Magnitude uncertainty

It is assumed that all magnitude values in the catalogue have an uncertainty of ± 0.25.

5.4.2 Data and information sources

5.4.2.1 Principal information sources

The report Potential Natural Changes and Implications for a UK GDF (Shaw *et al*., 2012) and information referred to therein is the principal information source for the Seismicity workflow.

For historical earthquakes from 1382 to present Musson (1994), along with subsequent updates, provides locations and magnitudes determined from the spatial variation of intensity, a qualitative measure of the strength of shaking of an earthquake determined from the observed effects on people, objects and buildings (e.g. Musson, 1996b).

For data from 1970 to present, the annual bulletins of earthquake activity published by BGS each year (e.g. Galloway *et al*, 2012) provide locations and magnitudes determined from recordings of ground motion on a network of sensors around the UK (e.g. Baptie, 2012). The bulletins also contain error estimates. Bulletin data are updated with revised parameter data published in BGS reports or peer-reviewed journal publications on specific earthquakes.

A number of BGS reports also contain key information relating to British earthquakes and earthquake hazard (e.g. Musson and Sargeant, 2008).

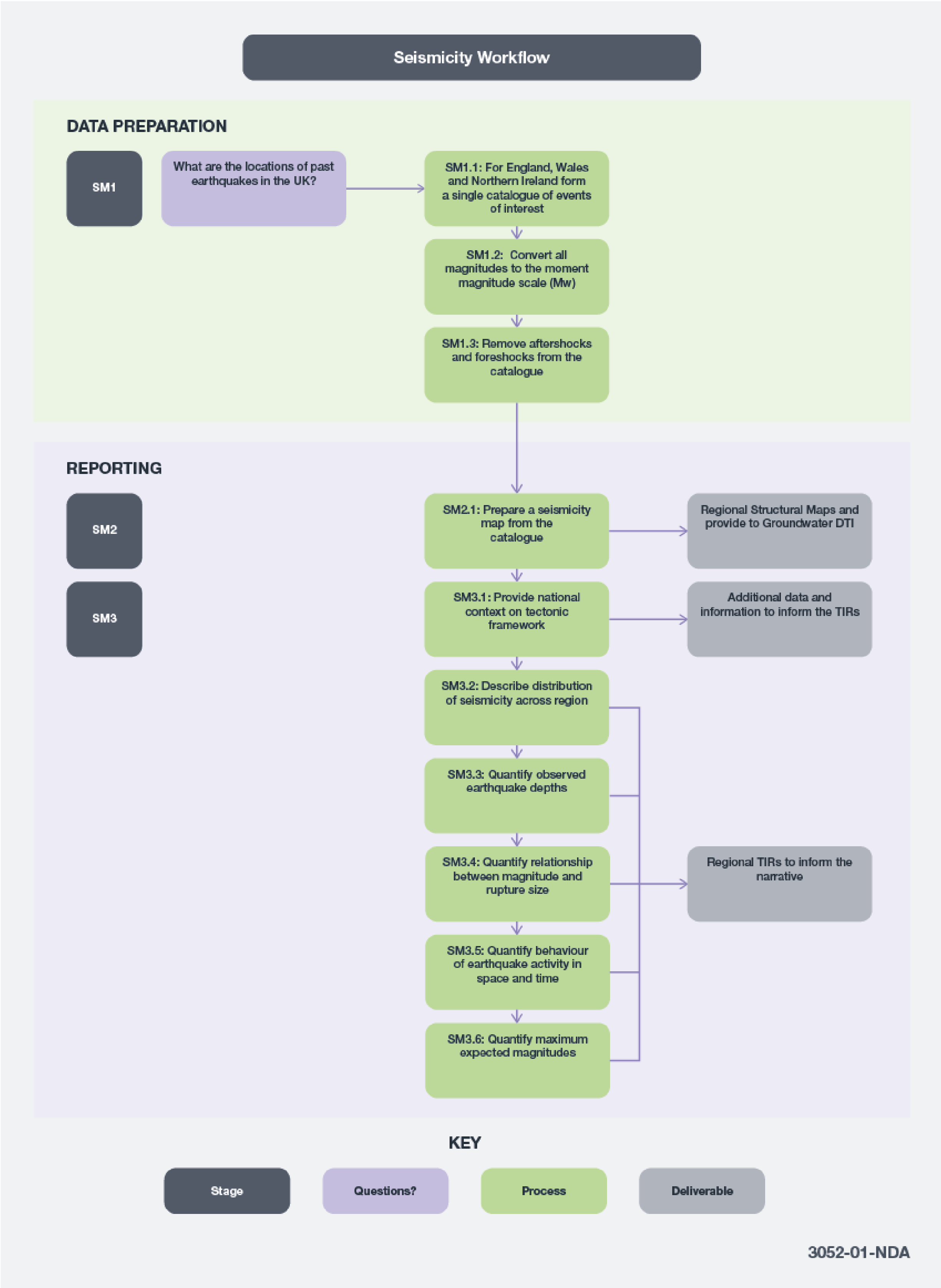
Other peer-reviewed publications that contain information on British earthquakes may also be used (e.g. Baptie, 2010).

5.4.3 Workflow overview

The seismicity workflow describes the methodology to be used to create the seismicity map and accompanying Technical Information Report for the seismicity component of the national geological screening exercise. It is organised in a series of ordered, linked steps to collate and process information.

Figure 7 is a schematic illustration of the seismicity component of the Natural Processes Detailed Technical Instruction workflow. The workflow itself is detailed below in Table 13 in Section 5.4.4.

Figure 7 Schematic Illustration of the Seismicity Workflow



5.4.4 Detailed workflow

Table 13 Seismicity Workflow

Step	Action	Description
Data Preparation		
What are the locations of past earthquakes in the UK?		
SM1	Extraction and concatenation of data	**S1.1**: Using the agreed area of interest (100 km from the shoreline of Britain and Ireland), extract data from the catalogue and concatenate. All earthquakes within the area and above the minimum magnitude of interest found in the data sources should be concatenated into a single catalogue. Entries for each earthquake should contain the information in Section 5.4.5 below.
SM1	Magnitude Conversion	**S1.2**: The magnitude for all earthquakes in the catalogue should be expressed as moment magnitude (Mw), since this is related to the physical properties of the rupture. Magnitudes of earthquakes expressed in terms of local magnitude (ML) should be converted to Mw using the well-constrained relationship derived by Grünthal *et al*. (2009) for earthquakes in northern Europe. $$M_w = 0.53 + 0.646\ M_L + 0.0376\ M_L^2$$
SM1	Removal of Dependent Events	**S1.3**: Dependent events (aftershocks and foreshocks) must be removed from the catalogue in order to reliably assess the frequency of occurrence of earthquakes of different magnitudes. The moving window method of Reasenberg (1985), as modified by Musson (1999), should be used for this purpose.
Reporting		
SM2	National Seismicity Map	**S2.1**: All events in the catalogue will be displayed on a national seismicity map. Symbols for earthquakes will be scaled in proportion to rupture area.
SM3	Geographic and Tectonic Context	**S3.1**: It is important to frame the national discussion of seismic activity in the wider context of earthquake activity in Europe. The European overview should contain a brief overview of earthquake activity at the nearest plate boundaries.
SM3	Spatial Distribution	**S3.2**. The spatial distribution of earthquake activity should be discussed in relation to known faults and driving forces for present day deformation. The difficulty of relating earthquakes to faults should be explained along with the uncertainties.

Step	Action	Description
SM3	Depth Distribution	**S3.3**: The observed depth distribution for British earthquakes should be presented in the form of a histogram. Uncertainties in earthquake depths will be presented. The Technical Information Report should include a discussion of the observed depth range in relation to the possible depth of any GDF. It should also be made clear that no British earthquake has resulted in a rupture of the surface.
SM3	Earthquake Scaling	**S3.4**: Earthquake magnitude scales with both rupture area and rupture displacement. This information will allow the rupture hazard to the GDF to be quantified. The scaling relationship should be presented in the form of a graph that relates magnitude to rupture area and rupture displacement. This should draw on the widely accepted empirical scaling relationship of Wells and Coppersmith (1994) for larger magnitudes and also a constant stress drop model for smaller earthquakes. The Technical Information Report should include a discussion of rupture dimensions and the possible impact on a GDF.
SM3	Earthquake frequency-magnitude distribution	**S3.5**: A penalised maximum likelihood procedure (e.g. Johnston *et al*., 1994) should be used to determine both the activity rate, a, which is a measure of the absolute levels of seismic activity, and the b value, the proportion of large events to small ones in the catalogue. The correction factor proposed by Rhoades and Dowrick (2000) is to be used in the activity rate calculations, based on the standard error of individual earthquake magnitudes, and this is applied here. It is assumed that all magnitude values in the catalogue have an uncertainty of ± 0.25.
SM3	Maximum magnitudes	**S3.6**: Maximum magnitudes should be discussed in the context of magnitudes for historical earthquakes in the British Isles and other comparable tectonic settings.

Note: The possibility of renewed glaciation in the next million years or even less means that estimates of the distribution and rates of regional seismicity cannot be considered the same as present. A number of studies (e.g. Pascal *et al*, 2010) suggest that earthquake activity beneath an ice sheet is likely to be suppressed, followed by much higher levels of activity after the ice has retreated again. Consequently, estimates of seismicity based on current rates may be quite misleading as to the possible levels of activity that could occur in the more distant future.

The Technical Information Reports should include a discussion of this issue, citing evidence for possible increase in seismicity in the next post-glacial period. Specific examples of this behaviour following previous periods of glaciation, either in the British Isles or elsewhere, should be included.

5.4.5 Information fields to extract from the earthquake catalogue

When extracting data from the earthquake catalogue, the following fields are required to be extracted:

1. Date
2. Time (GMT)
3. Hypocentre Longitude (decimal degrees)
4. Hypocentre Latitude (decimal degrees)
5. Hypocentre Depth (km)
6. Magnitude (Mw)
7. Horizontal Error (ERH)
8. Depth Error (ERZ)
9. Magnitude Error
10. RMS Error
11. Total number of readings used in the event location
12. Epicentral distance in kilometres to the closest station
13. Largest azimuthal separation in degrees between stations
14. HYPO71 type quality factor (S*D). S is the quality factor determined from RMS, ERH and ERZ. D is the quality factor based on the number and distribution of stations. The values are assigned according to Tables 14 and 15 and expressed as S*D, e.g. A*B

Table 14 QS is rated according to the RMS error and the errors in epicentre and depth

QS	RMS (sec)	ERH (km)	ERZ (km)
A	<0.15	1.0	2.0
B	<0.30	2.5	5.0
C	<0.50	5.0	
D	Others		

Table 15 QD rated according to the station distribution

QD	No of stations	GAP	DMIN
A	≥6	≤ 90o	≤DEPTH or 5 km
B	≥6	≤135o	≤2 x DEPTH or 10 km
C	≥6	≤180o	≤50 km
D	Others		

15. Overall hypocentre quality (Table 16)

Table 16 Overall hypocentre quality factor

Qal	Err Epicentre km	Err in Depth km
A	Excellent	good
B	Good	fair
C	fair	poor
D	Poor	poor

Quality rating (Qh) based on (a) locational uncertainty (Table 17) and (b) status of macroseismics (Table 18). The locational uncertainty codes are in upper case and the macroseismic status codes are in lower case. These codes are combined as in Ac, Bb, etc. It should be stressed that these quality codes represent a subjective assessment. Events codes b are those that have not been fully revised by BGS, though this is not to say they have not been revised by other authors. Parameters for such events draw upon either (i) studies by other authors, referenced in the descriptive paragraph for the event, (ii) an examination of material readily to hand in the BGS archives, or (iii) a combination of the two. Some events codes a still have room for improvement with respect to macroseismic effects outside the UK.

Table 17 Locational uncertainty codes (upper case)

A	well determined solution; accurate to within 5 km
B	moderately well determined; accurate to within 15 km
C	poorly determined; accurate to within 30 km
D	very poor; worse that 30 km

Table 18 Macroseismic status codes (lower case)

a	macroseimic study by BGS complete
b	potential for improvement in macroseismic parameters
c	macroseismic data for this event are very poor or non-existent

16. Epicentre error type flag (Fe). The errors indicate the radius within which it is 65% certain that the event occurred. Fe=1 if the epicentre error has been calculated using the bootstrap method. Fe=2 if the event was located using the HYPO71 or HYPOCENTER program. The errors are allocated according to the quality of the location and are assigned from Table 19. Fe=3 if the event does not have a quality assigned in the SQD field. The values are assigned from Table 20. Fe=4 if the epicentre was based on historical data and errors have been assigned according to expert judgement.

17. Magnitude error type (Fm). All values are equal to 0.25.

Table 19 Errors in epicentre and depth based on HYPO71 quality factor

Qal	Err Epicentre km	Err in Depth km
A	1.5	3
B	3	4
C	5	6
D	15	10

Table 20 Distances of epicentre from reference position and associated error in epicentre

Date/distance from position	Distance of epicentre from reference position	Reference position	Error in epicentre (km)	Error in depth (km)
01/01/1967-31/12/1977	<100km	320E 680N (Lownet)	5	5
01/01/1967-31/12/1977/	>100 km <250 km	320E 680N (Lownet)	20	10
01/01/1967-31/12/1977/	>250 km <400 km	320E 680N (Lownet)	50	20
01/01/1967-31/12/1977	>400 km	320E 680N (Lownet)	100	30
01/01/1978-01/01/1990	<150km	340E 250N (Hereford)	5	5
01/01/1978-01/01/1990	>150 km <250 km	340E 250N (Hereford)	20	10
01/01/1978-01/01/1990	>250 km <400 km	340E 250N (Hereford)	50	20
01/01/1978-01/01/1990/	>400 km	340E 250N (Hereford)	100	30

18. Depth error type (Fd). The errors indicate the radius within which it is 65% certain that the event occurred. Fd=1 if the depth error has been calculated from the bootstrap method. Fd=2 if the location was calculated using HYPO71 or HYPOCENTER. The errors are allocated according to the quality of the location. The values are assigned from Table 17. Fd=3 if the event does not have a quality assigned in the SQD field. The values are assigned from Table 21. Fd=4 if the epicentre was based on historical data and errors have been assigned according to expert judgement.

Table 21 Distances of epicentre from reference position and associated error in epicentre

Date/distance from position	Distance of epicentre from reference position	Position	Error in epicentre (km)	Error in depth (km)
01/01/1967-31/12/1977	<150km	320E 680N (Lownet)	5	5
01/01/1967-31/12/1977	>150 km <250 km	320E 680N (Lownet)	20	10

01/01/1967-31/12/1977	>250 km <400 km	320E 680N (Lownet)	50	20
01/01/1967-31/12/1977	>400 km	320E 680N (Lownet)	100	30
01/01/1978-01/01/1990	<150km	340E 250N (Hereford)	5	5
01/01/1978-010/1/1990	>150 km <250 km	340E 250N (Hereford)	20	10
01/01/1978-01/01/1990	>250 km <400 km	340E 250N (Hereford)	50	20
01/01/1978-01/01/1990	>400 km	340E 250N (Hereford)	100	30

5.5 Relationship with other Detailed Technical Instructions and the NGS Protocols

The Natural Processes Detailed Technical Instruction is not dependent on the other Detailed Technical Instructions which do not rely on the Natural Processes outputs. Work under the Detailed Technical Instruction will follow the NGS Protocols (Section 7).

5.6 References

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6 Detailed Technical Instruction: Resources

6.1 Introduction

This Detailed Technical Instruction sets out how data and information on the Resources topic will be assembled and presented as part of the national geological screening exercise. For the Resources attribute the following outputs for each of the 13 regions have been specified in the Guidance:

- narrative - description of the past history of deep resource exploration and exploitation with a discussion of the potential for future exploitation of resources in the region
- maps (1:625,000) - regional maps of historic and contemporary exploitation of metal ores, industrial minerals, coal and hydrocarbons at >100 m depths

This Detailed Technical Instruction sets out a step-by-step description of how information about UK geological resources will be assembled and presented as part of the national geological screening exercise. The Resources Detailed Technical Instruction has the following structure:

- definitions and assumptions – assumptions used to specify how the outputs are produced (Section 6.2)
- data and information sources – an overview of the data and information to be used (Section 6.3)
- topic process and workflow - an overview of the broad process, a step-by-step description of the Detailed Technical Instruction workflow and an outline of the Resources Technical Information Report text and map outputs that will be used as the basis for writing the narrative output (Section 6.4)
- relationship with other Instructions and Protocols - a brief note on the relationship between the Resources Detailed Technical Instruction, the other Detailed Technical Instructions prepared for the national geological screening exercise, and the NGS Protocols (Section 6.5)

6.2 Definitions and assumptions

6.2.1 Resources under consideration

The Resources topic relates to commodities such as metalliferous minerals, industrial minerals, coal, hydrocarbons and other energy resources that are known to be present, or thought to be present, below the Earth's surface at depths greater than 100 m. Geothermal energy, unconventional hydrocarbon resources and areas suitable for gas storage are included within the scope of this topic. Minerals worked in surface pits and quarries are not considered because such workings are considered to be too shallow to affect a GDF.

Commodities considered to have been worked by underground methods in England, Wales and Northern Ireland at depths greater than 100 m below the NGS datum (Protocol, Section 7.4.1) are listed below in Table 22.

Table 22 Commodities known to have been worked by underground methods (to greater than 100m below the NGS datum)

Bedded (sedimentary) deposits	
Coal	Coal
Bedded sedimentary reserves	Iron Ores (sedimentary)
	Oil shale
Bedded Evaporite Minerals	Anhydrite
	Gypsum
	Potash
	Polyhalite
	Salt (rock salt and brine)
Hydrocarbon fluids	Oil
	Gas (including abandoned mine methane and coal mine methane)
Miscellaneous commodities	Slate
Mineral vein type and other non-bedded deposits	
Metals and industrial minerals	Arsenic
	Barite
	Calcite
	Copper
	Fluorspar
	Iron Ores
	Lead
	Tin
	Tungsten
	Zinc

Other potential resources and uses of underground space considered under the Resources topic are listed in Table 23 below.

Table 23 Other potential resources and uses of underground spaces (to greater than 100m below the NGS datum)

Potential unexploited resources	
Hydrocarbon fluids	Unconventional oil
	Unconventional gas (including shale gas, coal bed methane and in-situ gasification of coal)
Heat	Geothermal energy
Use of underground space	
Gas storage	Salt caverns

6.2.2 Spatial extent of resources being considered

6.2.2.1 Lateral extent

In order to provide relevant information to a distance of 20 km offshore from the coastline, hydrocarbon fields to a distance of 30 km offshore will be considered. These may be relevant to the screening process because the presence of existing infrastructure may result in future exploration for and exploitation of similar resources that lie within the 20 km limit. All maps will, however, be to the 20 km limit.

6.2.2.2 Depth

The Guidance states that only past extraction and the presence of known resources at depths greater than 100 m below the surface will be considered. The presence of any exploratory shafts and boreholes deeper than 100 m that did not result in mining or extraction of resources will not be captured as part of the current process. They would, however, need to be considered during specific site evaluations.

Significant areas of historic mining at depths of less than 100 m are also identified in this Detailed Technical Instruction because the regional narrative will need to explain to the local public why they are not of relevance to the safety of a deep GDF.

Resources at depths greater than 1,000 m will be included in the screening assessments undertaken even though a GDF will not be situated below this depth. This is because exploitation of such resource may affect a GDF located at shallower depth.

The processes in the workflows (described below), make it clear when depths refer to below the actual ground surface or are relative to NGS datum (see Section 7.4).

6.3 Data and information sources

In line with the Guidance, information relating to the Resources attributes will be sourced and captured from publicly available national datasets and compilations. The specific sources to be used for map production for each sub-topic are detailed in the approaches described in the sub-tasks below. In addition to the maps showing known licensed and worked resources and areas with a high density of deep boreholes, a Technical Information Report will be produced for each region. This will discuss areas of unworked resources, which may be present underground. The principal information sources, including the equivalents for Northern Ireland, to be used are:

- BGS 1:1,500,000 Coal Resources Map (1999) (includes Northern Ireland)
- Department of Energy and Climate Change (DECC) information on conventional and unconventional hydrocarbons (for Northern Ireland wells, current (and historic) licence areas and Northern Ireland prospectivity review are available)
- BGS 1:1,500,000 Metallogenic Map (1996) (includes Northern Ireland)
- BGS County Mineral Resource maps (including for Northern Ireland) and reports
- BGS Economic Geology Memoir series, which is taken to include the BGS Economic Memoir series (including some memoirs not originally published under the BGS Economic Geology Series such as the Northern Pennine Orefield Volume 1 by KC Dunham and the Geological Survey of Great Britain Special reports on the mineral resources of Great Britain series (from 1st World War))
- BGS BRITPITS database of mines and quarries (This contains spatial but not depth information) (includes Northern Ireland)
- BGS GeoIndex (for information on onshore boreholes), NIINDEX (Northern Ireland borehole index)

- On- and Off-shore Hydrocarbon Wells (Off-shore Borehole Database) (equivalent available for Northern Ireland)
- Geothermal Prospectivity Map

Details of these data sources are provided in the Resources section of the Geological Data and Information Technical Note. The above information sources are considered to be the primary sources for the screening exercise; however derivatives may be used, if appropriate, to simplify the process.

6.4 Detailed Technical Instruction workflow

This Detailed Technical Instruction has been split into four main workflows because the data sources to be used and the outputs required are different and the processes that will be adopted to process the data and provide the outputs are slightly different.

As the Resources Detailed Technical Instruction workflow steps are undertaken, a specific ArcGIS project will be constructed which will be used to prepare the map based outputs and inform the preparation of the Resources Technical Information Report produced for each of the 13 regions. This report will also record the information sources for specific statements. In order to derive the information required to produce the Technical Information Report text and to prepare the associated map outputs, the Resources topic is divided into four different workflows to produce the outputs. These are:

1. Areas of historic, contemporary and potential future exploitation of the commodities in Table 22
2. Intensely drilled areas
3. Geothermal energy and gas storage (Table 23)
4. Potential for future unconventional hydrocarbons (Table 23)

Workflows 1 and 2 are presented in Sections 6.4.1 through 6.4.4. They are organised in a series of ordered, linked steps to collate and process information and presented as both schematic illustrations and detailed descriptions in tabular form.

Workflows 3 and 4, which are simpler, are presented as descriptions in Sections 6.4.5 and 6.4.6.

For each workflow, Table 24 summarises the specific information that will be extracted from the principal information sources for each of the commodities, resources or uses.

Table 24 Commodity Groupings and Principal Data Sources considered in Areas of historic, contemporary and future exploitation workflow

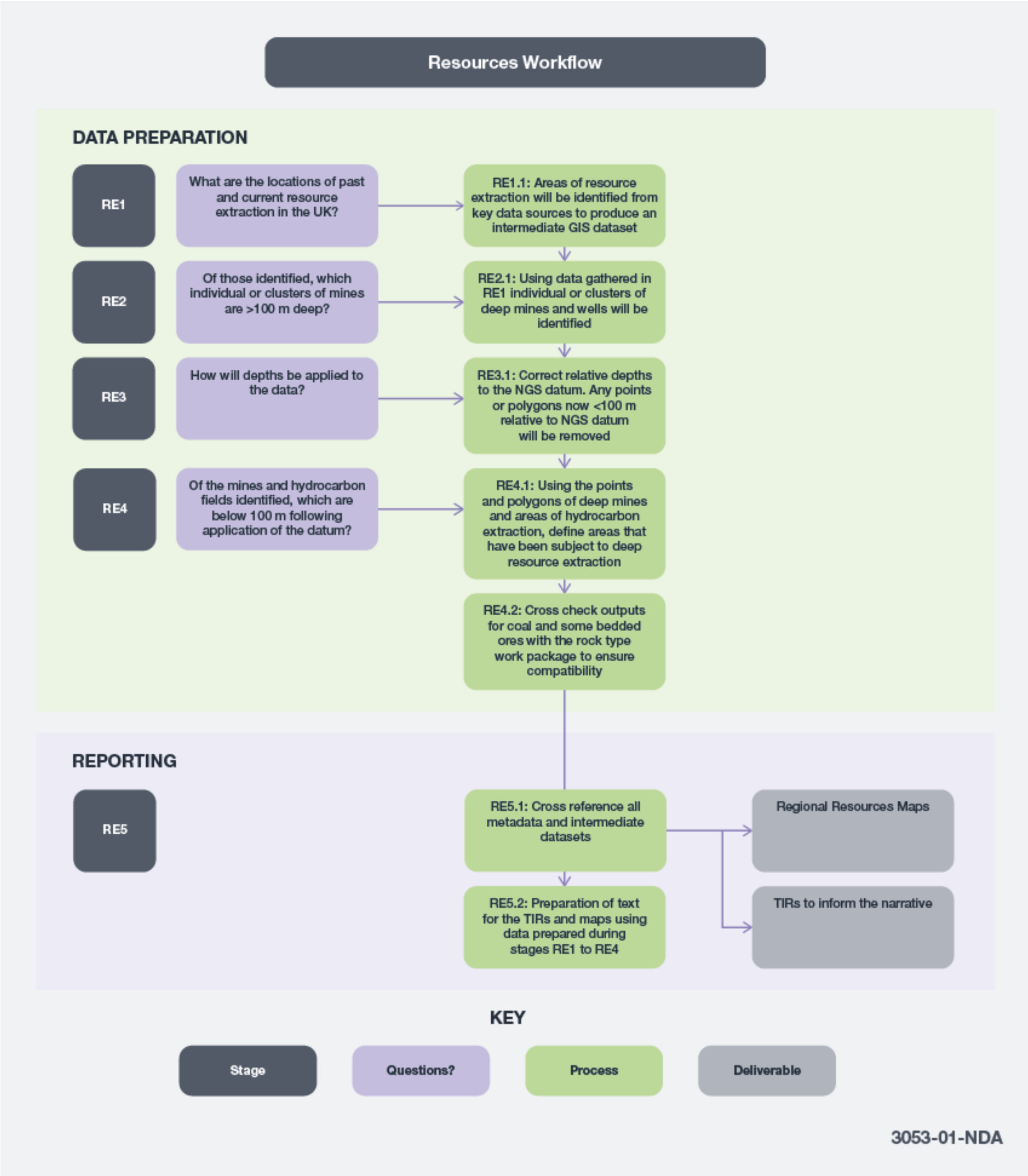
	Commodity	Principal information source	Commodity specific information that will be extracted from principal data
Workflow 1 - Areas of historic, contemporary and potential future exploitation of metal ores, industrial minerals, coal and hydrocarbons			
Bedded (sedimentary) deposits	Coal and oil shale	BGS 1:1,500,000 Coal Resources map, BGS BRITPITS database.	Areas where coal is greater than 100 m deep. Areas of principally shallow, small-scale mining (mainly pre–mid-20th century). Areas of mainly deep, large-scale mining (mainly post–mid-20th century). Areas of unworked coal. Areas of oil shale workings deeper than 100 m (if any).
	Bedded iron ores	BGS Economic Geology Memoir series, BGS BRITPITS database.	Areas where sedimentary Jurassic iron ores are known to have been mined deeper than 100 m.
	Bedded evaporite minerals: potash, halite, anhydrite and polyhalite	BGS Economic Geology Memoir series, BGS BRITPITS database. Publically available data on licence areas.	Areas of licensed/known mined salt exploitation. Areas of licensed/known solution-mined salt exploitation. Areas of known 'wild brine' salt exploitation. Areas of licensed/known mined gypsum exploitation. Areas of licensed/known mined anhydrite exploitation. Areas of licensed/known mined potash and polyhalite exploitation.
	Conventional hydrocarbons	DECC offshore and onshore licensing data.	Areas exploited for conventional oil/gas. Areas that have had significant exploration of hydrocarbons. Areas currently licensed for conventional hydrocarbon extraction and exploration.
Vein type and other non-bedded deposits	Vein minerals (including metal ores, industrial minerals (such as fluorspar and barytes) and stratiform sulphide deposits)	BGS 1:1,500,000 Metallogenic Map (1996). BGS County Mineral Resource maps and reports; BGS Economic Geology Memoir series; BGS BRITPITS database.	Areas of ore fields where there is a concentration of mineral veins or other non-bedded occurrences and known past workings deeper than 100 m. Areas of active or planned mining. Areas of evaluated (drilled) mineralisation not currently exploited.

	Commodity	Principal information source	Commodity specific information that will be extracted from principal data
Workflow 2 - Intensely drilled areas			
Deep Boreholes	Deep Boreholes for mineral resource evaluation, hydrocarbon and water abstraction	BGS GeoIndex (for information on onshore boreholes) (NIINDEX Northern Ireland borehole index). On- and Off-shore Hydrocarbon Wells (Off-shore Borehole Database) (equivalent available for Northern Ireland).	Location and depth of boreholes.
Workflow 3 – Energy and Gas storage			
Energy	Geothermal Energy	Geothermal Prospectivity map.	Information on the prospects for the future exploitation of geothermal energy within the region.
Gas Storage	Gas storage	Rock type Detailed Technical Instruction and publically available data on licence areas.	Areas of known gas storage caverns and potential for future development of such caverns.
Workflow 4 - Potential for future unconventional hydrocarbons			
Unconventional hydrocarbons	Shale gas, shale oil and coal bed methane	Department of Energy and Climate Change (DECC) published data information on unconventional hydrocarbons. DECC offshore and onshore licensing data.	Areas that have been evaluated for the potential resources of shale gas and oil. Areas that have had exploration for shale gas. Areas currently licensed for shale gas extraction. Areas that have had exploration for coal bed methane. Areas currently licenced for coal bed methane extraction. Areas that have had exploration for in-situ coal gasification. Areas currently licenced for in-situ coal gasification.

6.4.1 Workflow overview - areas of historic, contemporary and future exploitation workflow

Figure 8 is a schematic illustration of the workflow for areas of historic, contemporary and future exploitation of metal ores, industrial minerals, coal and hydrocarbons. The workflow itself is given in detail in Section 6.4.2 below.

Figure 8 Schematic Illustration of Resources Areas of historic, contemporary and future exploitation Workflow



6.4.2 Detailed workflow description - Resources areas of historic, contemporary and future exploitation workflow

Table 25 provides a detailed description of the linked steps to collate and process the information for this workflow.

Table 25 Deep Mineral Resources Detailed Technical Instruction Workflow

Step	Action	Procedure	Data Source
Data preparation			
What are the locations of past and current resource extraction in the UK?			
RE1	Identify areas of UK mineral extraction	Using a desk based approach, areas that have undergone past mining for or extraction of commodities in Table 22 will be identified. Analysis will be undertaken on a commodity specific basis which is identified in Table 24.	BGS Coal Resources Map, BGS Metallogenic Map, BGS County Mineral Resource maps and reports, BGS Economic Geology Memoir series, BGS BRITPITS, DECC data on conventional and unconventional hydrocarbons.
Of those identified, which individual or clusters of mines are >100 m deep?			
RE2	Production of GIS datasets of deep mining locations	Based on the desk study conducted in step RE1, areas where mineral extraction has only occurred less than 100 m bgl will be saved as an intermediate dataset (for use in any narrative discussion of historic mining). The locations of the remaining areas will be compiled in a commodity-specific GIS dataset. This will record the commodity worked and the maximum depth (m bgl) of shafts etc. If data indicating the spatial extent of the workings are available, for example from mine plans or licences this will be stored as polygons; this will most likely be at a constant depth (m bgl) over the entire area. If information allows, for bedded minerals, where the structure of the worked deposit is known or there are detailed shaft depths, it may be possible to differentiate the known mined area on the basis of depth (m bgl). If spatial data is not available then the locations of shafts will be recorded as point data. Metadata will be created for all new GIS datasets produced.	
How will depths be applied to the data?			
RE3.1	Apply NGS datum	All recorded depths of mining below ground level captured by step RE2 will be cross referenced against the NGS datum to ensure >100 m depths below NGS datum are still exceeded. This will be carried out using a GIS based comparison of land surface elevation (from which depth of workings have been determined) and the NGS datum.	NGS datum Digital Elevation Model.

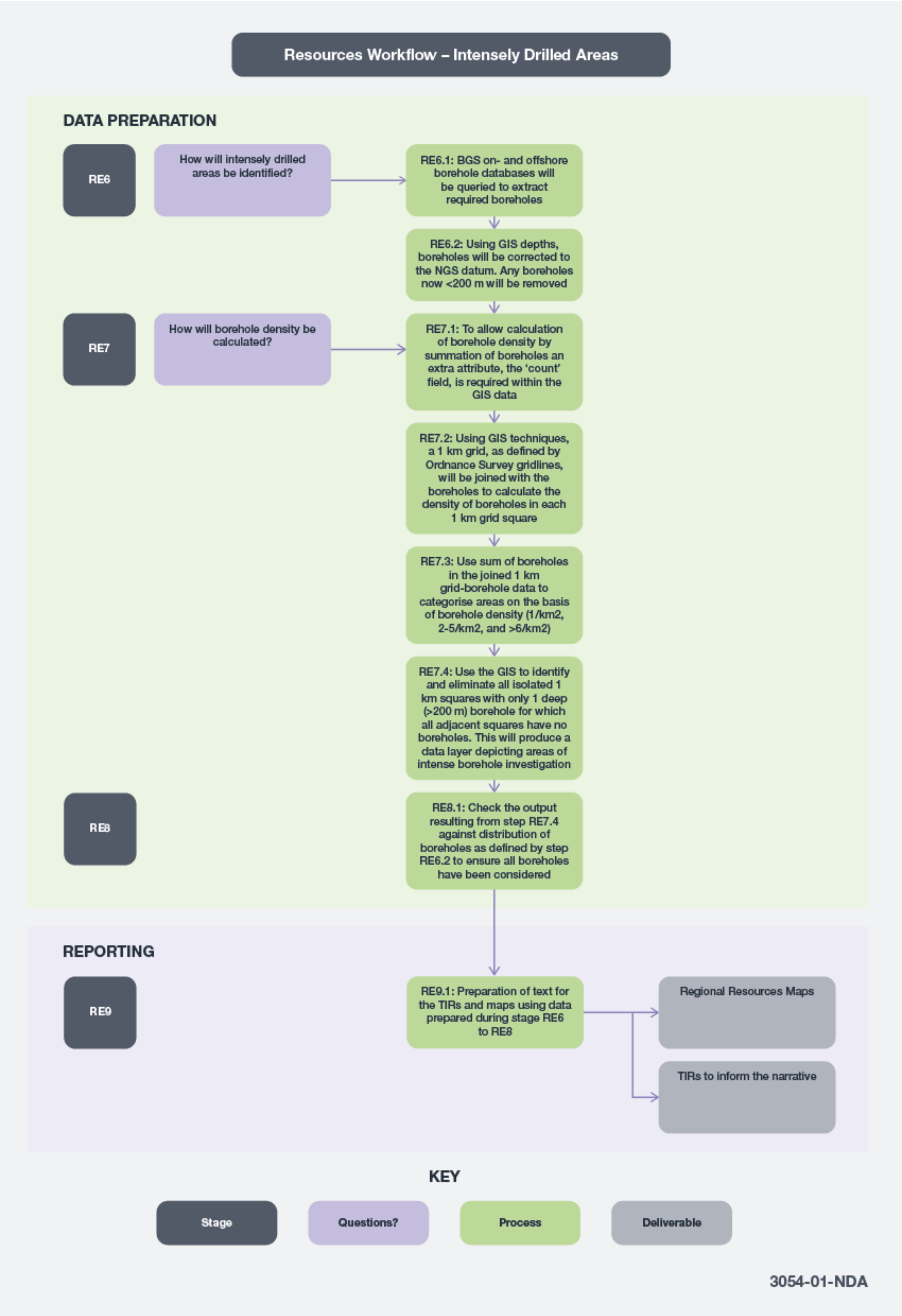
Step	Action	Procedure	Data Source
		The difference between these values will be subtracted from the depth of the mineral working to calculate depth below NGS datum. All areas of mineral extraction and mines that are now entirely <100 m deep with respect to the NGS datum will be transferred to the intermediate dataset.	
Of the mines and hydrocarbon fields identified, which are below 100 m following application of the datum?			
RE4.1	Creation of deep >100 m below NGS datum mining areas	Using the data for the locations of shafts and areas of deep mining, from step RE3.2, polygons depicting the location of deep mineral extraction will be created. If mine plans and license areas are available, these will be used to define boundaries. If several areas are in close proximity generalised areas around them will be created. If only point data is available, boundaries will be based on BGS expertise using the distribution of known shafts combined with structural and geological data depicting the extent of economic resources. The output will be a GIS polygon data layer of areas of mining >100m below NGS datum, attributed by commodity.	
RE4.2	Cross check outputs from the rock type work package	The areas produced by step RE4.1 will be compared against the outputs from the rock type work package to ensure that the commodities defined by areas of deep mining are compatible with the geology as defined by rock type. If any differences are noted this information will be fed back into the rock type work flow.	RT4
Produce Technical Information Report			
RE5.1	Cross reference all metadata and intermediate datasets	Production of the Technical Information Reports (Section 6.4.7) will need to draw upon information from intermediate datasets created throughout the workflow, therefore all intermediated datasets and metadata will be reviewed and if appropriate feed into the reporting process. Principal ore fields, including the full extent of historic mining districts <100m, will be indicated on the map, taking into account the intermediate datasets generated in previous steps, and an alpha notation will be used to indicate whether or not they have been exploited to depths below 100 m. This will allow easy reference to the principal mining districts in the Technical Information Reports.	
RE5.2		Text for the Technical Information Reports will be prepared that describes the past, current and potential future exploitation of the resources of the region using the map	

Step	Action	Procedure	Data Source
		output produced in the steps described above. This will include comment on the nature of the resources, the depth below ground level and NGS datum and any other relevant information that is not depicted on the map. It will include reference to principal ore fields that will be annotated on the map by use of an alpha notation whether or not they have been exploited to depths below 100 m. Further details are provided in Section 6.4.7 below. Maps will be prepared direct from the Arc GIS created in steps RE1 to 5.1. These outputs will also provide input to the Groundwater workflow.	

6.4.3 Workflow overview - Intensely drilled areas

is an illustration of the Intensely drilled areas workflow. The workflow itself is given in detail in Sections 6.4.4 below.

Figure 9 Schematic Illustration of the Resources Intensely Drilled Areas Workflow



6.4.4 Detailed workflow description - Intensely drilled areas

Table 26 provides a detailed description of the linked steps to collate and process the information for this workflow.

Table 26 Resources Detailed Technical Instruction Intensely Drilled Areas Workflow

Step	Action	Procedure	Data source
Data Preparation			
How will intensely drilled areas be drilled?			
RE6.1	Extract boreholes	ArcGIS queries will be produced that will extract boreholes >200 m bgl from the BGS on- and off-shore borehole databases. Results will be compiled into a GIS point file. Metadata will be created for this ArcGIS dataset.	BGS GeoIndex, NIINDEX, Off-shore Borehole Database.
RE6.2	Apply NGS datum	All borehole captured by step RE6.1 will be processed to identify all boreholes deeper than 200 m below NGS datum. This will be completed via a GIS based comparison of land surface elevation (from which depth of boreholes have been measured) and NGS datum. The difference of these two values will be subtracted from the depth below ground level of the boreholes to calculate depth relative to NGS datum. All boreholes that are now <200 m deep relative to the NGS datum will be rejected.	
How will borehole density be calculated?			
RE7.1	Edit borehole data to calculate borehole density	An extra attribute field will be added to all borehole locations. This will allow for the summation of boreholes within a defined grid size so that the borehole density can be calculated.	
RE7.2	Join borehole locations to grid data	The borehole locations will be joined to a pre-defined grid spacing, as defined by Ordinance Survey grid lines, using functions within ArcGIS. This will result in a 1 km grid with an attribute of the number of boreholes contained within each 1 km^2 cell.	
RE7.3	Use outputs to show areas of borehole density of >1 per km^2	Using the borehole density calculated by step RE7.1, the grid can be coloured to show different categories of borehole density. The categories of borehole density used will be 1 borehole, 2 to 5 boreholes and 6 or more boreholes per 1 km^2.	

Step	Action	Procedure	Data source
RE7.4	Remove 1 km squares with only one borehole and none in adjoining squares	The GIS will be used to identify and eliminate all isolated 1 km squares with only 1 deep (>200 m) borehole for which all adjacent squares have no boreholes. The areas of higher borehole density will then be selected as a final layer to show intensely drilled areas. This layer of intensely drilled areas will then by supplied to the Groundwater work package where it is also required.	
RE8	Processing review	Check the output resulting from step RE7.4 against distribution of boreholes, as defined by step RE6.2, to ensure all boreholes have been considered.	
Reporting			
RE9	Preparation of text for the Technical Information Reports	Draft text for the Technical Information Report that describes any areas of with a deep-borehole density of >6 boreholes/km^2 using the map output produced in the steps described above. This will include comment on their purpose, depth and any other relevant information that is not depicted on the map. Further details are provided in Section 6.4.7 below.	

6.4.5 Geothermal and gas storage

6.4.5.1 Geothermal energy

Text for the Technical Information Reports will be prepared that provides commentary on the geothermal energy potential for each regional area. It will provide a summary of the prospects for Engineered Geothermal Systems (where rocks at depths greater than 4 km are engineered with stimulation techniques to create a reservoir of accessible hot water that is exploited for the generation of electricity) and direct use geothermal (where water from deep saline aquifers is used to supply heat for various applications). To date, the only direct use exploitation is restricted to a district heating scheme at Southampton and spa facilities at Bath and Buxton and no Engineered Geothermal Systems have been developed in the UK. Standard text for all of the Technical Information Reports will be prepared that will note that ground source heat pump geothermal energy exploitation may occur in any location.

6.4.5.2 Gas storage

High level text summarising the presence of salt deposits of sufficient thickness for potential future use for the development of gas storage caverns will also be produced. This will include commentary on sites that have already been developed, or are at an advanced stage of planning, for gas storage (natural gas, hydrogen and compressed air). The areas for potential future use for gas storage will use the extent of evaporites provided by the Rock Type Detailed Technical Instruction supplemented with information on thickness of salt.

6.4.6 Potential for future unconventional hydrocarbons

Text for the TIRs will be prepared that provides commentary on the potential for unconventional hydrocarbon (Shale oil and shale gas) resources within each regional area. It will provide a summary of the prospects for the future exploitation of these commodities within the region based on the assessments carried out on behalf of DECC and will provide information on any existing licenced areas. Text will also be prepared that provides commentary on past exploration and areas currently licenced for coal bed methane and in situ coal gasification.

6.4.7 Technical Information Reports

Technical Information Reports will be produced for each region which will consist of a brief description of the past history of deep resource exploration and extraction along with a discussion on the potential future use of the resources present. This will be undertaken on a commodity specific basis and will use the following sub headings:

- coal and related commodities
- potash, halite, anhydrite and polyhalite deposits
- other bedded and miscellaneous commodities
- vein-type and other mineral deposits that are not bedded
- hydrocarbons (oil and gas)
- geothermal
- high density of deep boreholes (>6 per km^2)

Not all types of commodities will be present in all of the regions under consideration during the screening process, although many of the regions will have examples of several of the different groups of commodities listed above. Each report will be consistent across the regions using common classifications and will specifically note if none of the commodities covered by the above sub-headings are present.

For each of the above sub-headings the Technical Information Reports will provide:

- an overview of data displayed on map outputs. Information for this will be based on the screening maps themselves and the background data collected during this process. This will describe the past and current exploitation of resources within the region under consideration in particular noting areas of past deep exploitation and the depths at which this occurred
- historic mining that does not meet the criteria to be shown on map outputs but is important for context. This will be in the form of areas of extensive, mainly shallow, mineral extraction and information will be sourced from: steps used to construct the screening maps; BGS 1:1,500,000 Coal Resources map; BGS BRITPITS database; BGS 1:1,500,000 Metallogenic map and BGS economic memoirs. The general location of ore fields etc. will be identified on the resources map using an alpha coding to enable easy cross referencing from the text to the map
- future resources will be defined using:
    - areas of historic working and exploration, as shown in the BGS BRITPITS database and BGS economic memoirs
    - areas where the geology is known to be of potential for mineral resources, for example bedded resources can be defined from the 1:1,500,000 coal map, data from the BGS SOBI database and data from BGS geological mapping
    - vein type and other non-bedded deposits also defined by BGS geological mapping will be used as an indicator for potential future metallogenic resources
    - if appropriate, this section will also describe licensed, potential unconventional (gas and oil) resources and prospects for geothermal energy gas storage

6.5 Relationship with other Detailed Technical Instructions and the NGS Protocols

The Resources Detailed Technical Instruction is dependent on the Rock Type Detailed Technical Instruction for information on the lateral extent of evaporite deposits. It will also require a cross check of outputs from the Rock Type Detailed Technical Instruction in order to confirm that bedded resources (coal and some iron ores) are consistent between the work streams.

Work under the Detailed Technical Instruction will follow the NGS Protocols set out in Section 7 below.

Output from the Resources Detailed Technical Instruction is required by the Groundwater Detailed Technical Instruction in the form of maps of intensely drilled areas and areas of mining of any sort >100 m below NGS datum.

7 Protocols

The NGS Protocols are the agreed set of rules, methodologies and vocabularies that apply across the geological topic areas and outputs, and which require a consistency of approach to be applied, demonstrated and communicated.

There are five NGS Protocols which are listed in Table 27, and described below. The protocols reflect the high level workflow for the national geological screening exercise, including the data to be considered, the expert judgement to be applied to those data, the language and vocabularies to be used, any bespoke spatial reference datasets created for the national geological screening exercise, and the format of the NGS outputs.

Table 27 List of NGS Protocols

Protocol	Subcategory
Data.	Existing Data.
	Approach to Metadata.
	Approach to Data Collation.
	Road Map to Supporting Information.
Expert Judgement and Uncertainty.	Approach to Expert Judgement.
	Approach to Uncertainty.
Language and Vocabularies.	Terminology.
	Nomenclature.
	Assumptions.
	Acronyms.
NGS datum and Spatial Limits.	NGS datum for depth.
	Offshore limits. Overlaps between regions.
NGS Outputs.	Technical Information Reports and NGS Narratives.
	Map Formats and Conventions.

7.1 Protocol No. 1: Data

The NGS Outputs will be prepared as far as possible from existing, publicly available national datasets and compilations (see the Guidance). The Data Protocols provide a brief overview of the overarching definitions and approaches that will apply to the collation, cataloguing and referencing of the sources of information to be considered by the NGS. Additional details on the collation and management of the data will be provided in the BGS Project Quality Management Framework, which will be completed prior to the application of the Guidance.

7.1.1 Existing data

'Existing Data' are defined as the pre-existing datasets, published texts, maps, models and online information that will inform the outputs of the NGS, and which are publicly available at the end of February 2016. Data published or released into the public domain after this date will not be taken into account by the national geological screening but will be considered, as appropriate, later in the siting process during area or site-specific studies.

The following overarching principles will apply to the scope and use of Existing Data:

1. the NGS outputs will be based primarily on existing syntheses in the form of maps, texts, models and national data indexes. These will include, but not be restricted to, the principal information sources listed in the Guidance. Peer reviewed scientific publications will also be considered if, in the expert judgement of the BGS, they contribute significantly to the overall regional or national-scale geological understanding required to deliver the NGS

2. by default there will be no critical re-evaluation of the interpretations in those syntheses, though exceptions to this will be raised if:
    a. data have become available since publication that would improve certainty in areas of low data density
    b. more than one synthesis exists and each presents different interpretations which need to be resolved
    c. a Detailed Technical Instruction requires information at a higher resolution than considered in the published syntheses. For example, the Rock Type topic will require subsurface mapping of rock units at a higher level of stratigraphic resolution than the generalised rock units modelled in UK3D. Heterogeneities in the properties of those units will also need to be considered. UK3D will still provide the overarching framework for that more detailed interpretation, but other syntheses and data will need to be consulted to deliver the Rock Type outputs (see Detailed Technical Instruction for Rock Type)
3. all Existing Data consulted will be incorporated in the Data Collation (see below) and catalogued in the Metadata (see Geological Data and Information Technical Note)

7.1.2 Approach to metadata

Metadata is a grouped set of data that describes and gives information about other data. The national geological screening will capture and manage three types of metadata:

1. *Discovery Metadata*. Metadata describing each of the NGS outputs
2. *Technical Metadata*. Metadata describing each of the sources of information (the 'Existing Data') consulted in order to deliver the NGS outputs
3. *Inference Metadata*. Metadata describing and recording the processes followed to produce the NGS outputs, making reference to the corresponding Detailed Technical Instructions and including a record of the associated interpretations, decisions, assumptions, algorithms and expert judgements that were applied, and the experts involved

The Inference Metadata will also provide evidence of compliance with the BGS Project Quality Management Framework, and include checklists that confirm adherence to the Detailed Technical Instruction workflows and record any necessary exceptions. The Discovery Metadata standard will be compliant with UK legislation (INSPIRE Directive), which is UK Gemini v2.2. This is a UK standard derived from ISO19115/19149 metadata. Technical and Inference Metadata schemas are less formally regulated but in essence are also an extraction of the ISO metadata standard. In principle, the suite of Metadata together with the Data Collation of Existing Data and the Detailed Technical Instructions should allow a suitably skilled geologist(s) with comparable experience and knowledge to recreate the scientific outputs/recommendations of the NGS.

7.1.3 Approach to data collation

The NGS Data Collation will have two outputs, the *Data Collation* itself and the *Geological Data and Information Technical Note.*

1. the Data Collation constitutes the Existing Data considered in order to deliver the NGS outputs, and the associated Technical Metadata. The Data Collation will be populated on an ongoing basis during delivery of the project and a dated archive will be 'frozen' on final release of the completed NGS outputs. The Data Collation metadata record will include information on each dataset consulted, how it was used and an assessment of the data quality and associated uncertainties. The procedure for archiving the Data Collation, including any non-BGS data sources considered, will be detailed in the BGS Project Quality Management Framework, which will be completed prior to the application of the Guidance
2. *The Geological Data and Information Technical Note* is a high level catalogue and review of the sources of Existing Data consulted by the NGS. It will describe logical groupings or 'series' of Existing Data types (for example 'BGS Subsurface Memoirs', 'BGS 1:50,000 scale Onshore Geology Map Series') and provide an assessment of the content, quantity, provenance, quality and uncertainty inherent in each data series. Version 1 of the Geological Data and Information Technical Note is provided as an output of the development of the Detailed Technical Instructions. Its purpose is to provide assurance that the Detailed Technical Instructions are referenced against the appropriate sources of Existing Data. The Geological Data and Information Technical Note will be updated on an ongoing basis throughout the application of the Guidance and released as supporting information on conclusion of the project

7.1.4 Road map to supporting information

The Road Map to Supporting Information will serve four purposes:

1. to direct users of the NGS outputs to sources of further information
2. to provide RWM and DECC with references to sources of additional technical information that will assist with communications and responses to enquiries
3. to provide a checklist that all appropriate sources of information have been consulted and referenced by the NGS
4. to provide a hierarchical framework to assist with logical hyperlinking of online outputs to sources of additional information

A template high level Road Map for the national geological screening is shown in Table 28 below. It categorises sources of supporting information into a series of Tiers that reflect the nature, scope and relevance of the information. The approach to referencing each Tier may vary according to the nature of the information and the intended audience. For example, users of the NGS outputs will be directed to Tier 1 and 2 documents via an annotated bibliography in each Regional Narrative.

The high level Road Map will be refined during application of the Guidance and provide a framework to assist with online delivery of NGS outputs and their links to online sources of supporting information.

Table 28 High Level national geological screening Road Map to sources of supporting information

Tier	Type of Supporting Information	Status	Examples	Approach to referencing
0	NGS outputs.	Published.	Regional Narratives, Maps.	
1A	High Level Policy Documentation on Radioactive Waste Management.	Published.	Guidance, Implementing Geological Disposal White Paper 2014.	Annotated Bibliography in Regional Narratives, list to be agreed with RWM at during application of the Guidance.
1B	National Geological and Technical Syntheses.	Published.	Directory of Mines and Quarries, BGS Coal Resources Map, Water Framework Directive UK TAG.	Annotated Bibliography in Regional Narratives.
1C	National Geological Datasets.	Published or online.	UK3D, BGS GeoIndex, BRITPITS.	Annotated Bibliography in Regional Narratives.
2	Regional Geological Syntheses.	Published.	BGS Regional Guides, Subsurface Memoirs .	Annotated Bibliography in relevant Regional Narrative.
3	Scientific and technical references consulted by the NGS.	Published.	Peer reviewed papers, published scientific or technical reports, Sheet Explanations, 1:50,000 scale geological maps.	Standard Scientific Bibliography in NGS Technical Metadata.
4	Technical Data.	Unpublished, discoverable.	Glossaries, Assumptions, NGS Metadata, Geological Data and Information Technical Note.	Incorporated in the NGS Technical Metadata.

7.2 Protocol No.2: Expert judgement and uncertainty

Expert judgement involves the weighing of available evidence and reaching a balanced conclusion from that evidence (Hora, 2009). In the context of the NGS, there are known to be gaps and uncertainties in the available evidence (Existing Data, see above) that impact on the confidence of expert judgement. Furthermore, the national geological screening will primarily consider existing syntheses in the form of maps, texts and models available in the public domain. These syntheses are in themselves the products of expert judgement, and in many cases the decision-making processes, interpretations and assumptions that contributed to those syntheses are not explicitly recorded. The approaches to expert judgement and uncertainty are therefore intrinsically linked and are considered below as components of a single protocol.

7.2.1 Approach to expert judgement

When exercising expert judgements for an analysis or decision, a number of decisions are needed on how to proceed. These include (cf. Hora, 2009):

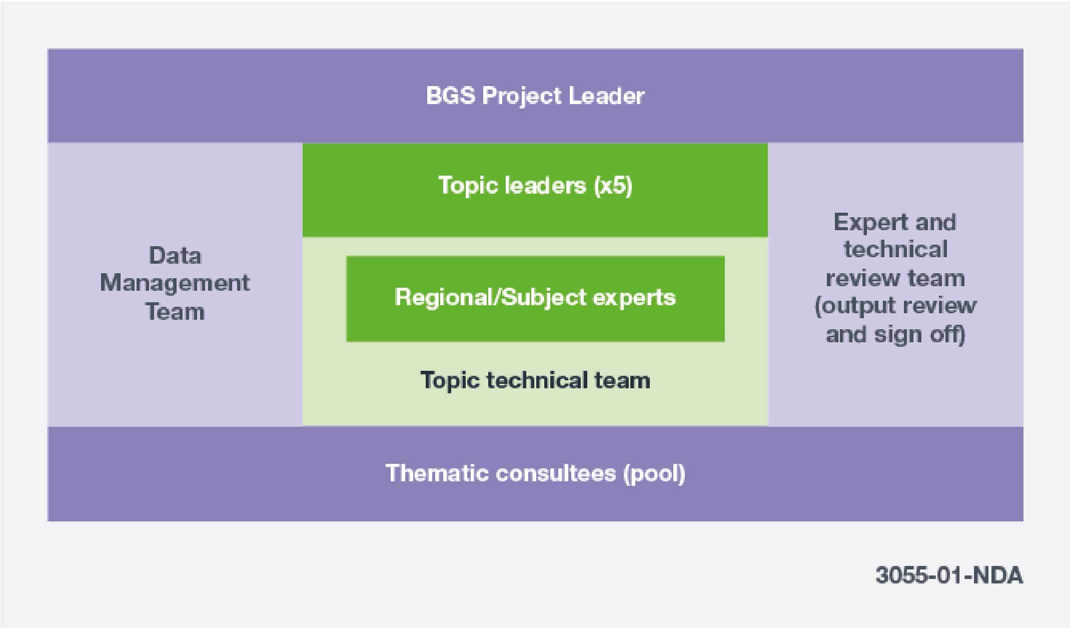
1. selecting the issues to be addressed
2. selecting the experts
3. organising the effort
4. choosing a method for combining or rationalising multiple judgements or conflicting opinions, if required

The issues to be addressed are defined by the Guidance and the Detailed Technical Instructions for each geological topic. This protocol therefore focusses on the approach to be taken on roles, organisation and interactions of experts within BGS, and the needs for external input.

7.2.1.1 Roles and organisation of experts

Expert judgement will contribute to delivery of the Map and Technical Information Report outputs for each of the 13 regions of England, Wales and Northern Ireland, covering the five geological topic areas. Expert roles at project, topic and regional level are summarised below and in Figure 10. Project-wide roles are shown in green, topic-specific roles in blue.

Figure 10 Organisational diagram showing the expert roles in the BGS Project team



NB Project-wide roles are shown in green, topic-specific roles in blue

Topic leader

Each of the five geological topics will have a topic leader reporting to the overall BGS Project leader for the NGS. Topic leaders will be responsible for the delivery of the outputs for each topic, which will ultimately be communicated as topic-based sections in each Technical Information Report (see Outputs Protocol), with accompanying maps as specified by the Guidance. Depending on the topic, the Topic leader will delegate expert judgement and text writing for individual regions or sub-topics to Regional or Subject experts respectively, but will retain ultimate responsibility for ensuring a robust and consistent scientific and technical approach to expert judgement and delivery of topic-based output across all regions, including review of outputs and compliance with protocols.

Regional or Subject experts

For each topic, Regional or Subject experts will be nominated to contribute to the Technical Information Report and map outputs and their level of input will reflect their expertise across a region (i.e. at regional scale). Geological knowledge across a region, rather than of a localised area, is considered proportionate to the national scale of this exercise. The organisation of these experts will vary from topic to topic. For example, the Rock Type topic will require interaction between nominated stratigraphic experts with national knowledge of potential host rock units, and regional experts familiar with more local variations in stratigraphy and rock properties. The regional experts will draft the Rock Type section in each regional Technical Information Report. In contrast, the Natural Processes Topic will have Subject experts for Glaciation, Permafrost and Earthquakes sub-topics who will firstly carry out national scale syntheses for each sub-topic and then scale down to the regional context when preparing text for the Technical Information Reports

Thematic consultees

Thematic consultees are a pool of individuals within the 'BGS Community' who will provide relevant expertise and knowledge on specific themes, for example Triassic evaporites, southern Britain Jurassic stratigraphy, regional geophysics or rock physical properties. The pool will provide a knowledge and expertise resource that will serve the needs of all five geological topics. These consultees will mostly be NERC BGS employees but will also include individuals from the wider community of BGS Honorary Research Associates. They will be consulted by Topic leaders, Regional experts and Subject experts as required for verification of specific interpretations, assessment of uncertainty or to help resolve differing scientific opinions among team members or conflicting interpretations within the Existing Data. Thematic consultees may also be asked to contribute to internal expert review of Map and Regional Technical Information Report outputs as part of the BGS Quality Management process.

Topic technical team

The Topic technical team will be the BGS in-house team of scientific and technical staff who will work under the direction of Topic leaders to assist with delivery of map and report outputs and the supporting interpreted information (e.g. models, maps, interpreted data) for each topic, following the Detailed Technical Instruction workflow.

Expert and technical review team

This team is responsible for review and sign-off of the NGS map and report outputs delivered by BGS. It will include Topic leaders and other individuals in the BGS management chain. The process for sign off will be included in the internal BGS Project Quality Management Framework, which will be completed prior to commencement of application of the Guidance.

Data Management team

This team is responsible for management of the NGS data environment which will include Existing Data, Metadata, NGS outputs and Supporting Information (interim interpretations and outputs created by the Detailed Technical Instruction workflows). The process for Data Management is included in the BGS Project Quality Management Framework, which will be completed prior to commencement of application of the Guidance.

7.2.1.2 Interactions of experts in the judgement process

A hierarchical approach to expert judgement is proposed for the NGS to ensure that:

- the most appropriate expert or pool of experts in the BGS is engaged or consulted at each workflow step so that judgement is as robust as possible
- multiple judgements and conflicting opinions are harmonised and consistent across and between regions and topic areas
- needs for any external (non-BGS) expert input to decisions is considered in the context of risk
- the type of expert judgement exercised at each workflow stage can be categorised in the Inference Metadata

The approach is described below under a hierarchical process with four levels of expert judgement. This allows for some flexibility for the approach to evolve during the course of the application of the Guidance.

Level 1 and 2 expert judgement processes involve individuals from the 'BGS Community' only. Levels 3 and 4, if invoked, will involve experts external to BGS as appointed by RWM.

Level 1 expert judgement process

Scientific and technical judgement at this level will be exercised by the Topic leaders and Regional/Subject experts, working with the Topic technical team and consulting on an informal basis with Thematic consultees. This will be the default level of expert judgement deployed on a day to day basis at most Detailed Technical Instruction workflow steps.

Level 2 expert judgment process

This process will operate at critical decisions or check points in each Detailed Technical Instruction workflow, when key judgements, decisions or issues of consistency need to be agreed and addressed before progression to the next stage of the workflow. The process is consensual and will involve meetings of the Topic leader, Regional/Subject experts and relevant Thematic consultees, informed by pre-circulated documentation and evidence. Design of these meetings (for example who chairs or facilitates, and whether these individuals need to be independent) will vary according to the issue to be addressed, the degree of uncertainty involved and extent of any difference of opinion between experts. The outcome of this process will be minutes of the discussion and decisions agreed at the meeting, and actions required to progress to the next workflow stage. Minutes will be archived in the Inference Metadata.

Level 3 expert judgement process

This process will operate only exceptionally in circumstances where expert judgement on a specific issue impacts specifically on safety case implications. It will involve input from scientific experts nominated by RWM. As at Level 2, the process will involve a minuted meeting or workshop bringing together the relevant BGS and external experts. The process will most likely be invoked in circumstances where, for example, expert judgement on a specific issue impacts significantly on safety case considerations, communications objectives or NGS project risks. At present it is envisaged that one instance of a Level 3 expert judgement process that will be required for the Rock Type topic – this is described in the example below. The decision to invoke a level 3 process for any issue will rest with RWM though may be advised by BGS and emerge from ongoing interaction between BGS and RWM during the application of the Guidance.

Level 4 expert judgement process

This process would involve an appropriately structured process of Expert Elicitation that may be required to address key issues of communication, uncertainty or conflicting expert opinion emerging from the national geological screening exercise. Design of the Expert Elicitation process would be bespoke to the issue being addressed. The need for Expert Elicitation is not likely to arise during application of the Guidance, and this process is therefore not considered in further detail in this protocol. Any decision to use a Level 4 expert judgement process will be made by RWM.

7.2.1.3 Example of Expert Judgement from the Rock Type Detailed Technical Instruction

The objective of the NGS Rock Detailed Technical Instruction is to deliver, using a combination of Narrative and Maps, information on the distribution of potentially suitable host rocks across England, Wales and Northern Ireland in the depth range 200 m to 1000 m (see the Guidance).

A critical decision in the workflow for Rock Type is to agree which of the rock units shown on BGS geological maps and in UK3D contain one or more of the potential host rock types (see the Guidance). UK3D provides the basic 3D geological framework used for mapping rock types of interest in the subsurface, but in many cases there is not a one-to-one match between those rock types of interest and the stratigraphic units modelled in UK3D. In many cases, rock types of interest will correspond to subdivisions within those stratigraphic units, rather than the entire unit. In these circumstances it will be necessary to:

1. map rock types of interest onto the stratigraphic units modelled in UK3D and identify where additional subdivision of those stratigraphic units is required (Rock Type Detailed Technical Instruction, Step 2)
2. carry out the additional interpretation and modelling required to delineate those additional subdivisions within NGS3D (Rock Type Detailed Technical Instruction, Step 4)

At the conclusion of Rock Type Detailed Technical Instruction Step 2, BGS will deploy a Level 2 expert judgement process that brings together all the scientific and technical experts needed to review and sign off a recommended list of additional stratigraphic subdivisions to be inserted into NGS3D. Considering the example of LSSR, that Level 2 expert judgement process will involve internal review by:

- the Topic leader for Rock Type
- Regional experts responsible for delivery of outputs for each region
- Stratigraphic experts with knowledge of the rock units modelled in UK3D and their correspondence with rock types of interest
- Thematic consultees with knowledge of the properties and heterogeneities of the rock types of interest and their host units within UK3D

At this point (Rock Type Detailed Technical Instruction, Step 3), the agreement of RWM will be sought, in the context of the safety case, on the list of additional stratigraphic units to be inserted into NGS3D and their correspondence with rock types of interest. It is recommended that a Level 3 Expert Judgement Process is invoked at Step 3. This will involve input from scientific experts nominated by RWM, who will meet at a workshop or workshops with the BGS Rock Type team to amend (if necessary) and approve the recommended list, allowing progression to Step 4 of the Detailed Technical Instruction.

7.2.2 Approach to uncertainty

Uncertainty in information can be described **quantitatively** or by **Qualitative Statements of Confidence** (e.g. Mastrandrea *et al*., 2010). A quantitative description of uncertainty may be expressed, for example, by the probability that some statement is true, or by a confidence interval that includes the true value of some predicted quantity with a specified probability. Such statements of probability must be based on a statistical model used to compute the information from data (e.g. Lark and Webster, 2006), post-hoc evaluation of information with test observations (e.g. Lark *et al*., 2013), or by a formal process of expert elicitation to obtain parameters of a statistical distribution for that information (e.g. Scourse *et al*., 2015).

Where information is not based on statistical inference or a formal elicitation of expert probabilities, and where there are not sufficient data to undertake a post-hoc evaluation **Qualitative Statements of Confidence** (QSC) are more appropriate and can be used. As defined by Mastrandrea *et al*. (2010), QSC are based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgement) and the degree of agreement. This approach uses a standard set of verbal categories to describe confidence. For example, Mastrandrea *et al*. (2010) propose five levels of confidence in their recommendations to the Intergovernmental Panel on Climate Change: Very Low, Low, Medium, High or Very High.

7.2.2.1 Approach to be adopted for NGS

The national geological screening exercise is using existing data based on prior, completed syntheses of observations. For most, if not all of the topic areas, considered at national scale, this synthesis was by geological interpretation and expert judgement rather than statistical modelling, so statistical measures of uncertainty are not available or calculable. Post-hoc evaluation of information is not possible because independent observations are not available systematically at national scale. Formal elicitation of expert opinion may be undertaken for specific scenarios within carefully defined settings (see, for example, Lark *et al*., 2015). This makes the process demanding and not feasible for characterization of uncertainty in all existing data at national scale.

On that basis, a similar, but simplified, approach to that proposed by Mastrandrea et al (2010) will be adopted for the NGS Technical Information Reports and associated narratives using a harmonised number of confidence levels between the five topics. These will be agreed with Topic Leaders as the Technical Information Reports and associated narratives for each region are written. The basis on which these confidence categories are selected for particular pieces of information will be set out in narrative form. Where appropriate, Topic Leaders may develop QSC to cover an appropriate range of data rather than individual data sets, for example where the boundaries between a number of nearby rock types of interest are subject to similar uncertainties.

7.2.2.2 Communication of uncertainty in NGS outputs

A structured approach to communicating uncertainty using QSC will be adopted in the Technical Information Reports to be delivered by BGS. The approach provides flexibility for some editorial adjustment to produce Plain English versions for the Regional Narratives, though requiring effective iteration between the NGS communications experts and the BGS project team to ensure the technical basis for the QSC remains intact. Because a QSC uses terms such as LOW or HIGH to refer to confidence in information, and others (e.g. LIMITED, ROBUST) to refer to quality of supporting data, it will be important to ensure consistency with terms used in the narratives. Using upper case, small capitals or some other distinctive font may help to avoid this.

For the qualitative assessment of uncertainty the text which presents the QSC is central to communication in that it presents a rationale for an expert judgement in a structured way. This statement may be supported by other elements, such as maps, but because a QSC is a matter of expert judgement rather than an algorithm, and refers partly to spatial information (e.g. data density) but also to ancillary information (e.g. on quality assurance procedures) it cannot be routinely represented as a map. The QSC may however be supported by two types of map. The first would represent factors that contribute to the QSC e.g. maps of the distribution of supporting information such as boreholes or seismic lines. Secondly, in the case of 2D information on the extent of a unit, it may be possible to represent boundaries with solid, pecked or dotted lines in cases where confidence is HIGH, MEDIUM or LOW respectively. A decision will be made during application on the approach to be adopted on the Published Map outputs.

7.3 Protocol No.3: Language and vocabularies

These protocols describe how definitions of the terminology, nomenclature, assumptions and acronyms adopted by the Detailed Technical Instructions, and communicated in the NGS outputs, are captured and recorded.

7.3.1 Terminology

Terminology is a 'system of terms used in a particular subject' (Oxford English Dictionary). NGS Narratives and Maps will be targeted at a non-specialist audience, but the terminology used must also be robust to technical scrutiny and audit. It is also essential that key terminology required for the Detailed Technical Instructions is clearly defined prior to the start of the application of the Guidance to ensure consistent and unambiguous application of the Detailed Technical Instructions and delivery of the Work Package outputs. Ongoing engagement between the BGS and the NGS communication team will be required in the application of the Guidance to identify and agree those terms used in the outputs that will require definition, and also to ensure the harmonisation of Technical and Plain English definitions of individual terms.

The NGS Glossaries will be produced in three steps:

1. the NGS Technical Glossary - this will comprise those technical definitions of terms that are essential for consistent, unambiguous and auditable application of the Detailed Technical Instructions. This will be delivered as an output of NGS Stage 1 to accompany the Detailed Technical Instructions

2. the NGS User Glossary - the User Glossary will contain Plain English definitions of terms used in the NGS Map and Regional Narrative outputs, and released online as supporting information. During the application of the Guidance, the NGS communications team will work with the BGS to agree a list of terms in the NGS outputs that require definition. The BGS will first provide Technical Definitions of those terms, and the Communications team will then draft the corresponding Plain English definitions, working closely with the BGS to ensure that Technical and Plain English versions of each definition are consistent. The NGS User Glossary will contain only Plain English definitions

3. the Master Glossary with both the technical and corresponding Plain English definitions of each term will also be produced and made available as supporting information for technical users of NGS outputs

Definitions of terms will by default follow those of the most current version of the RWM Glossary (RWM 2014) at end February 2016. Where BGS and /or the NGS communications experts agree that a modification of the RWM definition may be desirable, an exception shall be raised and discussed with the RWM management team to agree appropriate action.

7.3.2 Nomenclature

Nomenclature is 'a system of names for things' (Oxford English Dictionary). In the context of the NGS, nomenclature is the set of proper names assigned to geological features referred to in the NGS outputs.

The principal geological features that may be named in the outputs will be rock unit names (e.g. Mercia Mudstone Group) and major geological faults and deformation zones (e.g. Red Rock Fault). The NGS will use existing nomenclature only and not create new names for geological features. References to the source definitions will be captured in the Technical Metadata. For rock unit names, the default definitions will be those of the BGS Lexicon of Named Rock Units (http://www.bgs.ac.uk/lexicon/home.html) as at end February 2016. For named rock units not defined in the BGS Lexicon, the most up to date published definition will be used.

7.3.3 Assumptions

An assumption is ''an instance of accepting without proof' (Oxford English Dictionary). Assumptions can be either explicit (directly stated) or implicit (not directly stated, but implied).

Both the Narrative and Map outputs of the NGS will contain explicit and implicit assumptions. Examples are briefly discussed below.

1. an example explicit assumption - '… a maximum depth of 400 m for potable water will be assumed' (see the Guidance). This is a directly stated assumption, and in such cases a clear explanation of the technical or policy basis for the assumption can be provided

2. an example implicit assumption - a unit of LSSR proved in a number of boreholes is continuous between those boreholes. Depending on the spacing of the boreholes this might be considered a reasonable inference by an expert in the principles of uniformitarianism, stratigraphy and structural geology, but to a non-expert member of the public will appear as an unstated assumption (e.g. 'How do they know that….?') and could be challenged in a public enquiry, on a website or via social media

3. an example implicit assumption - the interpretations made in existing published syntheses, and used to prepare the NGS outputs, are correct. The NGS will mainly be developed by use of existing interpretations in published syntheses. The primary interpretations of geological data made in those syntheses will in most cases not be critically reviewed or challenged by the NGS (see Existing Data Protocol above). To a non-specialist audience this would lead to an implicit assumption that these interpretations are correct, whereas a specialist would know that these interpretations can be open to challenge and may be uncertain

The Detailed Technical Instructions for each geological topic include a list of explicit assumptions. Implicit assumptions may not appear obvious to the authors of NGS Detailed Technical Instructions or outputs because of their familiarity with the underpinning scientific and technical concepts, so assistance from the NGS communications experts at a facilitated 'assumptions workshop' (see below) will be required to help identify such assumptions. Once identified and stated, the assumption will become explicit.

All assumptions will be captured into a master NGS assumptions list, using the following process:

1. BGS will compile an initial list of all explicit assumptions in the Detailed Technical Instructions
2. this initial list will be augmented with implicit assumptions identified at the 'assumptions workshop'
3. BGS will draft (or refer to) the Technical Basis for each assumption on the list.

The NGS Communications experts will produce Plain English explanations of each assumption, iterating with the BGS team.

The completed NGS assumptions list with both Technical and Plain English explanations (following the proforma shown in Table 29) will be archived in the Technical Metadata.

It is recommended that the assumptions workshop is held towards the end of the application of the Guidance once the first Regional Narratives have been prepared. The workshop will involve selected RWM staff, BGS project team members and the NGS communications experts.

A communications plan for each assumption, which might for example include a list of Frequently Asked Questions with Plain English answers, will be developed as required by the NGS communications experts consulting with RWM and BGS and using the NGS assumptions list as source material.

Table 29 Proposed tabulation for explanation of assumptions, using examples from the Guidance

Assumption	Where Assumption is stated	Technical Basis for Assumption	Plain English of the Assumption
The maximum depth of potable water is 400 m	Guidance, paragraph 3.25	Water Framework Directive UK TAG 2012 http://www.wfduk.org/sites/default/files/Media/Characterisation%20of%20the%20water%20environment/Defining%20Reporting%20on%20Groundwater%20Bodies_Final_300312.pdf	To be drafted with assistance of communications team
Future mineral exploration often takes place at sites where shallower mining has taken place in the past.	Guidance, paragraph 3.29	[Provide evidence supporting this assumption]	To be drafted with assistance of communications team

7.3.4 Acronyms

Each acronym used in the Technical Information Reports will be written in full on first use, following the example in this sentence, and then in acronym format throughout the rest of each document. A master list of acronyms and their expanded form will be compiled and archived in the Technical Metadata. This will be cross-checked for consistency against acronyms listed in the most current version of the RWM Glossary at end February 2016.

7.4 Protocol No.4: NGS datum and spatial limits

This Protocol describes the rationale and process for creating two key bespoke datasets required for spatial querying and referencing by the NGS Detailed Technical Instructions. The detailed procedure for creating these is included in Technical Appendices 1-3.

7.4.1 NGS datum for depth

Depth contributes to the isolation and containment safety functions of a GDF and is hence a key parameter requiring consideration in the delivery of several NGS outputs, for example:

- Rock Type - distribution of potential host rocks between 200 m and 1000 m depth (Narrative and Maps)
- Groundwater - a maximum depth of 400 m for potable water will be assumed (Narrative); the potential presence of karst at depths greater than 200 m (Narrative)

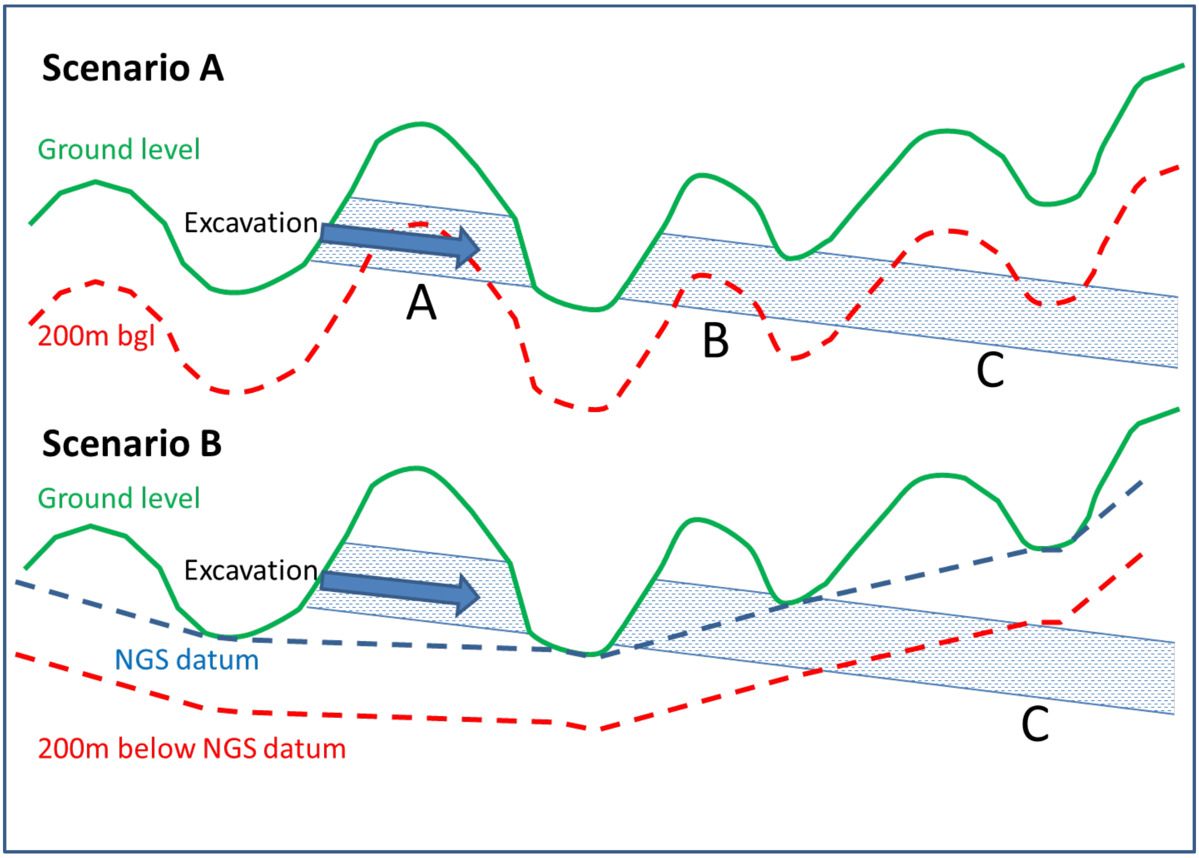
- Resources - known locations of mineral and energy resources below a depth of 100 m (Narrative and Maps)

The NGS will produce maps for 'Rock Type' that show the distribution of potentially suitable host rocks across England, Wales and Northern Ireland in the depth range 200 m to 1000 m (see the Guidance). This Protocol illustrates how the datum chosen for depth, and applied to the production of Rock Type maps, may have significant bearing on the safety functions of a GDF.

In areas of high topographic relief, maps produced using depths of 200 m and 1000 m below ground level will indicate volumes of potentially suitable host rocks below hills and mountains. Although these rocks would be located at greater than 200 m below ground level, a GDF constructed in them could be penetrated in the future by a horizontal or gently inclined tunnel (e.g. an aqueduct or transport tunnel) excavated into a nearby hillside (see Figure 11, Scenario A).

To address this safety consideration, an alternative datum for depth, described in this Protocol and in the Detailed Technical Instructions as the 'NGS datum', was agreed. This datum is defined by a digital elevation model interpolated between natural courses of surface drainage. A GDF constructed within volumes of potentially suitable host rocks at 200 m to 1000 m below the NGS datum should not be penetrated by a horizontal or gently inclined tunnel excavated into a hillside or cliff (see Figure 11, Scenario B).

Figure 11 Impact of GDF safety functions of mapping a potential host rock unit (shaded) using alternative data for depth.



The NGS datum will be derived from the BGS National Depth to Groundwater Dataset (http://nora.nerc.ac.uk/id/eprint/510752). The methodology for creating the NGS datum is documented in Appendix 3.

Since the NGS datum is used to define the 200 m to1000 m depth interval of interest for Rock Type, it is essential that the same datum is used for consideration of resources and aquifers at depth. Use of the NGS datum for the Groundwater, Rock Structure and Resources outputs is described in the respective Detailed Technical Instructions.

7.4.2 Offshore limits

The NGS will consider and interpret Existing Data and knowledge up to 30 km offshore, and present information in Narratives and Maps up to 20 km offshore. A line delineating this 20 km offshore limit is therefore required to produce NGS Map and Narrative outputs.

The offshore limit to be used by the NGS is illustrated using a small scale summary map in Figure 12. The summary process for creating this map is as follows:

1. extend Coastline (source Ordnance Survey (OS)) of England, Wales and Northern Ireland 20 km offshore
2. simplify coastline extension line to create 20 km smoothed offshore limit
3. clip the smoothed offshore limit to maritime boundaries so as not to encroach into French and Irish waters
4. further clip the offshore limit to ensure that it remains equidistant between England and Scotland, and between Northern Ireland and Scotland, and to exclude Isle of Man

Figure 12 Illustration of the 20 km offshore limit to be used by the NGS.

NB Dark blue lines show maritime boundaries based on the Exclusive Economic Zone Boundaries version 8 http://www.marineregions.org.

7.4.3 Overlaps between regions

Information presented on the map outputs for each region will extend into a 10 km-wide overlap zone with adjacent regions. Overlaps will not extend into Scotland or the Republic of Ireland. Northern Ireland has no adjacent regions so an overlap is not required.

The overlap will be created by extending a 10 km buffer along the boundary of each region. This is a simple operation using the standard functionality of Geographic Information System software. No smoothing of the boundary is required. Overlaps of greater extent can be considered and trialled before a final decision on Published Map format is made during the application of the Guidance.

7.5 Protocol No.5: NGS outputs

7.5.1 Technical Information Reports and NGS Narratives - format and contents

The NGS Regional Narratives will be plain English published outputs drafted by the NGS communications team, and derived from Technical Information Reports to be delivered for each region by the BGS. The Technical Information Reports will present a technical synthesis of the relevant geological information for each of the five NGS geological topics in each region, and will be discoverable as supporting information underpinning the NGS Regional Narratives. Drafting of the Narratives by the communications team will involve iterative consultation with the BGS to ensure that the plain English content is consistent with the technical information in the Technical Information Reports.

A high level Table of Contents for each Technical Information Report is set out in Table 30 below. The Table of Contents is intended to provide guidance to assist with planning the application of the Guidance, and not to provide rigid constraint. Some adjustment of document structure is likely once application of the Guidance is in progress.

Technical Information Reports for each region will include information on a 10 km overlap zone extending into adjacent regions, and a 20 km extension offshore (see also Map Formats and Conventions).

Table 30 Proposed Table of Contents for the BGS Technical Information Reports

Primary Heading	Secondary Heading	Technical Information Report - Content
Geological Summary		Geological context and summary abbreviated from the relevant BGS Regional Geological Accounts, (http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) referring to those documents but without significant duplication.
Existing Geological Data		Overview of existing data and knowledge, and associated uncertainties and assumptions in the region.
Geological Topics	Introduction and definitions.	Text will be the same for all regions and cross-reference to the Guidance.
	Rock Type.	To be specified by Detailed Technical Instructions for Rock Type.
	Rock Structure.	To be specified by Detailed Technical Instructions for Rock Structure.
	Groundwater.	To be specified by Detailed Technical Instructions for Groundwater.
	Natural Processes.	To be specified by Detailed Technical Instructions for Natural Processes. Note that information on this attribute will be presented on national maps, the narrative in this section will provide the regional context on that national information.
	Resources.	To be specified by Detailed Technical Instructions for Resources.
Sources of additional information	References.	Reference list of information sources cited in the Report (including Road Map Tiers 1-4).
	Additional Information	

7.5.2 Map formats and conventions

The purpose of the NGS Map outputs is to communicate the spatial context of geological information provided in the Narratives. Maps or packages of maps will be produced for each of the five geological topics as specified in the Guidance.

The Map Formats and Conventions differentiate between Production Maps, which will be produced for each geological topic following application of the Detailed Technical Instructions, and Published Maps, which will be sourced from the Production Maps and delivered as NGS output alongside the corresponding Narratives. Production Maps will be prepared digitally with national coverage, the Published Maps will be ‘cookie cut’ from Production Maps and delivered as regional maps to accompany the Regional Narratives, except for the Natural Processes outputs which will be delivered as national maps (see the Guidance). Production Maps will be managed and archived as potential supporting information for consultation and communication, and as source material for delivery of bespoke map outputs to inform discussion with communities following completion of the NGS. The Production Maps will also provide the source for any national maps to be delivered online. The requirement and format for these national maps will be trialled and agreed in the early part of the application of the Guidance. Similarly, the format of Published Maps will be developed and trialled early in the application of the Guidance in consultation with the NGS communications team. A wide range of approaches to presenting the geological information on maps will be considered by RWM as part of this process.

Protocols for Production Maps and Published maps are given in Table 31 below.

Table 31 Key elements of map design and format

Production Maps	
Digital Format.	ESRI ArcGIS Geodatabase.
Output Format.	The requirement and format of national maps for online delivery will be trialled and agreed in the early part of the application of the Guidance.
Spatial Reference.	British National Grid
Coverage.	England, Wales and Northern Ireland, including 20 km offshore extension. Exception: The offshore extension will not encroach into offshore territories of France or the Republic of Ireland.
Scale.	1:625,000, or 1 km = 1.6 millimetres (Guidance).
Representation of Uncertainty.	To be decided in consultation with NGS Communications Experts. See Discussion under Approach To Uncertainty Protocol.
Published Maps	
Digital Format.	ESRI ArcGIS Geodatabase.
Output Formats.	Paper, pdf.
Spatial Reference.	British National Grid.
Coverage.	Regional, corresponding to areas shown in Guidance and Figure 4.
Scale.	1:625,000, or 1 km = 1.6 mm (Guidance).
Lines, Edges and Colours.	To be decided in consultation with NGS Communications Experts following trials early in the application of the Guidance.
Representation of Uncertainty.	To be decided in consultation with NGS Communications Experts. See Discussion under Approach To Uncertainty Protocol.
Topographic base.	Comparable design and format to current BGS 1:625,000 Bedrock Geology Map UK North and South, i.e. greyscale with major towns and cities, transport routes and major drainage. 20 km offshore extension. 10 km overlap buffer with adjacent regions. Exceptions: Onshore buffers will not extend into Scotland or the Republic of Ireland. Offshore extension will not encroach into offshore territories of France or Republic of Ireland.
Key and marginalia.	Map Title. Key to symbology on the map. Scale Indicator. North Indicator. Map header panel with key output metadata.

Because of the varying size and shape of the regions, the resulting size and shape of the mapped areas will vary when plotted at a constant scale of 1:625,000. Adoption of a standard paper size will therefore create a varying amount of unused ‘whitespace’ in the marginalia assuming a degree of constancy in margin content. Maps can be prepared in Flat and/or Folder format.

RWM recognise that the nature of polygons produced by BGS will vary significantly by attribute and region due to a number of factors including the information available, variations in the NGS Datum and the complexity of the distribution of the attribute being mapped. The variations in the polygons will need to be addressed in the final outputs and RWM will work with BGS to ensure that this is treated consistently in the Technical Information Reports and the Regional Narratives.

7.6 References

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Lark, R. M. and Webster, R. 2006. Geostatistical mapping of geomorphic variables in the presence of trend. *Earth Surface Processes and Landforms,* 31 862–874.

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Appendix 1: Methodology for extracting lithology, by selected region, from UK3D and section attribution

A1.0 Introduction

This Appendix describes the methodology that will be employed to extract lithological data in four steps:

- isolating a screening region from UK3D
- isolating the relevant GSI3D GVS for that region
- identifying ‘*Rock Type of Interest*’ versus ‘*not a Rock Type of Interest*’ in the GVS
- reattributing UK3D section lines with ‘*Rock Types of Interest*’

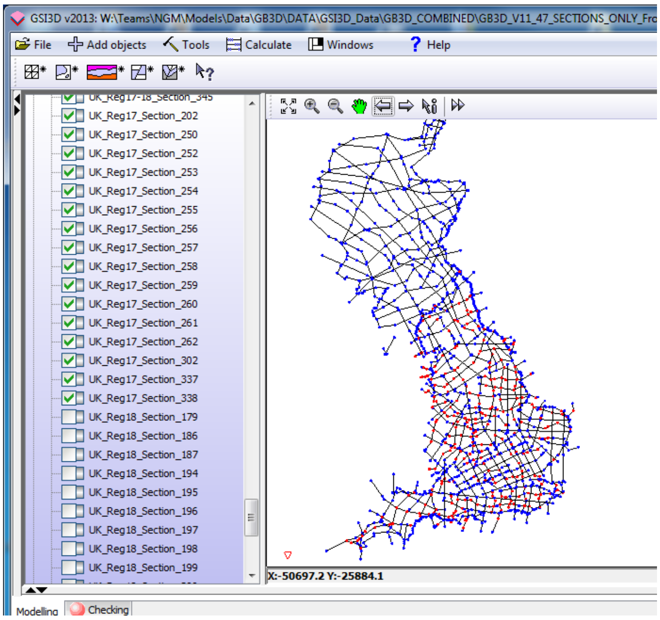
A1.1 Step 1 Isolating a screening region from UK3D (Area Clipping)

The main purpose of this step is to demonstrate the feasibility of selecting UK3D objects by region. For the purposes of this Appendix, this is illustrated by splitting UK3D sections for north Wales from those of south Wales. The methodology is illustrated by a series of screen-grabs of UK3D data in GSI3D software:

1. UK3D project loaded into GSI3D

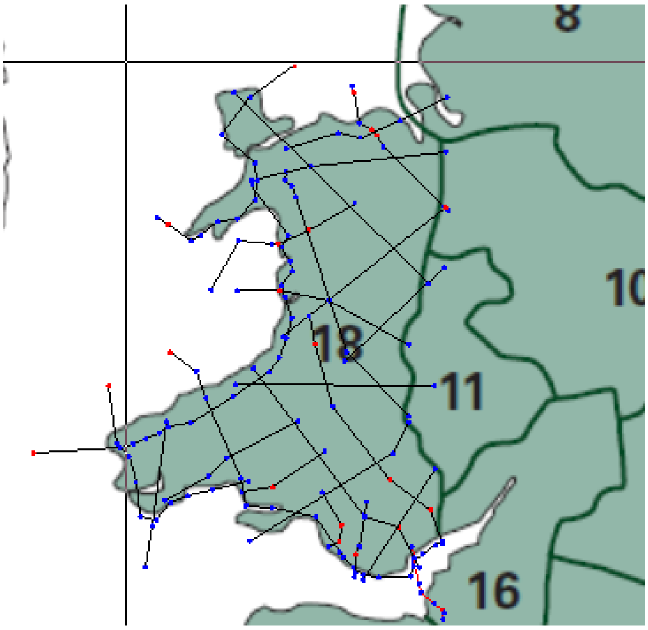
The image below (Figure 13) shows the map window of GSI3D. The map window shows the distribution of all existing cross-sections within UK3D apart from Region 18 (Wales). Sections for Region 18 (Wales) are intentionally left unchecked which is part of the process for separating these cross-sections from England and Scotland as described in the next stage below.

Figure 13 GSI3D graphical user interface showing UK3D section with Wales unchecked.



2. Delete all cross-sections in GSI3D apart from Region 18 (Wales). Selected objects outside Region 18 are deleted, leaving the unchecked cross-sections in Region 18 ().

Figure 14 GSI3D screen grab showing UK3D sections for Region 18 Wales.



3. Clip sections to the area of interest (AOI) in north Wales using the GSI3D functions Insert borehole or knickpoint>Point on Line of Section (and).

Figure 15 GSI3D screen grab function to insert borehole or knickpoint

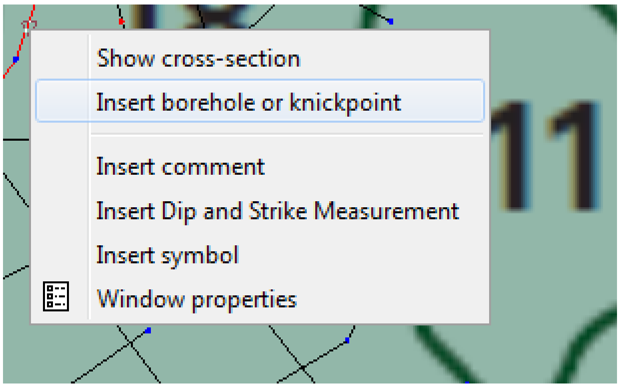
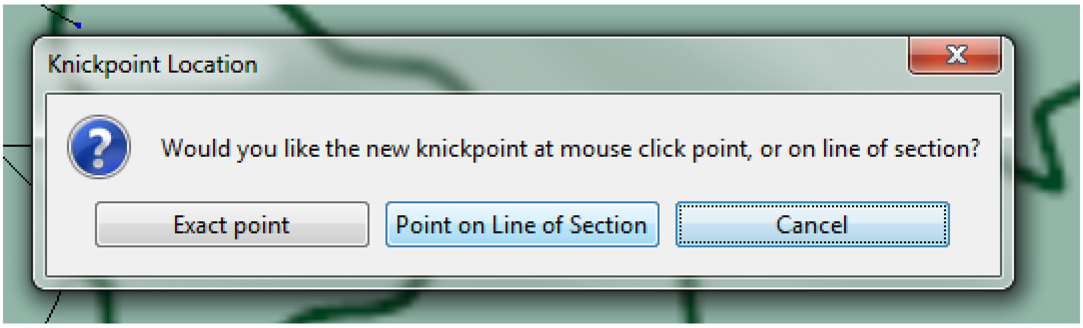
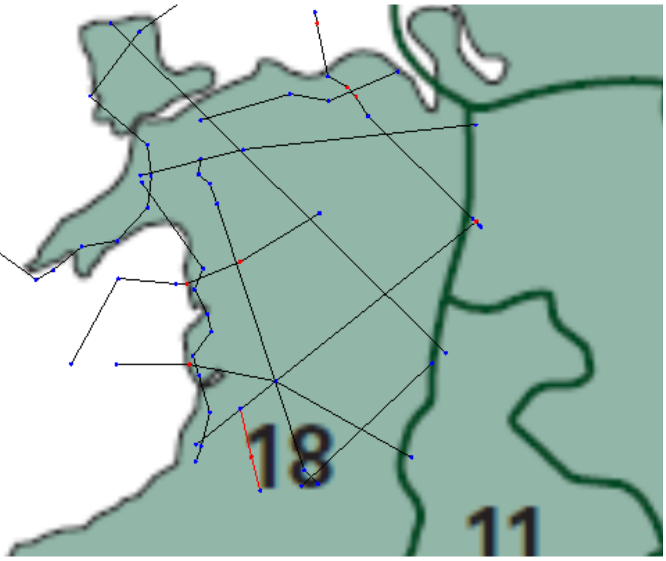


Figure 16 GSI3D function used to clip section lines.



4. Delete unwanted parts of cross-section to leave only the section part in the north Wales AOI ().

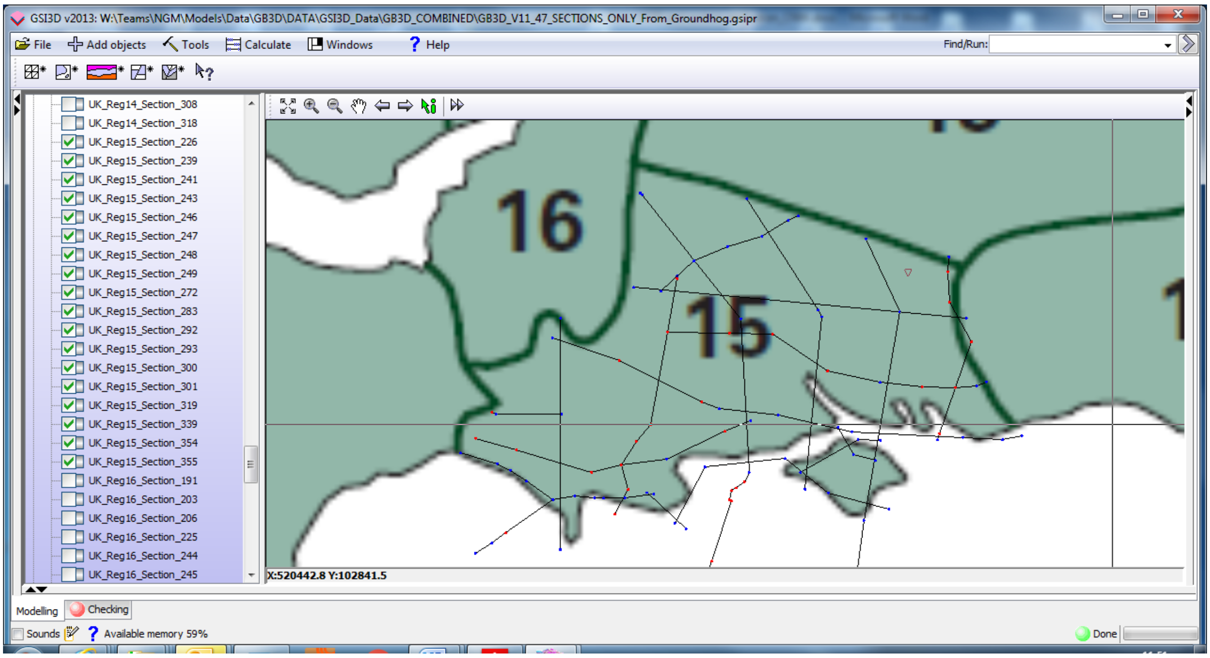
Figure 17 UK3D sections clipped to north Wales.



5. Save clipped project file (GSIPR) to derive unique GVS for the AOI only

The above procedure for the north of Region 18 (Wales) has been applied by selecting only part of a UK region. Alternatively, cross-sections can be selected by entire Region using their name identifier, e.g. for Region 15 (Hampshire Basin and adjoining area) below ():

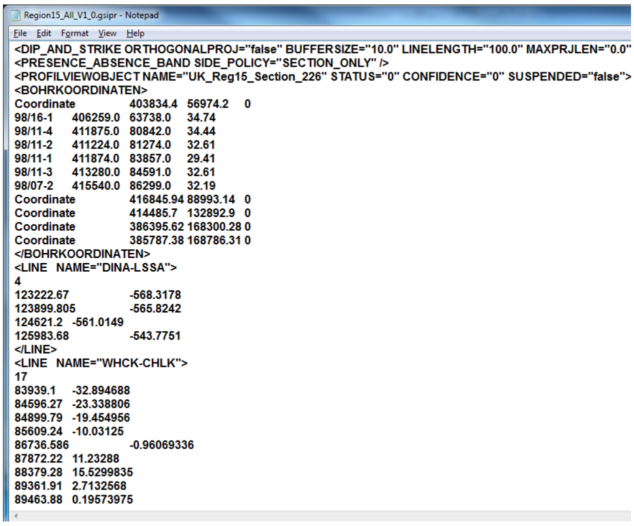
Figure 18 GSI3D window showing clipped out Hampshire Basin section lines.



A1.2 Step 2 Extracting the area-specific GVS from Master GVS file

1. Copy the GSIPR file as a text file and open with Excel ().

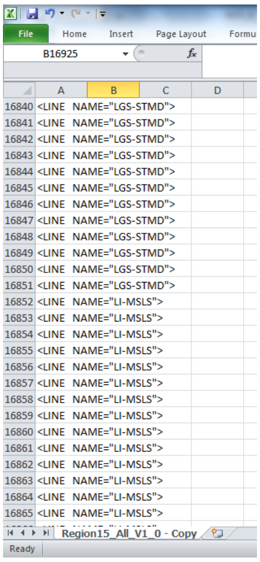
Figure 19 Example GSIPR text file



```
Region15_All_V1_0.gsipr - Notepad
File Edit Format View Help
<DIP_AND_STRIKE ORTHOGONALPROJ="false" BUFFERSIZE="10.0" LINELENGTH="100.0" MAXPRJLEN="0.0"
<PRESENCE_ABSENCE_BAND SIDE_POLICY="SECTION_ONLY" />
<PROFILVIEWOBJECT NAME="UK_Reg15_Section_226" STATUS="0" CONFIDENCE="0" SUSPENDED="false">
<BOHRKOORDINATEN>
Coordinate        403834.4  56974.2   0
98/16-1   406259.0  63738.0   34.74
98/11-4   411875.0  80842.0   34.44
98/11-2   411224.0  81274.0   32.61
98/11-1   411874.0  83857.0   29.41
98/11-3   413280.0  84591.0   32.61
98/07-2   415540.0  86299.0   32.19
Coordinate        416845.94 88993.14  0
Coordinate        414485.7  132892.9  0
Coordinate        386395.62 168300.28 0
Coordinate        385787.38 168786.31 0
</BOHRKOORDINATEN>
<LINE  NAME="DINA-LSSA">
4
123222.67         -568.3178
123899.805        -565.8242
124621.2  -561.0149
125983.68         -543.7751
</LINE>
<LINE  NAME="WHCK-CHLK">
17
83939.1   -32.894688
84596.27  -23.338806
84899.79  -19.454956
85609.24  -10.03125
86736.586         -0.96069336
87872.22  11.23288
88379.28  15.5299835
89361.91  2.7132568
89463.88  0.19573975
```

2. Order the entries alphabetically ().

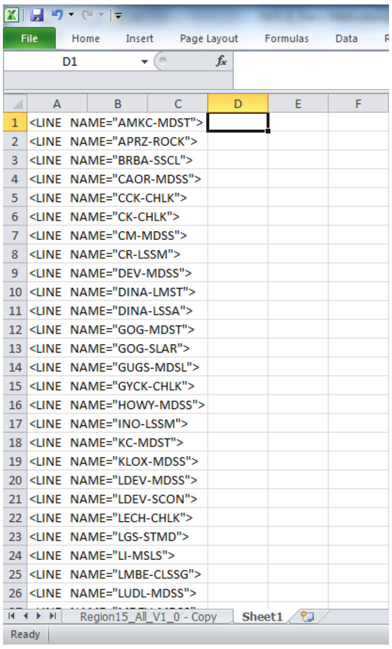
Figure 20 Example of alphabetically ordered GVS entries in Excel



	A	B	C	D
16840	<LINE NAME="LGS-STMD">			
16841	<LINE NAME="LGS-STMD">			
16842	<LINE NAME="LGS-STMD">			
16843	<LINE NAME="LGS-STMD">			
16844	<LINE NAME="LGS-STMD">			
16845	<LINE NAME="LGS-STMD">			
16846	<LINE NAME="LGS-STMD">			
16847	<LINE NAME="LGS-STMD">			
16848	<LINE NAME="LGS-STMD">			
16849	<LINE NAME="LGS-STMD">			
16850	<LINE NAME="LGS-STMD">			
16851	<LINE NAME="LGS-STMD">			
16852	<LINE NAME="LI-MSLS">			
16853	<LINE NAME="LI-MSLS">			
16854	<LINE NAME="LI-MSLS">			
16855	<LINE NAME="LI-MSLS">			
16856	<LINE NAME="LI-MSLS">			
16857	<LINE NAME="LI-MSLS">			
16858	<LINE NAME="LI-MSLS">			
16859	<LINE NAME="LI-MSLS">			
16860	<LINE NAME="LI-MSLS">			
16861	<LINE NAME="LI-MSLS">			
16862	<LINE NAME="LI-MSLS">			
16863	<LINE NAME="LI-MSLS">			
16864	<LINE NAME="LI-MSLS">			
16865	<LINE NAME="LI-MSLS">			

3. Delete all entries except those that are related to the correlation line attributes i.e. lines that begin <LINE NAME……> should be retained.
4. Use Excel to remove all duplicate entries, so that a unique “Region List” of geological units drawn in the sections relating to that particular Region is compiled (Figure 21).

Figure 21 Unique Region list in Excel

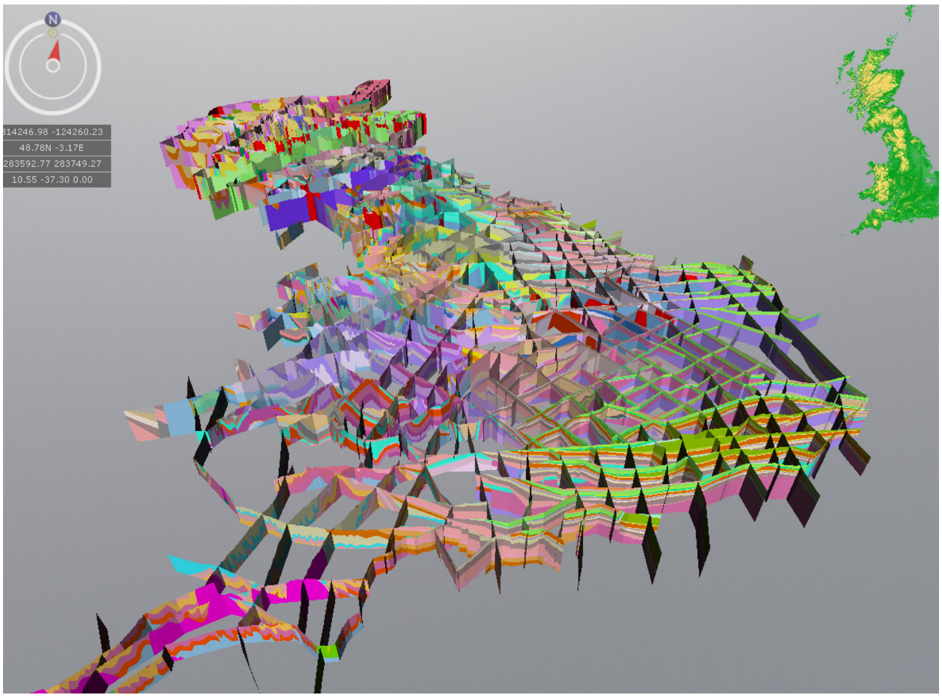


5. Remove the tag information (using the find/replace tools in Excel) leaving just the LEX-RCS code intact.
6. Use this list to create a VLOOKUP formula in Excel, matching the Region list against the Master GVS list.
7. Filter the Master GVS list to show only those matched codes, and ensure that the number of units from the Region List matches the number in the filtered Master GVS list:
    a. If the number of filtered codes matches the Region list then progress to step 8;
    b. If the number of filtered codes does not match the Region list then this needs to be resolved because all codes should match with the Master GVS. The GSIPR file should be reviewed and the non-matching code should be changed to that shown in the Master GVS entry.
8. With the list still filtered, copy to a new text file ensuring that the order of the GVS is retained, together with the numbering system and all other GVS information (so it can be related back to the Master GVS if necessary).
9. Save out the text file with the name format Region_XX_specific_GVS.gvs.

A1.3 Step 3 Identifying rock types of interest in the region-specific GVS file

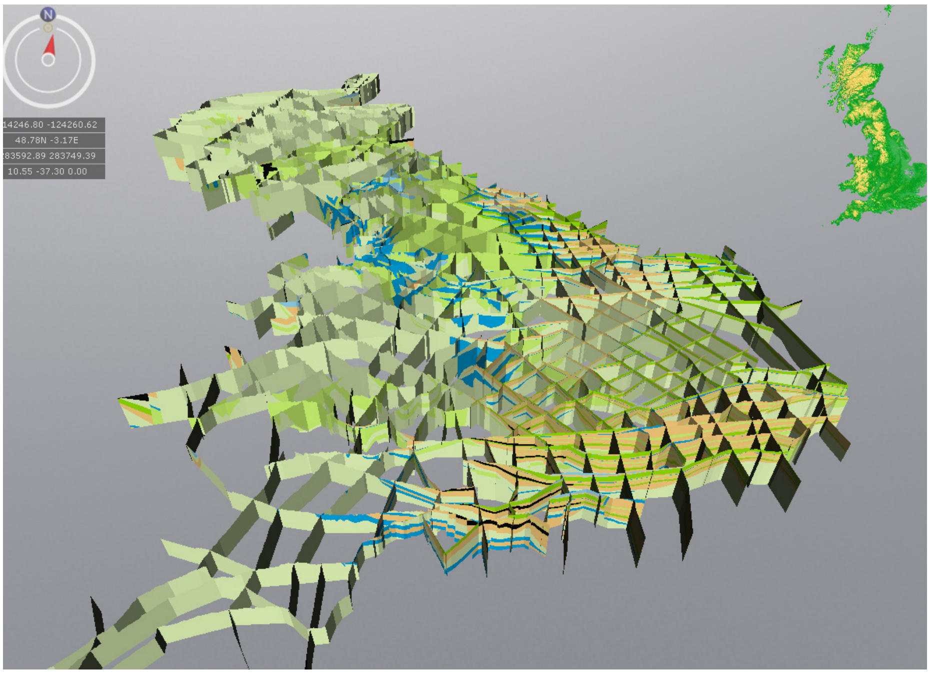
The v2015 UK3D cross-sections are currently attributed according to a GVS that describes the stratigraphy, lithology and additional attributes such as aquifer designation and hydrology codes. The GVS exists as a tab delimited text file with headers describing the attribute that the cross-sections are being coloured up by. In the example below the sections are coloured by the stratigraphy as shown in the 625k DigMap V5 product (Figure 22):

Figure 22 UK3D section coded by lithostratigraphy



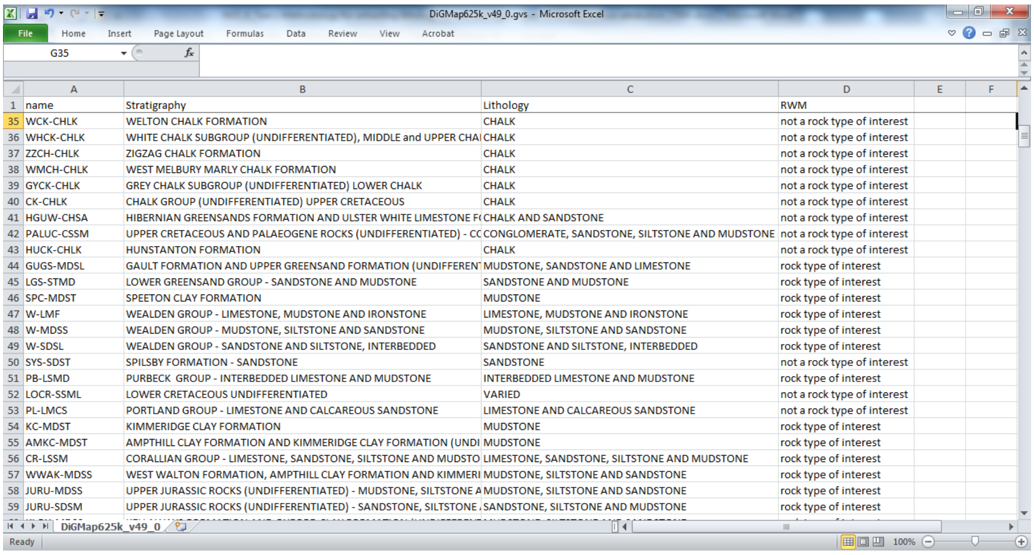
In the following example, the GVS is coloured up the hydrogeological domain using a nationally applicable attribute (HydroCode) supplied by the regulator (Environment Agency) (Figure 23).

Figure 23 UK3D section coded by 'hydrocode' attribute.



In order to achieve an additional attribution of '*rock type of interest*' or '*not a rock type of interest*' an additional column is added to the region-specific GVS file which identifies the status of individual line entries, which in turn correspond to UK3D geological units (Figure 24).

Figure 24 **GVS for the Hampshire Basin with ‘rock type of interest’ attribute added for LEX_RCS codes containing mudstone as a component lithology.**



	name	Stratigraphy	Lithology	RWM
35	WCK-CHLK	WELTON CHALK FORMATION	CHALK	not a rock type of interest
36	WHCK-CHLK	WHITE CHALK SUBGROUP (UNDIFFERENTIATED), MIDDLE and UPPER CHAI	CHALK	not a rock type of interest
37	ZZCH-CHLK	ZIGZAG CHALK FORMATION	CHALK	not a rock type of interest
38	WMCH-CHLK	WEST MELBURY MARLY CHALK FORMATION	CHALK	not a rock type of interest
39	GYCK-CHLK	GREY CHALK SUBGROUP (UNDIFFERENTIATED) LOWER CHALK	CHALK	not a rock type of interest
40	CK-CHLK	CHALK GROUP (UNDIFFERENTIATED) UPPER CRETACEOUS	CHALK	not a rock type of interest
41	HGUW-CHSA	HIBERNIAN GREENSANDS FORMATION AND ULSTER WHITE LIMESTONE F(	CHALK AND SANDSTONE	not a rock type of interest
42	PALUC-CSSM	UPPER CRETACEOUS AND PALAEOGENE ROCKS (UNDIFFERENTIATED) - CC	CONGLOMERATE, SANDSTONE, SILTSTONE AND MUDSTONE	not a rock type of interest
43	HUCK-CHLK	HUNSTANTON FORMATION	CHALK	not a rock type of interest
44	GUGS-MDSL	GAULT FORMATION AND UPPER GREENSAND FORMATION (UNDIFFERENT	MUDSTONE, SANDSTONE AND LIMESTONE	rock type of interest
45	LGS-STMD	LOWER GREENSAND GROUP - SANDSTONE AND MUDSTONE	SANDSTONE AND MUDSTONE	rock type of interest
46	SPC-MDST	SPEETON CLAY FORMATION	MUDSTONE	rock type of interest
47	W-LMF	WEALDEN GROUP - LIMESTONE, MUDSTONE AND IRONSTONE	LIMESTONE, MUDSTONE AND IRONSTONE	rock type of interest
48	W-MDSS	WEALDEN GROUP - MUDSTONE, SILTSTONE AND SANDSTONE	MUDSTONE, SILTSTONE AND SANDSTONE	rock type of interest
49	W-SDSL	WEALDEN GROUP - SANDSTONE AND SILTSTONE, INTERBEDDED	SANDSTONE AND SILTSTONE, INTERBEDDED	rock type of interest
50	SYS-SDST	SPILSBY FORMATION - SANDSTONE	SANDSTONE	not a rock type of interest
51	PB-LSMD	PURBECK GROUP - INTERBEDDED LIMESTONE AND MUDSTONE	INTERBEDDED LIMESTONE AND MUDSTONE	rock type of interest
52	LOCR-SSML	LOWER CRETACEOUS UNDIFFERENTIATED	VARIED	not a rock type of interest
53	PL-LMCS	PORTLAND GROUP - LIMESTONE AND CALCAREOUS SANDSTONE	LIMESTONE AND CALCAREOUS SANDSTONE	not a rock type of interest
54	KC-MDST	KIMMERIDGE CLAY FORMATION	MUDSTONE	rock type of interest
55	AMKC-MDST	AMPTHILL CLAY FORMATION AND KIMMERIDGE CLAY FORMATION (UNDI	MUDSTONE	rock type of interest
56	CR-LSSM	CORALLIAN GROUP - LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTO	LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE	rock type of interest
57	WWAK-MDSS	WEST WALTON FORMATION, AMPTHILL CLAY FORMATION AND KIMMERI	MUDSTONE, SILTSTONE AND SANDSTONE	rock type of interest
58	JURU-MDSS	UPPER JURASSIC ROCKS (UNDIFFERENTIATED) - MUDSTONE, SILTSTONE A	MUDSTONE, SILTSTONE AND SANDSTONE	rock type of interest
59	JURU-SDSM	UPPER JURASSIC ROCKS (UNDIFFERENTIATED) - SANDSTONE, SILTSTONE	SANDSTONE, SILTSTONE AND MUDSTONE	rock type of interest

In the above test, it is assumed that mudstone is a ‘*rock type of interest*’, and following the Rock Type Detailed Technical Instruction, LEX_RCS codes (column A in the above GVS file) identifying mudstone as a component of the UK3D lithostratigraphic unit are all identified as ‘*rock type of interest*’. For the purpose of this test only, no other possible ‘*rock type of interest*’ have been identified.

The LEX (Lexicon) component of the LEX_RCS code is used to indicate a lithostratigraphic unit (e.g. KC representing Kimmeridge Clay Formation), the full name of which is displayed in Column B. Definitions of these units are held within the BGS Lexicon of Named Rock Units (http://www.bgs.ac.uk/lexicon/). As the UK3D cross-sections are based on the 1:625 000 scale geological map (BGS 625K DigMap V5), many of the lithostratigraphic subdivisions shown on the cross-sections are composite units comprising more than one formation.

The RCS (Rock Classification Scheme) component of the LEX_RCS code indicates the principal lithologies (rock types) present within the named stratigraphical unit. For example in the case of Kimmeridge Clay (KC) it is mudstone (coded MDST in column A above and expanded in column C). The BGS Rock Classification Scheme and the definitions of the codes are held within a publically-available online database (http://www.bgs.ac.uk/bgsrcs/searchrcs.html). Many of these RCS codes are composite lithologies which are recorded in the BGS Dictionary DIC_ROCK_SIGMA.

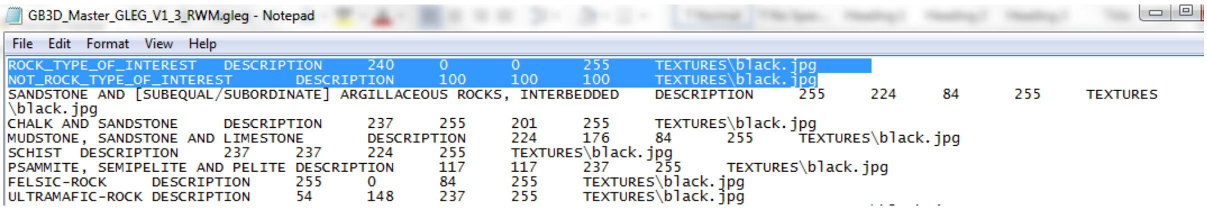
For example, the above extract includes GUGS-MDSL, the LEX code representing Gault Formation and Upper Greensand Formation. The RCS code (MDSL) indicates that the composite lithostratigraphic unit is composed of Mudstone, Sandstone and Limestone. In this example, the order that the lithologies are mentioned does not necessarily relate to relative abundance. However, the main lithology of the Gault Formation is mudstone (MDST) and thus it would represent a ‘*rock type of interest*’. The overlying Upper Greensand Formation is dominated by glauconitic sandstone (GLSST) and could be recognised as a ‘*not Rock Type of Interest*’. However, currently as the UK3D model does not subdivide these units into the component formations it is necessary to identify all volumes attributed as GUGS as ‘Rock Type of Interest’. The decision making process for retaining, rejecting or iterating this is encapsulated in key processes 4 to 7 of the Rock Type Detailed Technical Instruction workflow but it can only be successfully tested or applied once Gateway B has been passed.

A1.4 Step 4 Reattributing UK3D section lines

Following the identification of '*Rock Types of Interest*' in the region-specific GVS file, these can be assigned RGB colour values in the GSI3D legend. This controls the display of '*Rock Types of Interest*' in the cross-sections of the selected test screening region:

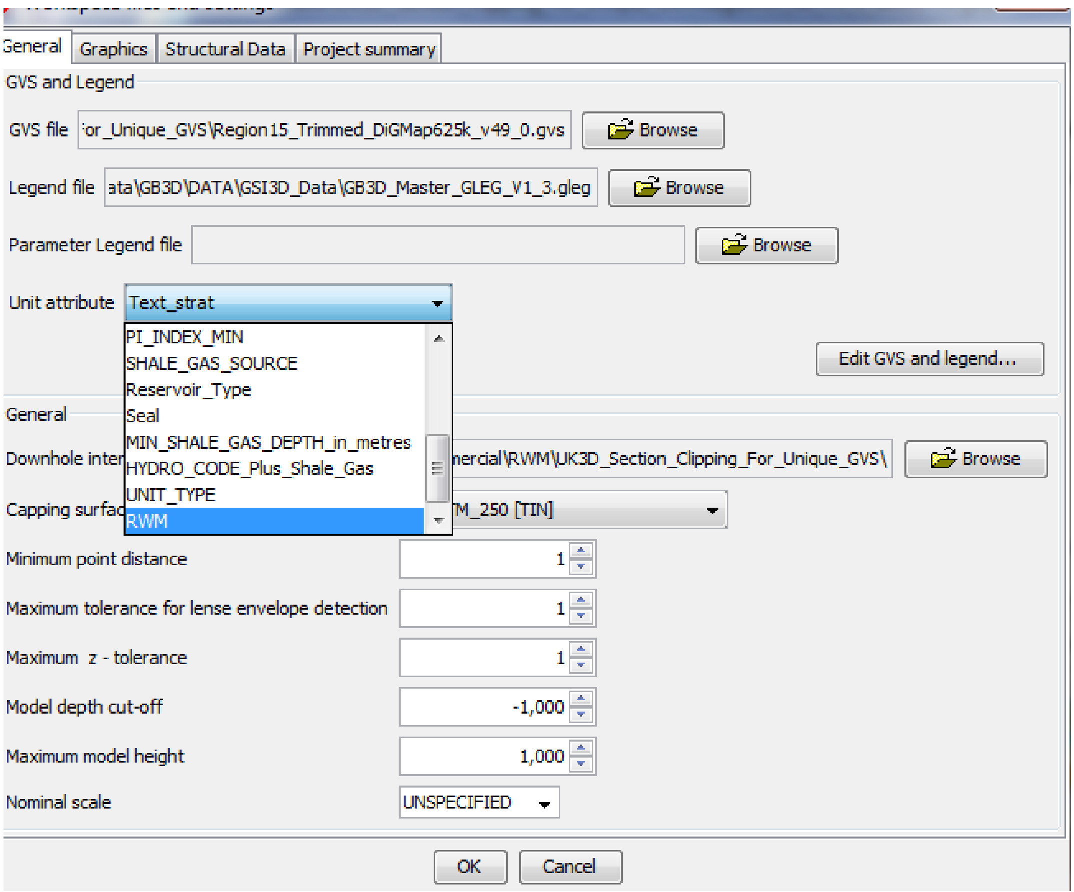
1. In the legend, an RGB colour is assigned to display '*Rock Types of Interest*' in a different colour to '*not Rock Types of Interest*' (Figure 25):

Figure 25 Editing GSI3D legend to display unique colour for 'Rock Types of Interest'



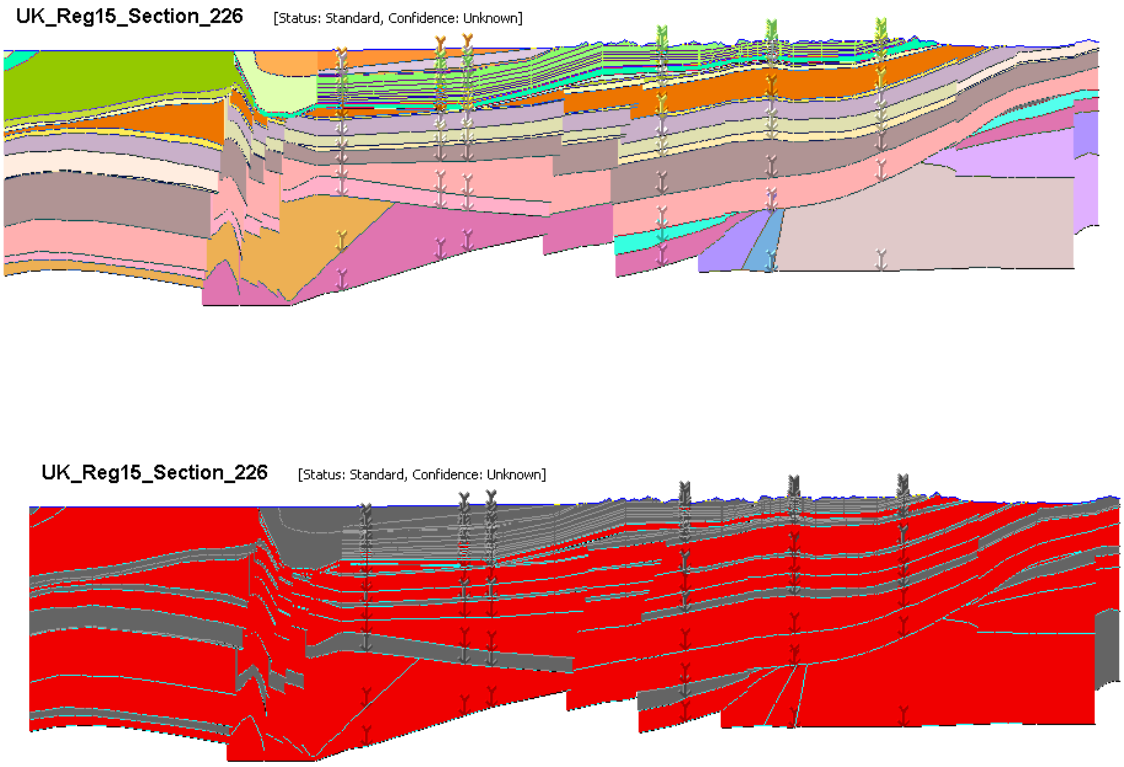
The resulting sections can then be changed from the DigMap 625k lithostratigraphic colour coding to colours assigned to '*Rock Type of Interest*' or '*not Rock Type of Interest*'. In GSI3D software this is done using the Unit attribute drop-down box as shown below (Figure 26).

Figure 26 GSI3D unit attribute box



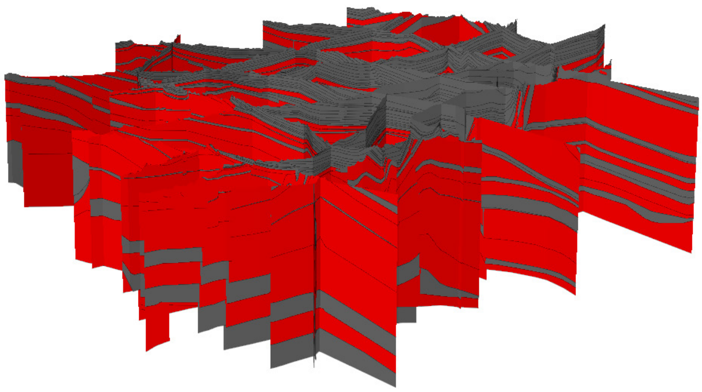
The effect of changing the colour coding from lithostratigraphy (LEX_RCS) to '*Rock Type of Interest*'/ '*not Rock Type of Interest*' is illustrated below using a cross-section from the Hampshire Basin test screening region (Figure 27).

Figure 27 Upper section coded for UK3D lithostratigraphic units. Lower section coded to show 'Rock Types of Interest' in red. Grey units are those in which mudstone is not identified in the LEX_RCS code.



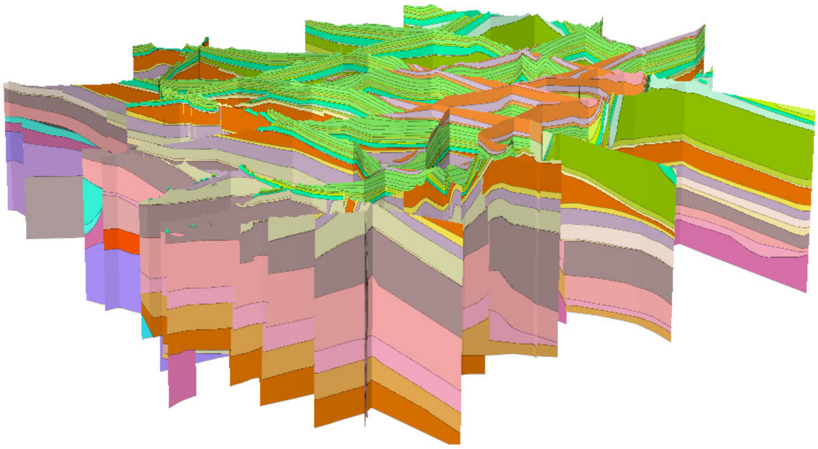
The following image shows the fence diagram for the clipped-out Hampshire Basin test screening region colour attributed as above to show units that contain mudstone as potential '*Rock Types of Interest*' (Figure 28):

Figure 28 UK3D fence diagram for the Hampshire Basin showing mudstone-bearing 'Rock Types of Interest' in red



The following image shows the fence diagram for the clipped out Hampshire Basin test screening region attributed to LEX_RCS lithostratigraphic units (Figure 29):

Figure 29 UK3D fence diagram for the Hampshire Basin showing lithostratigraphic units



Appendix 2: Workflow for iterating UK3D/NGS_3D for 'Rock Types of Interest'

A2.0 Introduction

This Appendix contains a description of four workflows for the Rock Type Detailed Technical Instruction applied to LSSR for Region 15 (the Hampshire Basin). The purpose of these workflows is to identify:

- which UK3D units for the region contain mudstone or clay as their 'main' lithology
- which UK3D units for the region contain mudstone or clay as their 'dominant' lithology
- specific units in which a component mudstone/clay unit may be a 'Rock Type of Interest' but is represented in UK3D as a component of a more heterogeneous parent unit
- an example of such a mudstone/clay unit and show the process that it can be introduced to the regional model

A2.1 Identifying Rock Types of Interest as a 'main' lithology in the region-specific GVS file

In the workflow described in Appendix 1, units were identified from the GVS for UK3D in which the LEX_RCS code indicated the presence or absence of mudstone/clay/argillaceous rocks. As noted in Appendix 1 the lithological descriptor in this code is based upon, but not equivalent to the BGS Rock Classification Scheme, with the codes used from BGS Dictionary DIC_ROCK_SIGMA being able to show the presence of multiple lithologies within any unit. However, the workflow described in Appendix 1 using the BGS Dictionary DIC_ROCK_SIGMA code provided no indication of whether it was the dominant lithology, which is a key requirement for mapping lithology 'rock types of interest' on to UK3D units.

For example, the BGS Dictionary DIC_ROCK_SIGMA code MDSL identifies the principal lithologies of Mudstone, Sandstone and Limestone. The order that the lithologies are mentioned in that code does not necessarily relate to relative abundance. For the Hampshire Basin Region, the only unit in which the BGS Dictionary DIC_ROCK_SIGMA code provides an indication of abundance is DINA-LSSA (LSSA indicating 'Limestone with subordinate sandstone and argillaceous rocks'). In the workflow described in Appendix 1 this was identified as a 'Rock Type of Interest' on the basis of argillaceous rock being present (Table 32, Column D). In this workflow the descriptor of Limestone With Subordinate Sandstone And Argillaceous Rocks allows this unit to be identified as 'not a Rock Type of Interest'.

This workflow aims to address the relative abundance of mudstone/clay within the unit by using the lithological description of the formal definition of the unit, as shown in the BGS Lexicon of Named Rock Units. Geological rock units that appear on BGS published maps and models require a Lexicon code. Where these are groups, formations or members, the BGS Lexicon provides a formal definition of the unit. The database is not complete, but most important Late Palaeozoic, Mesozoic and Cenozoic rock units have detailed descriptions. A component of the definition is the provision of a lithological description, which appears in free-form text. Different views of the Lexicon are available internally and externally to BGS. The externally accessible Lexicon has a slightly different output of the definition, missing some items that appear in the internal BGS view, though both access their

Table 32 Lithology assessment for the Hampshire Basin GVS. Composite LEX_RCS codes are highlighted in grey

Name	Stratigraphy	Lithology	Appendix 1 workflow mdst/clay present	Main Lithology 1	Main Lithology 2	Main Lithology 3	Main Lithology 4	Main lithology	Dominant lithology	MDST/CLAY SUBUNTS
Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K
SOLT-CLSISA	SOLENT GROUP	CLAY, SILT AND SAND	Rock Type of Interest (RTI)	CLAY	SILT	SAND		Rock Type of Interest (RTI)	not a Rock Type of Interest (not a RTI)	
BRBA-SSCL	BRACKLESHAM GROUP AND BARTON GROUP (UNDIFFERENTIATED)	SAND, SILT AND CLAY	RTI	CLAY	SANDU	SILT		RTI	not a RTI	BAC; MARF; POOL; WTT
THAM-CLSSG	THAMES GROUP	CLAY, SILT, SAND AND GRAVEL	RTI	SANDU	SICL			RTI	not a RTI	LC
LMBE-CLSSG	LAMBETH GROUP	CLAY, SILT, SAND AND GRAVEL	RTI	CLAY	SANDU			RTI	not a RTI	
PCK-CHLK	PORTSDOWN CHALK FORMATION	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
CUCK-CHLK	CULVER CHALK FORMATION	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
NCK-CHLK	NEWHAVEN CHALK FORMATION	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
SECK-CHLK	SEAFORD CHALK FORMATION	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
LECH-CHLK	LEWES NODULAR CHALK FORMATION	CHALK	not a RTI	CHLK	LMST			not a RTI	not a RTI	
NPCH-CHLK	NEW PIT CHALK FORMATION	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
WHCK-	WHITE CHALK SUBGROUP	CHALK	not a RTI	CHLK				not a RTI	not a RTI	

Name	Stratigraphy	Lithology	Appendix 1 workflow mdst/clay present	Main Lithology 1	Main Lithology 2	Main Lithology 3	Main Lithology 4	Main lithology	Dominant lithology	MDST/CLAY SUBUNTS
Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K
CHLK	(UNDIFFERENTIATED), MIDDLE and UPPER CHALK									
ZZCH-CHLK	ZIGZAG CHALK FORMATION	CHALK	not a RTI	CAMDST	CHLK			not a RTI	not a RTI	
GYCK-CHLK	GREY CHALK SUBGROUP (UNDIFFERENTIATED) LOWER CHALK	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
CK-CHLK	CHALK GROUP (UNDIFFERENTIATED) UPPER CRETACEOUS	CHALK	not a RTI	CHLK				not a RTI	not a RTI	
GUGS-MDSL	GAULT FORMATION AND UPPER GREENSAND FORMATION (UNDIFFERENTIATED)	MUDSTONE, SANDSTONE AND LIMESTONE	RTI	CLAY	MDST	SDST		RTI	not a RTI	GLT
LGS-STMD	LOWER GREENSAND GROUP	SANDSTONE AND MUDSTONE	RTI	SANDU	SDST			not a RTI	not a RTI	
W-MDSS	WEALDEN GROUP	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	VTIS; WC; WDC; WSEX
PB-LSMD	PURBECK GROUP	INTERBEDDED LIMESTONE AND MUDSTONE	RTI	LMST	MDST			RTI	not a RTI	DURN
PL-LMCS	PORTLAND GROUP	LIMESTONE AND CALCAREOUS SANDSTONE	not a RTI	LMST	SANDU	SDST		not a RTI	not a RTI	
KC-MDST	KIMMERIDGE CLAY FORMATION	MUDSTONE	RTI	MDST				RTI	RTI	

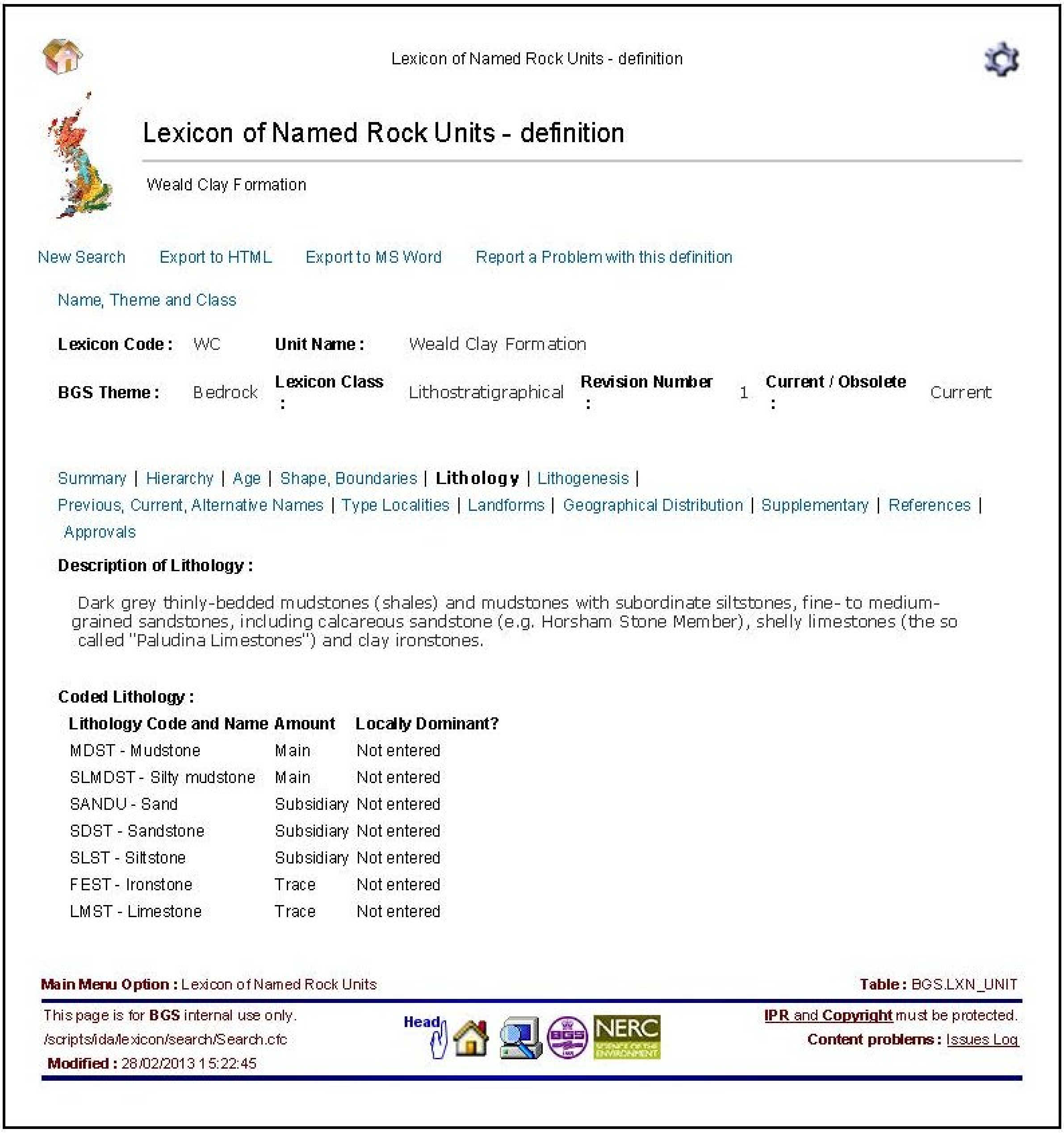
Name	Stratigraphy	Lithology	Appendix 1 workflow mdst/clay present	Main Lithology 1	Main Lithology 2	Main Lithology 3	Main Lithology 4	Main lithology	Dominant lithology	MDST/CLAY SUBUNTS
Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K
AMKC-MDST	AMPTHILL CLAY FORMATION AND KIMMERIDGE CLAY FORMATION (UNDIFFERENTIATED)	MUDSTONE	RTI	MDST				RTI	RTI	
CR-LSSM	CORALLIAN GROUP	LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE	RTI	LMST	SANDU	SDST		not a RTI	not a RTI	
KLOX-MDSS	KELLAWAYS FORMATION AND OXFORD CLAY FORMATION (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	CLAY	MDST	SANDU	SILT	RTI	not a RTI	
GOG-MDST	GREAT OOLITE GROUP	MUDSTONE	RTI	CAMDST	LMOOL	LMST	MDST	RTI	not a RTI	FE; FRC
GOG-SLAR	GREAT OOLITE GROUP	SANDSTONE, LIMESTONE AND ARGILLACEOUS ROCKS	RTI	CAMDST	LMOOL	LMST	MDST	RTI	not a RTI	
INO-LSSM	INFERIOR OOLITE GROUP	LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE	RTI	LMOOL	LMST	locally dominant FEOOL		not a RTI	not a RTI	
LI-MSLS	LIAS GROUP	MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE	RTI	CAMDST	MDST	SLMDST		RTI	not a RTI	BLI; CHAM
MMG-MDSS	MERCIA MUDSTONE GROUP	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	CAMDST	MDST	SLMDST	locally dominant BREC	RTI	not a RTI	

Name	Stratigraphy	Lithology	Appendix 1 workflow mdst/clay present	Main Lithology 1	Main Lithology 2	Main Lithology 3	Main Lithology 4	Main lithology	Dominant lithology	MDST/CLAY SUBUNTS
Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K
SSG-SDSM	SHERWOOD SANDSTONE GROUP	SANDSTONE, SILTSTONE AND MUDSTONE	RTI	PESST	SDST			not a RTI	not a RTI	
PUND-MDSS	PERMIAN ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	SDST	locally dominant MFIR			not a RTI	not a RTI	
PUND-SCON	PERMIAN ROCKS (UNDIFFERENTIATED)	INTERBEDDED SANDSTONE AND CONGLOMERATE	not a RTI	SDST	locally dominant MFIR			not a RTI	not a RTI	
CM-MDSS	COAL MEASURES SUPERGROUP	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
DINA-LMST	DINANTIAN ROCKS	LIMESTONE	not a RTI	LMST				not a RTI	not a RTI	
HOWY-MDSS	HOLSWORTHY GROUP	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST			RTI	not a RTI	
TEVYT-MDSS	TEIGN VALLEY GROUP AND TINTAGEL GROUP (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SLST	SDST		RTI	not a RTI	
DINA-LSSA	DINANTIAN ROCKS (UNDIFFERENTIATED)	LIMESTONE WITH SUBORDINATE SANDSTONE AND ARGILLACEOUS ROCKS	not a RTI	LMST				not a RTI	not a RTI	
UDEV-MDSS	UPPER DEVONIAN ROCKS	MUDSTONE, SILTSTONE AND	RTI	MDST	SDST	SLST		RTI	not a RTI	

Name	Stratigraphy	Lithology	Appendix 1 workflow mdst/clay present	Main Lithology 1	Main Lithology 2	Main Lithology 3	Main Lithology 4	Main lithology	Dominant lithology	MDST/CLAY SUBUNTS
Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K
	(UNDIFFERENTIATED)	SANDSTONE								
MDEV-MDSS	MIDDLE DEVONIAN (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
LDEV-MDSS	LOWER DEVONIAN ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
LDEV-SCON	LOWER DEVONIAN ROCKS (UNDIFFERENTIATED)	INTERBEDDED SANDSTONE AND CONGLOMERATE	not a RTI	SDST	CONG			not a RTI	not a RTI	
LUDL-MDSS	LUDLOW ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST				RTI	RTI	
SILU-MDSS	SILURIAN ROCKS, UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
ORD-MDSS_2	ORDOVICIAN ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
ORD-MDSS_3	ORDOVICIAN ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
CAOR-MDSS	CAMBRIAN AND ORDOVICIAN ROCKS (UNDIFFERENTIATED)	MUDSTONE, SILTSTONE AND SANDSTONE	RTI	MDST	SDST	SLST		RTI	not a RTI	
APRZ-ROCK	PROTEROZOIC TO PALAEOZOIC ROCKS (UNDIFFERENTIATED)	ROCK	not a RTI	ROCK				not a RTI	not a RTI	

data from the same database. One of the differences is that the internal view of the definitions also summarises the lithological description as a series coded lithologies using the RCS classification scheme (i.e. each code identifies a single lithology). These lithological codes are identified as being ‘Main’, ‘Subsidiary’ or ‘Trace’ in the database (See Figure 30 for the Weald Clay Formation).

Figure 30 **Extract of the BGS Lexicon entry for the Weald Clay Formation from the BGS intranet. The detailed descriptions appear behind a series of tabs (in blue) and in this example the ‘Lithology’ tab has been selected**



The process followed requires that the GVS for the region of interest has previously been isolated, as described in Appendix 1. A linkage was made between the units shown in the regional GVS for the Hampshire Basin and the ‘Main’ lithologies as recorded in the BGS Lexicon. To do this a database query based on the Lexicon code from the GVS extracted all the ‘Main Lithology’ entries, which were then exported to a spreadsheet format. Table 32 lists the rock units in the Hampshire Basin Region, with a full listing of the ‘Main’ lithologies shown in columns E-H. Note that the order that these ‘Main’ lithologies are shown in Table 32 does not indicate relative abundance. If ‘CLAY’ or ‘MDST’ is as a ‘Main’ constituent for a unit then it is regarded as a ‘Rock Type of Interest’. The units that meet these criteria are shown by those with entries in column I of Table 32.

The Hampshire Basin GVS contains 13 rock units that do not have lithological descriptions in the Lexicon (highlighted in green in Table 32). In most cases this reflects the rock unit being a composite body that was generated for the purposes of the UK3D model to produce rock masses equivalent to those shown on the 1:625 000 scale map and which lacks a Lexicon entry, e.g. Ordovician Rocks (undifferentiated). For these units, the main units (in columns E-H) are simply identified as those lithologies recognised in the LEX_RCS code for the model.

A comparison of the results between Appendix 1 workflow and the Main Lithology workflow described here Table 32 (columns D and I) shows broadly the same results. The exceptions are:

- Lower Greensand Group which was shown as a Rock Type of Interest in Column D as the DIC_ROCK_SIGMA code indicates the presence of Sandstone and Mudstone, but the Lexicon entry for this unit does not identify Mudstone as a ‘main’ lithology
- Corallian Group has an DIC_ROCK_SIGMA code of Limestone, Sandstone, Siltstone And Mudstone, but the Lexicon entry for this unit does not identify Mudstone as a ‘main’ lithology
- Inferior Oolite Group has an DIC_ROCK_SIGMA code of Limestone, Sandstone, Siltstone And Mudstone, but the Lexicon entry for this unit does not identify Mudstone as a ‘main’ lithology
- Sherwood Sandstone Group has an DIC_ROCK_SIGMA code of Sandstone, Siltstone And Mudstone, but the Lexicon entry for this unit does not identify Mudstone as a ‘main’ lithology’
- Permian Rocks (Undifferentiated) is shown as two units in UK3D with two different DIC_ROCK_SIGMA codes, one of which is shown as comprising Mudstone, Siltstone And Sandstone (MDSS) and one as interbedded sandstone and conglomerate (SCON), whereas the Lexicon has only one definition for the unit, which identifies Sandstone (RCS code SDST) as the only ‘main’ lithology’ with locally dominant Mafic igneous-rock (RCS code MFIR). Mudstone is not a ‘Main’ lithology

A2.2 Identifying Rock Types of Interest as a ‘dominant’ lithology in the region-specific GVS file

An alternative definition of UK3D units in which mudstone/clay is a ‘dominant’ component would be to select only those units in which these two lithologies are the only ones to be shown to be ‘Main’ lithologies (Dominant Lithology workflow in column J in Table 32). In this workflow, such a definition is represented only by the Kimmeridge Clay Formation, Ampthill Clay Formation and Kimmeridge Clay Formation, and the Ludlow Rocks (undifferentiated). Note, that such a narrow definition of ‘dominant’ would exclude the Mercia Mudstone Group. Hence, it is considered that this is too narrow a definition and would exclude potentially suitable rock types of interest. However, units such as the Mercia Mudstone Group could potentially be subdivided at Formation level which requires expert review of the region-specific GVS described below.

A2.3 Selecting rock types of interest which are not in the region-specific GVS file

The rock units shown in UK3D are modelled at the level of detail resolved on the 1:625 000 scale geological map. As such, only thicker geological units, mainly groups or composite groups, are shown. As a consequence, some units dominated by rocks of potential interest are likely to be undivided from their parent, but may be of sufficient thickness to be suitable to locate a GDF. This describes the process by which such clay/mudstone dominated units could be recognised.

For those units identified in the above workflows that include clay/mudstone as a ‘dominant’ or ‘main’ lithology (Table 32) the LEX code was entered into the BGS lexicon search page, then the ‘hierarchy’ tab was selected to identify the component (‘daughter’) units (Figure 30). Each named formation was then accessed via the hyperlink to the relevant page, in order to identify which daughter units included clay or mudstone as a ‘main’ lithology. For each daughter unit that met this criterion, a further search of the ‘geographical distribution’ (Figure 31) was used to check if the unit occurred in the Hampshire Basin. It should be noted that ‘geographical distribution’ is a free text general description, which can provide specific mentions of areas that the unit is present (or absent). The check was made to ensure that this text did not indicate Hampshire Basin was excluded as an area of presence. Those units that fulfilled both criteria (15 in total), being distinctively argillaceous compared with adjacent units, are then shown in column K of Table 32.

Figure 31 Extract of the BGS Lexicon entry for the Wealden Group. The detailed descriptions appear behind a series of tabs (in blue) and in this example the 'Hierarchy' tab has been selected. This shows all the daughter units, with hyperlink to their full Lexicon entry

Lexicon of Named Rock Units - definition

Lexicon of Named Rock Units - definition

Wealden Group

Return to Results of Your Search   New Search   Export to HTML   Export to MS Word   Report a Problem with this definition

Name, Theme and Class

Lexicon Code :	W	**Unit Name :**	Wealden Group				
BGS Theme :	Bedrock	**Lexicon Class :**	Lithostratigraphical	**Revision Number :**	2	**Current / Obsolete :**	Current

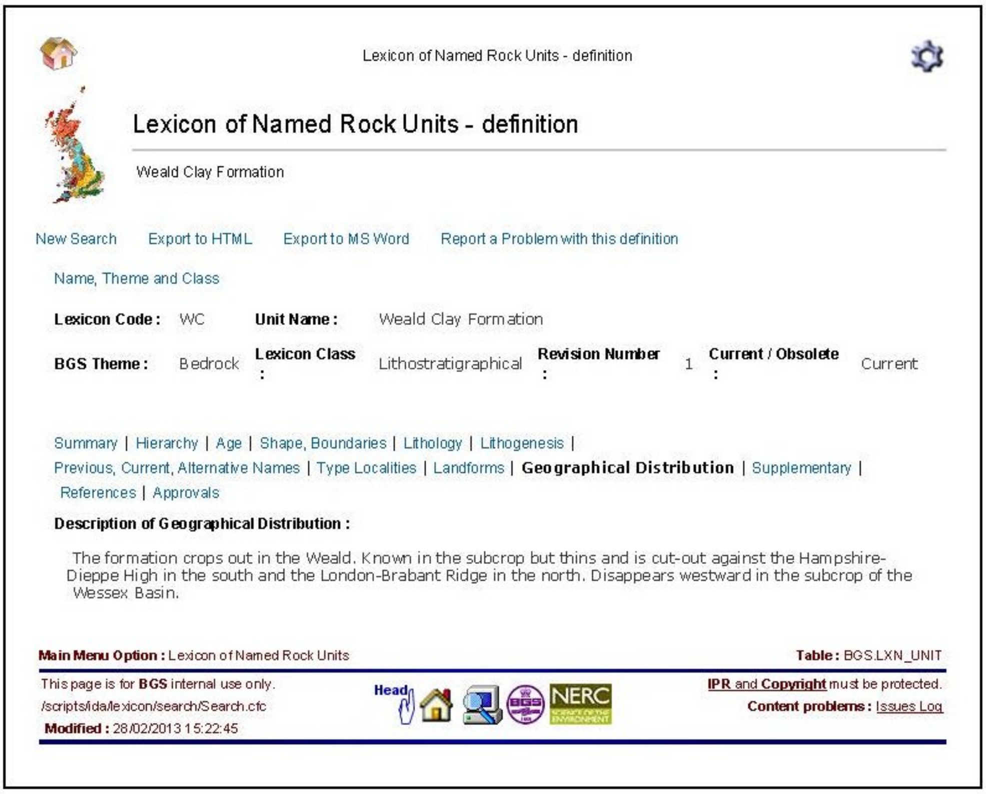
Summary | **Hierarchy** | Age | Shape, Boundaries | Lithology | Lithogenesis |
Previous, Current, Alternative Names | Type Localities | Landforms | Geographical Distribution | Supplementary |
References | Approvals

- - Not Applicable - [Current, Index Level]

W - Wealden Group

- ASD - Ashdown Formation - [Current, Full]
- TWS - Tunbridge Wells Sand Formation - [Current, Full]
  - ARS - Ardingly Sandstone Member - [Current, Full]
  - CGS - Colgate Sandstone - [Current, Index Level]
  - GRC - Grinstead Clay Member - [Current, Full]
    - CKST - Cuckfield Stone Bed - [Current, Full]
    - LGRC - Lower Grinstead Clay - [Current, Index Level]
    - UGRC - Upper Grinstead Clay - [Current, Index Level]
  - LTW - Lower Tunbridge Wells Sand - [Current, Index Level]
  - RPS - Roffey Park Sandstone - [Current, Index Level]
  - SPS - Shelley Plain Sandstone - [Current, Index Level]
  - UTW - Upper Tunbridge Wells Sand - [Current, Index Level]
- VTIS - Vectis Formation - [Current, Full]
  - BHSA - Barnes High Sandstone Member - [Current, Full]
  - CCH - Cowleaze Chine Member - [Current, Full]
  - SHCH - Shepherd's Chine Member - [Current, Full]
- WC - Weald Clay Formation - [Current, Full]
  - HST - Horsham Stone Member - [Current, Full]
  - LWY - Lower Weald Clay - [Current, Index Level]
  - UWC - Upper Weald Clay - [Current, Index Level]
- WDC - Wadhurst Clay Formation - [Current, Full]
- WHS - Whitchurch Sand Formation - [Current, Full]
- WSEX - Wessex Formation - [Current, Full]

Figure 32 Extract of the BGS Lexicon entry for the Wealden Clay Formation. The detailed descriptions appear behind a series of tabs (in blue) and in this example the ‘Geographical Description’ tab has been selected. Where the unit is identified in the Wessex/Hampshire Basin the unit is considered to be present in the Hampshire Basin region



A2.4 Edits to the UK3D

There is scope, as part of the Detailed Technical Instruction workflow, to generate additional units in cross-sections in the UK3D platform if required, using published data sources.

As mentioned in the previous section, 15 units in the Hampshire Basin Region were identified that were considered as potential rocks of interest that could be considered as suitable for further modelling in order to isolate them from their more heterogeneous parent units currently modelled in the UK3D that include strata which could be considered unsuitable. These units, shown in column K of Table 32 include:

- Barton Clay Formation, Marsh Farm Formation, Poole Formation, Wittering Formation (currently modelled as Bracklesham Group And Barton Group (Undifferentiated))
- London Clay Formation (currently modelled as Thames Group)
- Gault Clay Formation (currently modelled as Gault Formation And Upper Greensand Formation (Undifferentiated))
- Vectis Formation, Weald Clay Formation, Wadhurst Clay Formation, Wessex Formation (currently modelled as Wealden Group)
- Durlston Formation (currently modelled as Purbeck Group)

- Fuller's Earth Formation, Frome Clay Formation (currently modelled as Great Oolite Group)
- Blue Lias Formation, Charmouth Mudstone Formation (currently modelled as Lias Group)

Note that the Oxford Clay Formation is not included in this exercise as the current parent unit shown in UK3D, Kellaways Formation And Oxford Clay Formation (Undifferentiated), includes two formations that are both mudstone-dominated and there would be no immediate value of segregating the Oxford Clay Formation from the parent unit.

In the Rock Type Detailed Technical Instruction workflow, the final selection of units to be subdivided and modelled as a Rock Type of Interest will follow a region-specific workshop with RWM. This should examine the suitability of these units for subdivision (e.g. data availability, thickness, other safety criteria). The default position will be that, if there is insufficient information to subdivide a combined unit that may contain a daughter unit that is dominantly argillaceous, then the combined unit will be retained as a Rock Type of Interest.

For this workflow the process by which the Gault Clay Formation could be modelled as a separate unit from the parent unit of Gault Formation And Upper Greensand Formation (Undifferentiated) was investigated. The other component of the unit, the Upper Greensand Formation is a sandstone-dominated unit which would be an unsuitable rock unit. This workflow would thus isolate one single suitable rock type from one unsuitable rock type.

The stages are as follows:

1) The first stage is to isolate a copy of the regional model for Hampshire Basin, through the process described in Appendix 1. This copy included the details of the golden spike boreholes (onshore and offshore boreholes) for the region that had been generated as part of the development of GB3D_v2014 (as described by Mathers *et al*. 2014). The lithostratigraphic details for the boreholes had been entered into the corporate database, Borehole Geology, with all key formational details, rather than just the rock units that appeared in the UK3D GVS. Consequently, the distinction between Gault Clay Formation (GLT on) and Upper Greensand Formation (UGS on Figure 33) has already been identified and can be directly incorporated into the section drawing, as shown in Figure 34. 30 such golden spike boreholes are present within the Hampshire Basin Region and were used to inform the remodelling of the two component formations. Note, however, that for other regions / potential unit subdivisions, the current borehole database may not be comprehensively populated with the corresponding stratigraphic picks, in some cases the initial coding may have been at the level of the combined unit only and will require a stage of modification of the borehole stratigraphy.
2) The base of the Gault Clay Formation (GLT) is everywhere coincident with the base of the existing modelled surface for the parent Gault Formation And Upper Greensand Formation (Undifferentiated; GUGS). The next stage was to rename the GUGS surface as GLT throughout the model.
3) The Gault Formation And Upper Greensand Formation (Undifferentiated; GUGS) is the unit shown on the 1:625 000-scale map. In the offshore, where the 625k map data is not available, the UK3D model used the 1:250 000-scale offshore Bedrock map dataset, which recognises the nearest equivalent succession as Lower Greensand And Upper Greensand (Undifferentiated) [Offshore Areas] (LGUG-STMD), with no mention of the Gault Clay Formation. The onshore 1:50 000-scale Bedrock DigMap data resolves GUGS into their two component formations (Figure 34). As part of the proposed workflow, the 1:50 000-scale Bedrock DigMap data was added to the map viewer so that the position of the boundary between GLT and UGS could be captured at crop at least onshore. It should be noted that these are

two quite distinct map datasets with different degrees of accuracy and no attempt was made to modify the base of GLT (former GUGS boundary derived from the 625k model dataset) to match the DigMap50k dataset.

Figure 33 Extract of section UK_Reg15_section_239 showing the stratigraphical interpretation of the Netherhampton Borehole and the introduction of two new surfaces for the Gault Clay Formation (GLT) and Upper Greensand Formation (UGS)

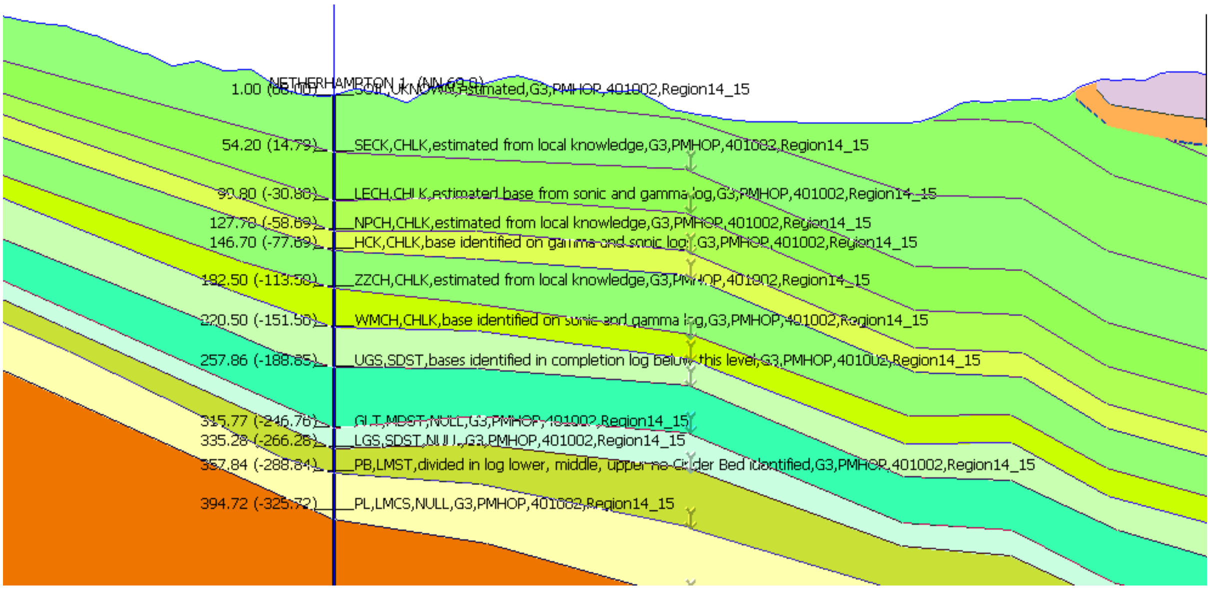
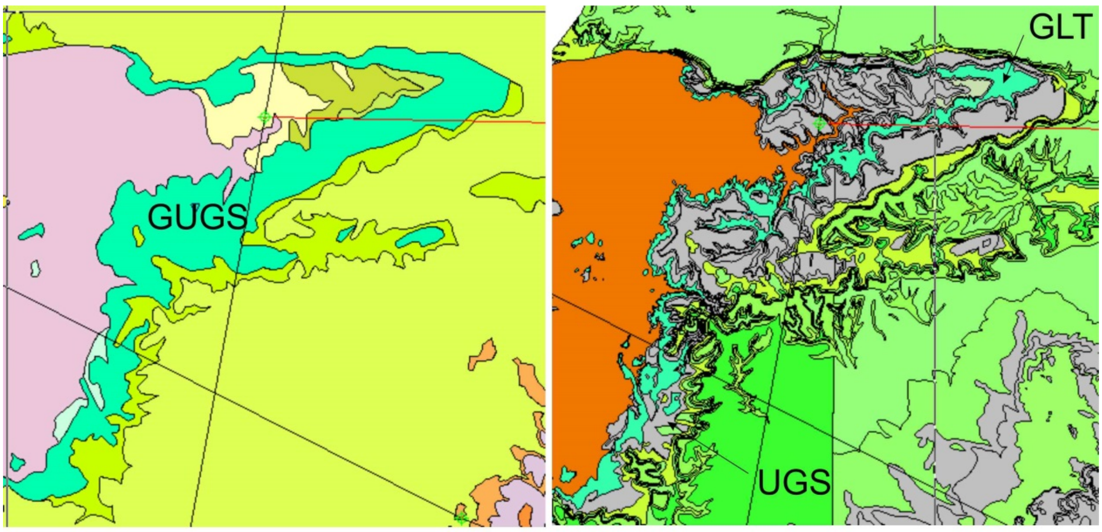


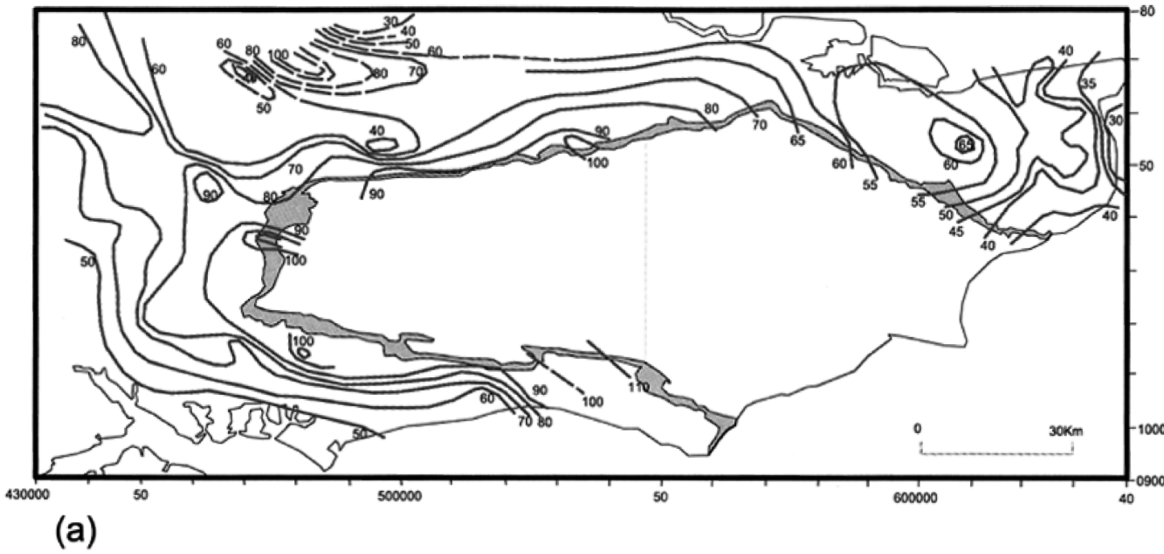
Figure 34 Comparison of mapped resolution of lithostratigraphic units at 1:625 000-scale (left image), the resolution of the UK3D model, and that at 1:50 000-scale (right image) showing that component formations are resolved at outcrop



1:625 000-scale map data　　1:50 000-scale map data

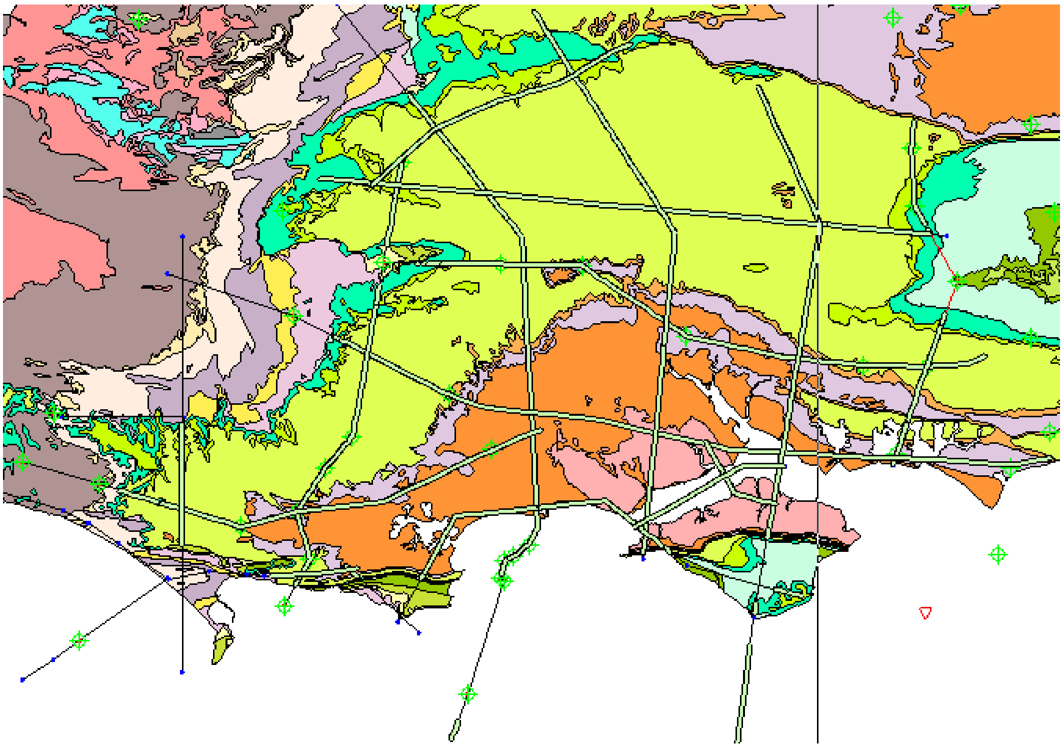
4) There is legacy data available which provides information on the thickness of the Gault Clay Formation that covers part of the east of the Hampshire Basin Region (and all of the Wealden Region). A copy of the map (Figure 35) was scanned, georegistered, and included within the GSI3D map viewer. When the base UGS line was captured, an attempt was made to ensure that it resulted in the underlying Gault Clay Formation honouring the thickness shown on this map.

Figure 35 Extract from Hopson *et al*. (2001, Fig. 11a), which provides isopachytes (in metres) for the thickness of the Gault Clay Formation



5) Remodelling the 18 sections to include both GLT and UGS took approximately one person day. Priority was given to ensure the sections honoured the picks on the boreholes. The UGS surface was modelled to the 1:50 000 scale DigMap dataset where available (not offshore) and unless it disagreed with current borehole picks, all attempt was made to honour the GLT thicknesses shown in Figure 35 (see Figure 36). The result was greatest certainty in the interpretation in the extreme east of the region, where the combination of borehole data, legacy isopachyte data and crop information nearby provide the most comprehensive datasets to resolve the interpretation. The next level of certainty is from the west of the region where the combination of available borehole data and mapped crop provides the constraint of the distribution and relative thicknesses of the units. In the central parts of the Hampshire Basin (onshore) and the entire offshore, reliance is placed solely from the picks from the golden spike boreholes and for some sections no boreholes were available (Figure 36) and reliance of intercepts from crossing sections was the only information available, and should indicate lowest level of certainty (especially in the northern part of the model).

Figure 36 **Extent of the distribution of the Upper Greensand Formation across the Hampshire Basin Region, shown by pale green ribbons along the line of sections. This image shows the location of the golden spike boreholes (in green)**



A2.5 References

Hopson, P. M., Farrant, A. R. & Booth, K. A. 2001. Lithostratigraphy and regional correlation of the basal Chalk, Upper Greensand, Gault, and uppermost Folkestone formations (Mid-Cretaceous) from cored boreholes near Selborne, Hampshire. Proceedings of the Geologists' Association, 112, 193-210.

Mathers, S.J., Terrington, R.L., Waters, C.N. & Thorpe, S. 2014b. The construction of a bedrock geology model for England and Wales. British Geological Survey Open Report, OR/14/039. 23pp. http://nora.nerc.ac.uk/507670/

Appendix 3: Methodology for producing a generalised Digital Terrain Model and aerial unit distributions map at -200 m and -1000 m below ground level volume of interest

A3.1 Introduction

In order to produce production maps of Rock Types of Interest there are a number of steps that need to be undertaken. The method for applying a Rock Type of Interest to UK3D is described in Appendix 2. This Appendix describes the method for developing a generalised DTM that represents 'ground level' in a way that is considered proportionate to national scale screening. It further describes how this GLM is applied to the subsurface to form a VOI which lies between -200 and -1000 m below the GLM (Step 2).

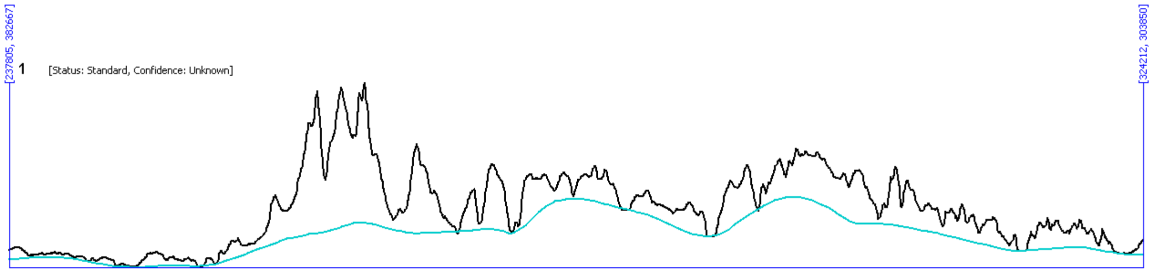
In order to develop the production maps of 'rock types of interest' this VOI is used to slice through surfaces that show the top and bottom of the 'rock types of interest' identified in the UK3D sections. Hence, this Appendix also describes a methodology where these surfaces are extrapolated from the UK3D section lines that have been reattributed to show 'rock types of interest' (Step 3); and how the VOI is applied to these surfaces to show their extent in the volume of interest (Step 4).

The outlined methodologies are tested by application to part of the Hampshire Basin screening region.

A3.2 Step 1 Creating a generalised Ground Level Model (GLM)

The main purpose of this step is to demonstrate the feasibility of developing a generalised GLM that represents smoothed areas of raised relief but retains elevation in areas where the relief is low e.g. river/ drainage channels. The approach to doing this is to carry out generalisation of an existing Digital Terrane Model (DTM). Figure 37 shows an example DTM and generalised GLM produced for North Wales in profile. The generalised GLM is needed so that the production maps that are ultimately produced are not overly complex. Because the methodology involves cutting through the geological surfaces with a 'ground level' reduced to -200 m and -1000 m to form the VOI, it is necessary to smooth out the topography in a way that reduces the complexity of the intersection in a way that is proportionate to the 625K scale of the source geological information and output production maps. Our approach to doing this is to initially reduce a DTM to a generalised groundwater level. Groundwater level will tend to be lower in areas of low relief (relative to surrounding areas) and will intersect the river valleys, but will rise to a certain extent under areas of higher relief to provide a generalised approximation of the topography (McKenzie 2010). A further methodology to manually reduce areas where the applying groundwater level may have provided insufficient generalisation of the topography is also described.

Figure 37 DTM (in black) with a generalised DTM (in blue)

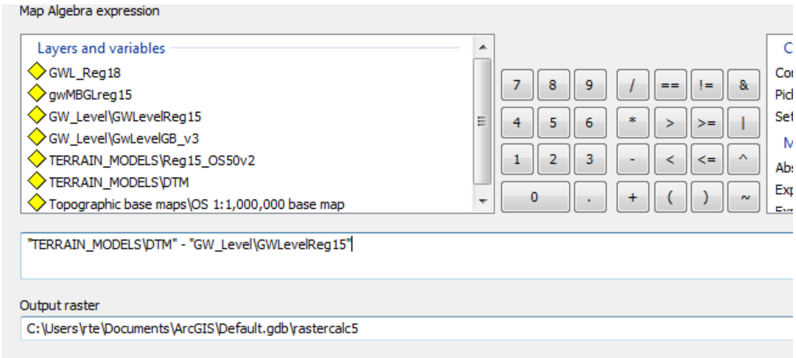


The following 3 datasets were used to produce this DTM generalisation:

- OS Open Terrain 50 (https://www.ordnancesurvey.co.uk/business-and-government/products/terrain-50.html)
- National Depth to Groundwater Dataset (http://nora.nerc.ac.uk/510752/)
- DigBath 250 (http://www.bgs.ac.uk/products/digbath250/home.html)

The National Depth to Groundwater dataset only exists onshore, and is currently measured depth, not relative to OD. To derive the elevation relative to OD, the Raster Calculator in ArcGIS was used to subtract the National Depth to Groundwater Dataset from the OS Open Terrain 50 dataset ()

Figure 38 Calculation used to derive the generalised DTM from the National Depth to Groundwater Dataset



Using the calculated output, the Groundwater derived generalised DTM was merged with DigBath 250 to give combined onshore and offshore coverage. The combined generalised DTM was subsampled to a 250 m cell size so as to make it manageable when using it with the modelling and GIS software. The results of this generalised surface are compared against the ungeneralised topography from the OS Open Terrain 50 dataset in profile (Figure 39 and Figure 40)

Figure 39 Generalised DTM (in red) comparison against OS Open terrain 50 (in blue) in Region 15 (Hampshire Basin)

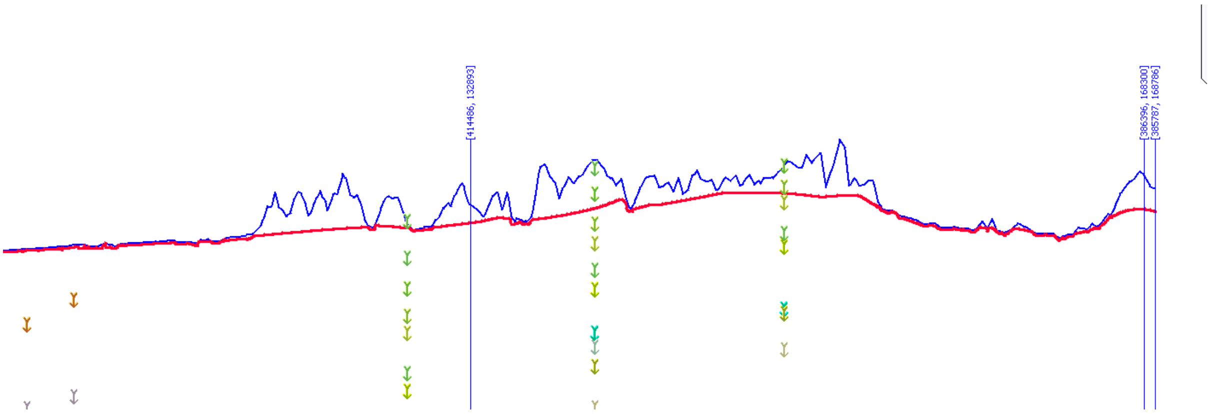
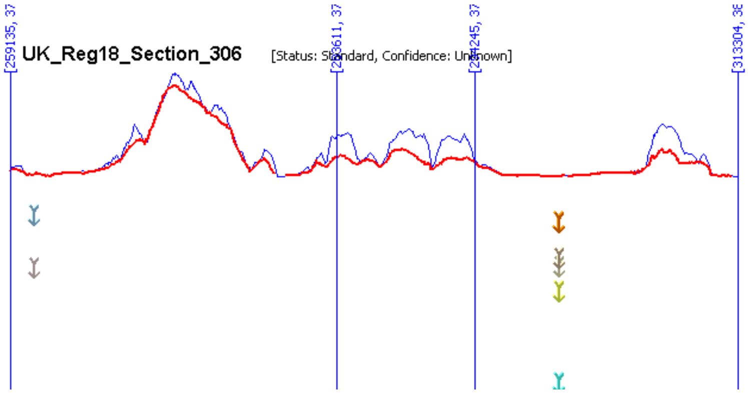
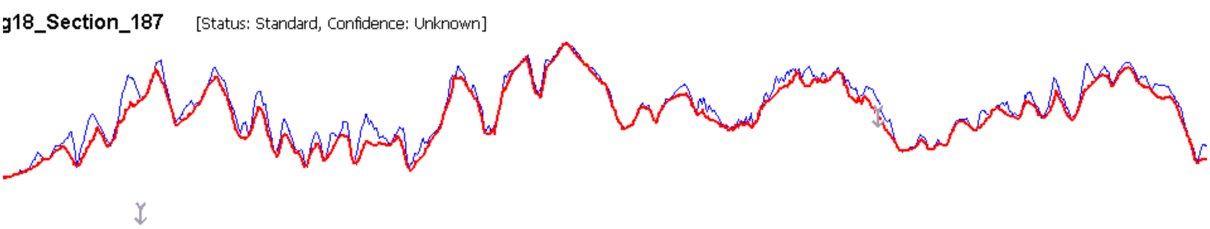


Figure 40 Generalised DTM (in red) comparison against OS Open terrain 50 (in blue) in part of Region 18 (North Wales)



In some areas of complex topography, where groundwater level from the National Depth to Groundwater dataset is more or less coincident further smoothing of the generalised DTM will be required so that the relief of the surface profile is not too closely followed in areas of raised relief, for example see Figure 41. The amount of smoothing required will need iteration and will largely be dependent on whether the output production maps require further generalisation to be suitable at 625K scale. This is also likely to vary by region depending on the style of the topography.

Figure 41 Generalised DTM (in red) comparison against OS Open terrain 50 (in blue) in part of Region 18 (North Wales)

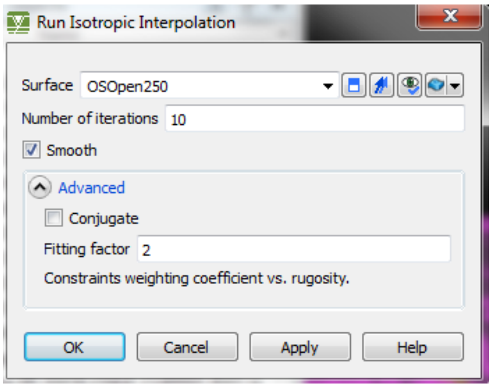


The following workflow in SKUA-GOCAD™ can be applied to do this from which an example output can be seen in Figure 37:

1) Set control points at river channels using the OS Open Strategi – River Lines dataset, so that the Z elevation at these points are fixed.

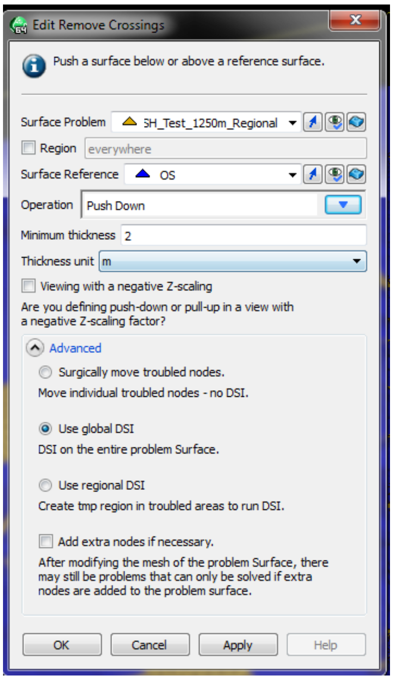
2) Use the Interpolation tool with Smoothing applied (Figure 42)

Figure 42 Interpolation on entire surface with smoothing factor



The conjugate factor can be altered to produce further smoothing if required. Cross-overs between the smoothed surface and the OS Open Terrain 50 DTM are checked in SKUA-GOCAD™ to ensure that the generalised DTM is always below the OS Open 50 Terrain DTM (Figure 43).

Figure 43 Remove surface cross-overs tool



A3.3 Step 2 Creating the volume of interest

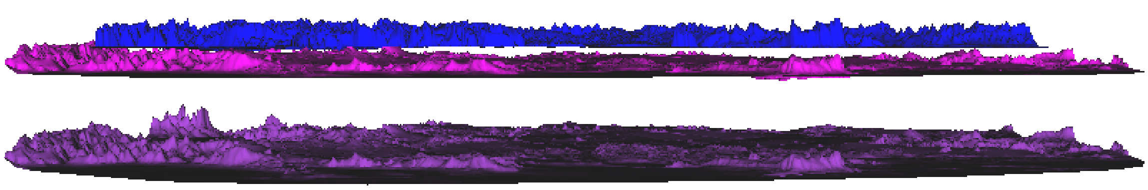
The VOI is created by projecting the generalised DTM in the subsurface at -200 m and -1000 m to define its top and bottom surfaces. In order to derive the VOI the generalised DTM surface was converted to a triangulated surface (tsurf) file using GSI3D imported into SKUA-GOCAD™ v14.1. The following calculation was used to derive the horizon at -200 m and -1000 m below ground level in SKUA-GOCAD™:

Z=Z-200;

Z=Z-1000;

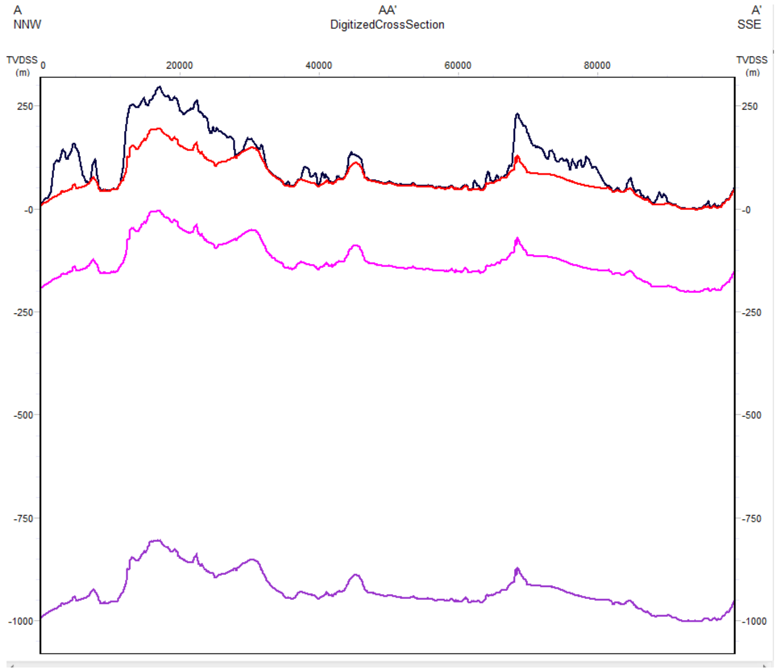
Figure 44 shows 3 horizons which are the OS Open Terrain 50 Data (onshore only), the generalised DTM at 200 m below generalised DTM ground level and the generalised DTM at 1000 m below generalised DTM ground level.

Figure 44 OS Open Terrain 50 DTM (in blue), generalised DTM at 200 m below generalised DTM ground level (in pink) and generalised DTM 1000 m below generalised DTM ground level (in purple)



These surfaces can also be analysed in profile (Figure 45). The VOI of interest has now to be created to isolate the distribution of rock units from UK3D that occur within these boundaries.

Figure 45 OS Open Terrain 50 (in black), Generalised DTM (in red), generalised DTM at -200 below generalised DTM (in pink) and -1000 m below generalised DTM (in purple)



A3.4 Step 3 Generating base and top surfaces from the NGS_3D cross-sections

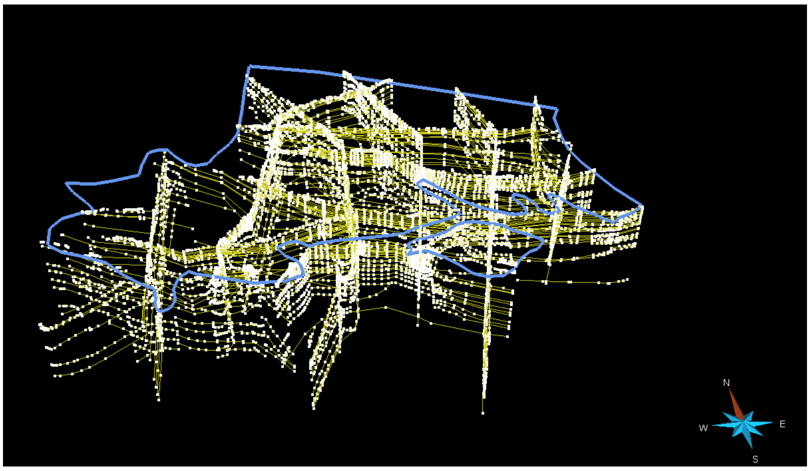
This step describes the method by which the top and bottom of formations containing a Rock Type of Interest identified in UK3D cross-sections for a screening region can be extrapolated to define surfaces. The method involves exporting GDI3D section lines as polylines (plines, points from lines of cross-section) comprising individual cross-section correlation points with X,Y, Z coordinates and interpolating these as a triangulated mesh constrained by surface and subcrop intercepts.

The following methodology was used to produce unfaulted surface horizons from the cross-sections in UK3D Region 15 (Hampshire Basin Screening Region). For expediency, in this test, the raw UK 3D dataset has been used.

1) Region 15 cross-sections were exported as plines from GSI3D

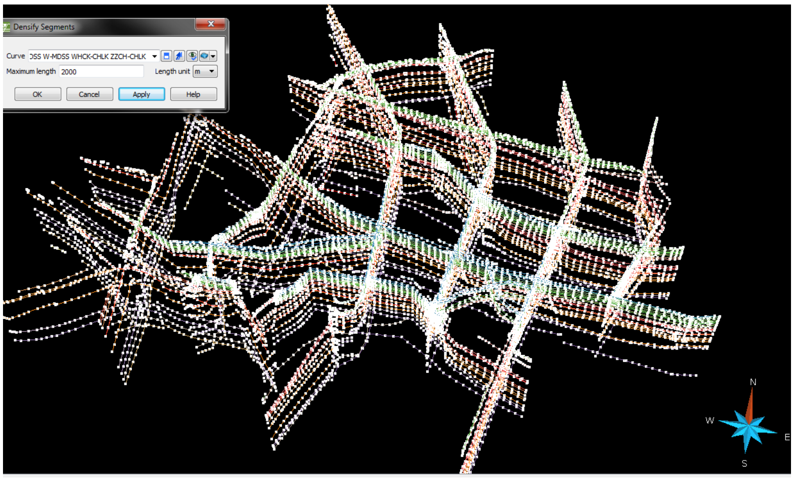
2) plines were imported into SKUA-GOCAD™ v14.1 (Figure 46)

Figure 46 UK 3D cross-section imported into SKUA-GOCAD™ as plines



3) Each line was densified at a 2000 m spacing (Figure 47) so that the interpolation was improved between points

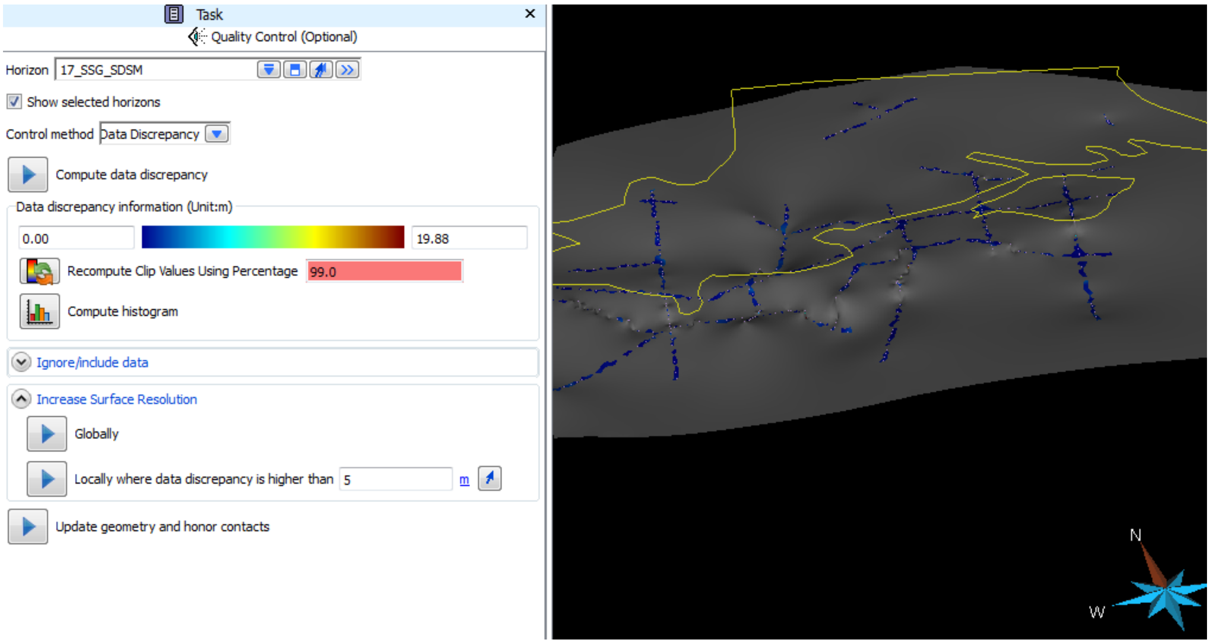
Figure 47 UK 3D densified with nodes on cross-section



4) Surface horizons were constructed using the GOCAD Structural Modelling Workflow by interpolating between cross-section correlation points, constrained by the surface intercept from the 625Kdigital geological map on the DTM, and subcrop elevation points derived in GSI3D by calculating the bases of overlying units.

5) Initially horizons were produced at 1000 m mesh sampling and then further refined using the quality control mechanism in the Structural Modelling Workflow to regionally increase surface resolution where there is a poor fit to the original data (Figure 48)

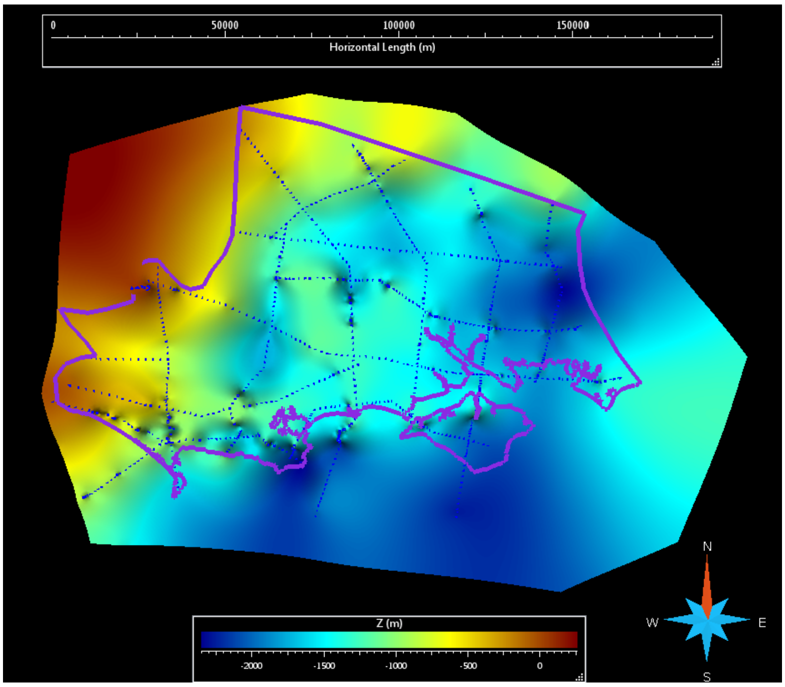
Figure 48 Quality Control Editor in the Structural Modelling Workflow



6) As in 5. surface cross-overs between the horizon and the DTM and between individual horizons were checked. If any occurred, they were removed using a regionalised interpolation using the Remove Cross-over tool.

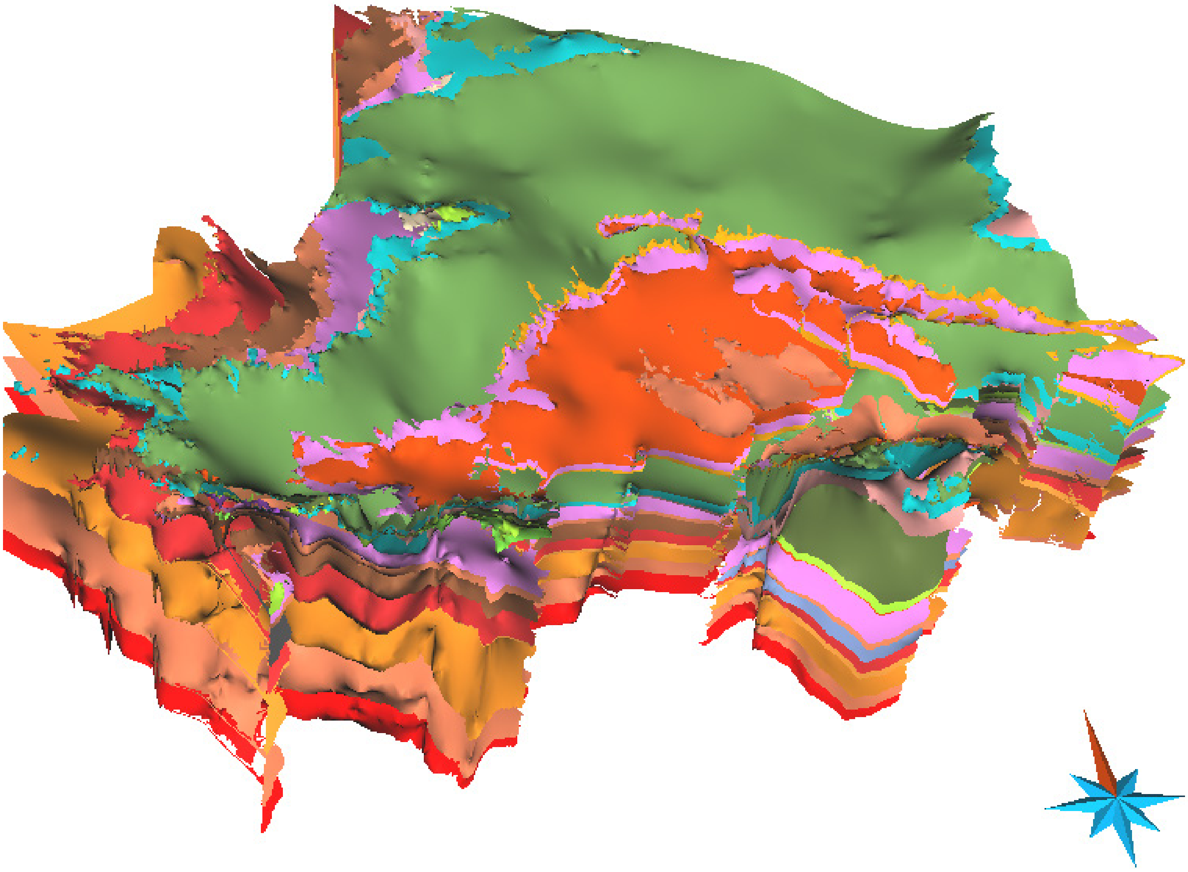
7) Surface horizons were initially calculated beyond the Region 15 boundary to give full onshore and offshore coverage (Figure 49).

Figure 49 Base Lias (LI-MSLS) surface horizon with the Region 15 boundary (in purple)



8) Each modelled surface horizon was then clipped to the Region 15 boundary. Figure 50 shows the full surface horizon distribution for region 18 down to the Sherwood Sandstone Group (SSG-SDSM).

Figure 50 Surface horizon construction for Region 15 (Hampshire Basin)



9) GSI3D only attributes the base of a formation. However, in order to identify the extent of a formation in the VOI, it is necessary to define its top surface. This is done by importing the base horizons created in GOCAD back into GSI3D and calculating the stratigraphy from the top down to identify a top surface for each formation.

A3.5 Step 4 Calculating the aerial distribution of the horizons generated within the VOI

The following methodology was used to calculate the aerial distribution of each surface horizon that occurs within the -200 m and -1000 m VOI.

1) The base and top surfaces for each unit, generated in steps 1 to 3, were exported as ASCII grids at 100 m resolution and imported into ArcGIS.
2) The -200 m and -1000 m generalised DTMs which define the VOI were also imported into ArcGIS.
3) The Raster Calculator tool was used to derive aerial distribution of each unit that occurred within these -200 m and -1000 m vertical limits for Region 15 in a raster

format. The following calculation was used in the Raster Calculator to derive this, using the base Lias Group as an example:

Where:

base Lias Group horizon was less than or equal to the -200 m top VOI, but greater than or equal to the -1000 m base VOI, or top Lias Group horizon was less than or equals to the -200 m top VOI but greater than or equal to the -1000 m base VOI

Then:

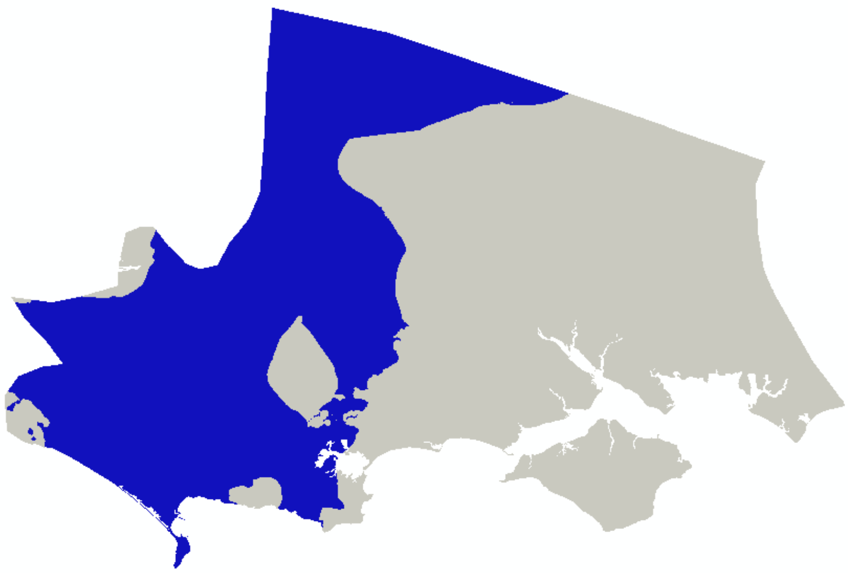
export their distribution.

In the Raster Calculator, the equation looked like this:

("LI-MSLS_B.asc" <= "Minus200m_100mcellsize.asc") & ("LI-MSLS_B.asc" >= "Minus1000m_100mcellsize.asc") | ("LI-MSLS_T.asc" <= "Minus200m_100mcellsize.asc") & ("LI-MSLS_T.asc" >= "Minus1000m_100mcellsize.asc")

Figure 51 shows the output produced from the above equation for the Lias Group, which shows the total distribution of the Lias Group and the distribution within the -200 m and -1000 m VOI.

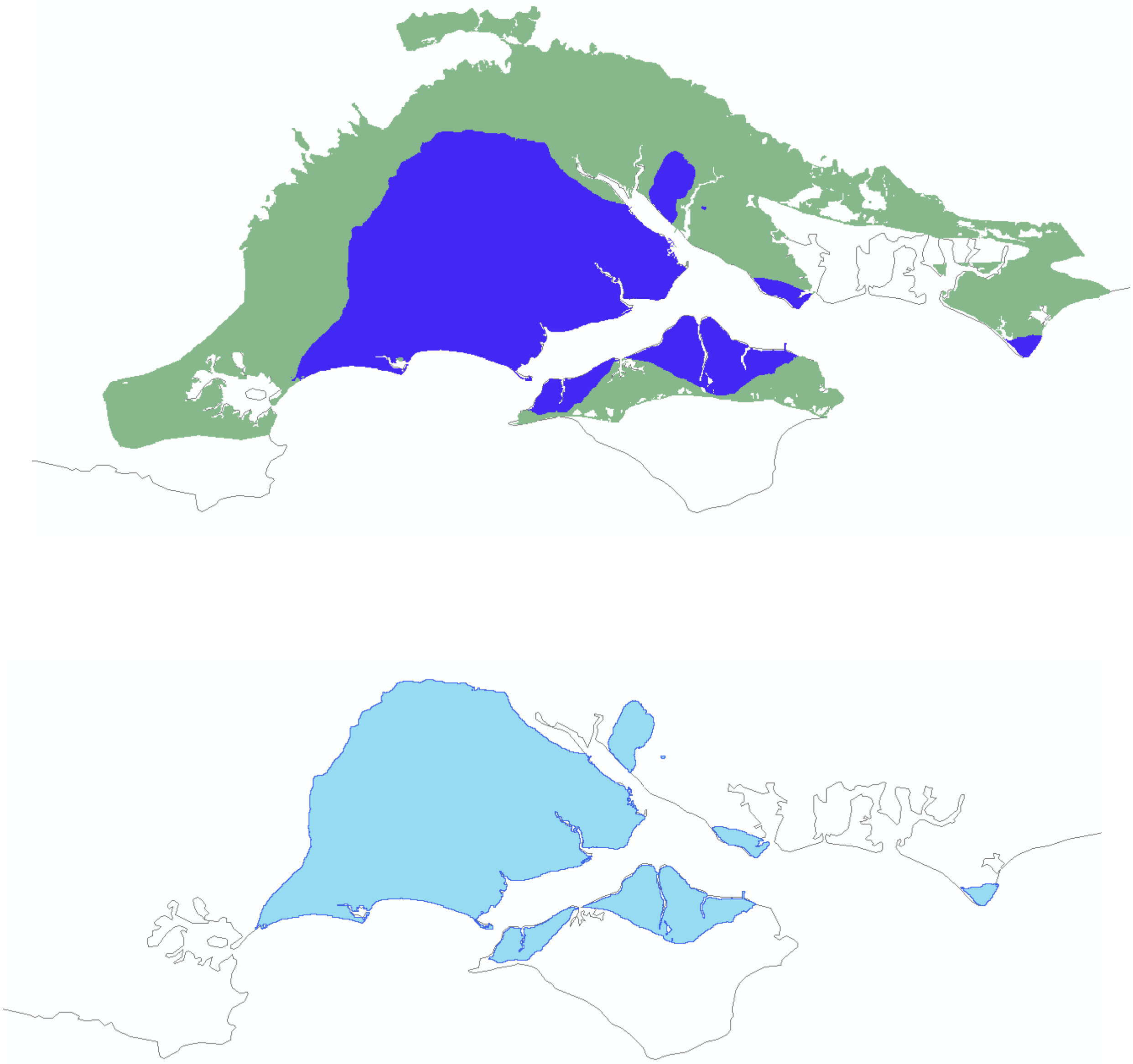
Figure 51 Distribution of the Lias Group in Region 15 (Hampshire Basin.) not in VOI (in grey), within the -200 m and -1000 m VOI (in blue)



4) Raster areas are converted to ArcGIS shapefiles and exported to into the Production Map layout.

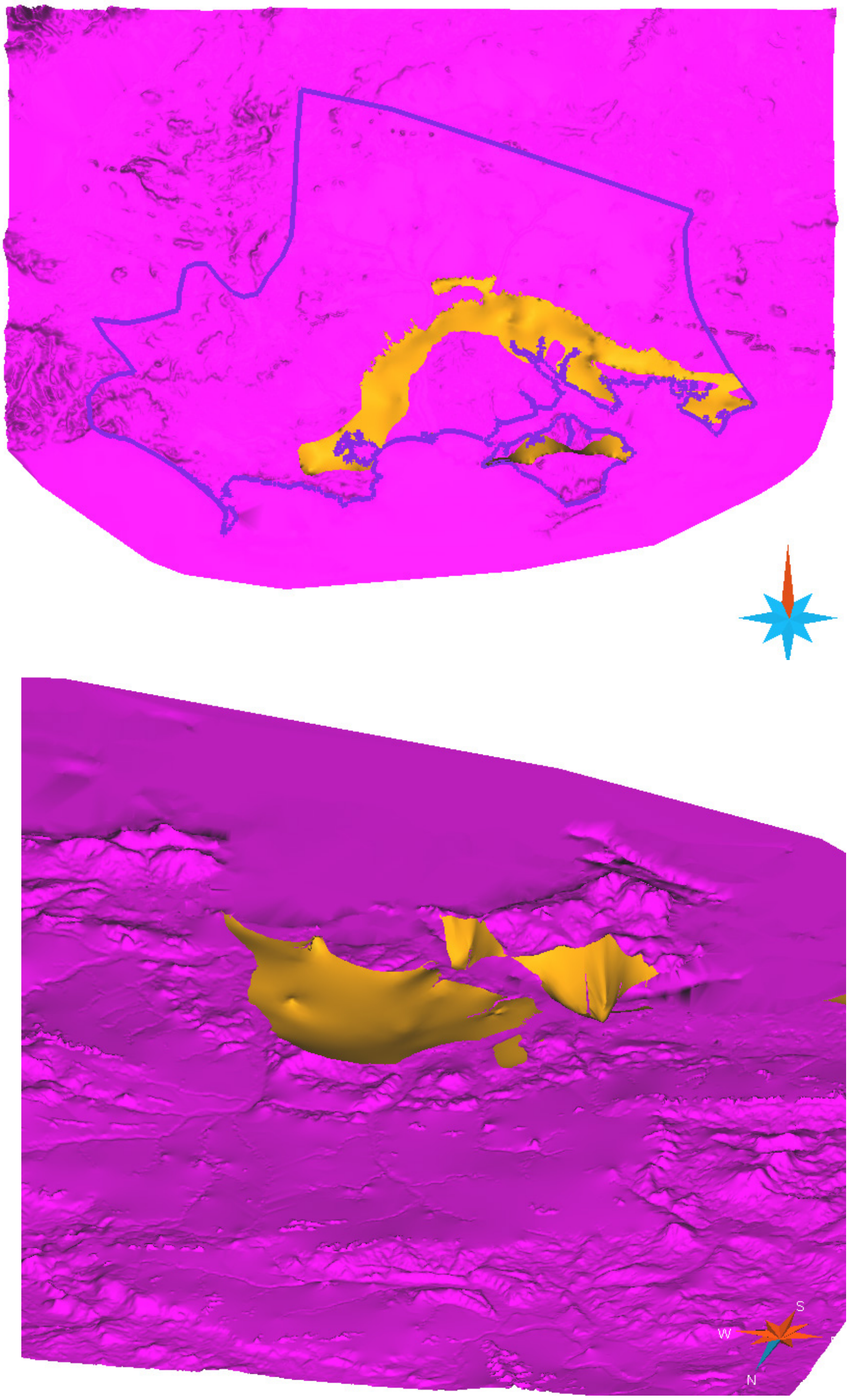
5) In order to cross-validate the results, a similar process was carried out using an alternative data processing tool (FME). This applied the same surfaces to produce the same output as using the Raster Calculator (Figure 53). For this test the Lambeth Group was chosen as the example rock unit.

Figure 52 Rasterized output from Raster Calculator (above) for the Lambeth group, shapefile polygon output for the Lambeth Group (below) to show distribution in the VOI



6) As a further cross-validation the resulting areas were visually inspected against the surfaces produced in SKUA-GOCAD™ v14.1. For example, from looking above and below against the -200 m generalised DTM (Figure 54)

Figure 53 The Lambeth Group surface horizon distribution from above (in top picture) and below (bottom picture) in SKUA-GOCAD™



A3.6 References

McKenzie A A 2010. User Guide for the British Geological Survey National Depth to Groundwater Dataset. British Geological Survey Internal Report OR/10/006.

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