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- Science infrastructure

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UK GEOENERGY OBSERVATORIES PROGRAMME

OPEN REPORT OR/19/052

UKGEOS Cheshire Energy Research Field Site

SCIENCE INFRASTRUCTURE

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Foreword

This report provides an overview of the planned geological characterisation, research infrastructure and data acquisition at the Cheshire Energy Research Field Site. The report is intended for a technical, science community audience.

The design of the infrastructure is based on the UK Geoenergy Observatories' Science Plan, which was generated following science community consultation. As with all drilling projects, the realities of what can be achieved in the context of geological constraints, health and safety, and budget have meant that the final design is necessarily a compromise.

As the site is developed this document will be updated to reflect the actual built infrastructure and any changes to the planned design. Researchers are requested to refer to the UKGEOS website to check that they are using the latest version of this document: ukgeos.ac.uk and to refer to this report in their published outputs.

Data generated during the construction and operation of the Cheshire Energy Research Field Site will be made freely available via an online platform, which is currently in development.

Professor David Manning

NERC Senior Science User, UK Geoenergy Observatories

Acknowledgements

The British Geological Survey (BGS) is constructing and operating the UK Geoenergy Observatories on behalf of the Natural Environment Research Council and UK Research and Innovation (UKRI). Funding for the Observatories has been provided by the UK Government Department for Business, Energy and Industrial Strategy (BEIS).

The authors wish to thank the UK Geoenergy Observatories delivery team for their contribution to the content of this report.

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1.1 OVERVIEW

The aim of the UK Geoenergy Observatories project is to establish new centres for world-leading research into the subsurface environment. The knowledge generated will contribute to the responsible development of new subsurface technologies, both in the UK and internationally.

The project, commissioned by the Natural Environment Research Council (NERC) and UKRI on behalf of BEIS, follows the 2014 decision that the Government would spend £31 million to create world-class, subsurface energy-research test centres. The British Geological Survey (BGS) has the responsibility for delivering the research infrastructure and managing access to these facilities over their anticipated 15-year lifetime.

The BGS consulted with a range of stakeholders to identify two preferred geological locations. The first research field site will be in Cheshire south of the River Mersey near the villages of Thornton and Elton, and will provide data to underpin research into a number of new energy technologies that will directly help reduce atmospheric carbon emissions, for example CO_2 storage, shallow geothermal, and aquifer storage of heat and compressed air. The second research field site (Monaghan, 2018) will be in Glasgow, close to the Cuningar Loop in the River Clyde and will focus on shallow geothermal energy. The Science Plan, developed through a consultation process, ensures that UKGEOS provides for the current and future needs of the scientific user community.

Figure 1 View over Ince Marshes towards Runcorn including Frodsham windfarm. Image © Peter Cocoran

1.2 GEOLOGICAL OVERVIEW & RESEARCH POTENTIAL OF THIS LOCATION

The Cheshire site was chosen for its scientific potential, as the geology underlying the location presents opportunities for both academic and industrial research:

Quaternary deposits - At the surface are Quaternary sediments that are representative of surface 'ice age' sediments across the UK. They provide opportunities for research relating to engineering problems, natural shallow gas migration, the potential for shallow geothermal technologies, anthropogenic influences as well as groundwater flow and transport.

Permo-Triassic sandstones - Beneath the Quaternary sediments are sandstones of the Permian-Triassic Sherwood Sandstone and the Collyhurst Sandstone. The Sherwood Sandstone, is the UK's second most important aquifer and so research is envisaged to characterise controls on groundwater flow and the factors that affect its quality. The Sherwood Sandstone and Collyhurst Sandstone will also be investigated and described as they are potential targets for carbon capture and storage (CCS) in the North Sea and east Irish Sea. The Sherwood Sandstone and Collyhurst Sandstone also suitable rocks for geothermal energy research, specifically low enthalpy heat.

Caprock sedimentary layers - The Manchester Marl is a low permeability Permian age sedimentary rock that is, in some UK locations, the caprock envisaged for proposed exploitation of unconventional hydrocarbon resources. This strata is relatively close to the surface at Ince Marshes, allowing research into the flow characteristics of low permeability layers. The Permo-Triassic overlies mudstone beds of the Carboniferous Halesowen Formation and also the mudstone and siltstone and scattered sandstone beds of the Pennine Coal Measures Group and Millstone Grit Formation, which offer similar research opportunities.

Prospective shale - Beneath the Pennine Coal Measures Group and Millstone Grit Formation are the shales and limestones of the Craven Group, which are a target for shale gas exploration in the north of England. The Cheshire observatory would be used to independently monitor and observe any industrial shale gas exploration activities that took place in the Ince Marches area by observing groundwater quality (temperature, pH, gas content, water level), seismicity, and other possible ground movements. Such data could also provide insights into the response of the subsurface to shale gas extraction, which would be of benefit to planners, local authorities, policy makers, regulators, researchers and the public.

Structural and basin complexity - The Ince Marshes site has an almost geologically unique structural position on a geological structural 'high' between the large East Irish Sea and Cheshire basins (Figure 2). The area is structurally complex, with faults on each side that offer excellent opportunities to study whether these faults are seals, or whether they allow transmission of fluids and gases. In addition, there is the potential for research to investigate the processes that led to fault formation and seismicity. Such structural highs are important when considering buoyant fluids such as CO2, and the management of fluid flow and geomechanics in basins.

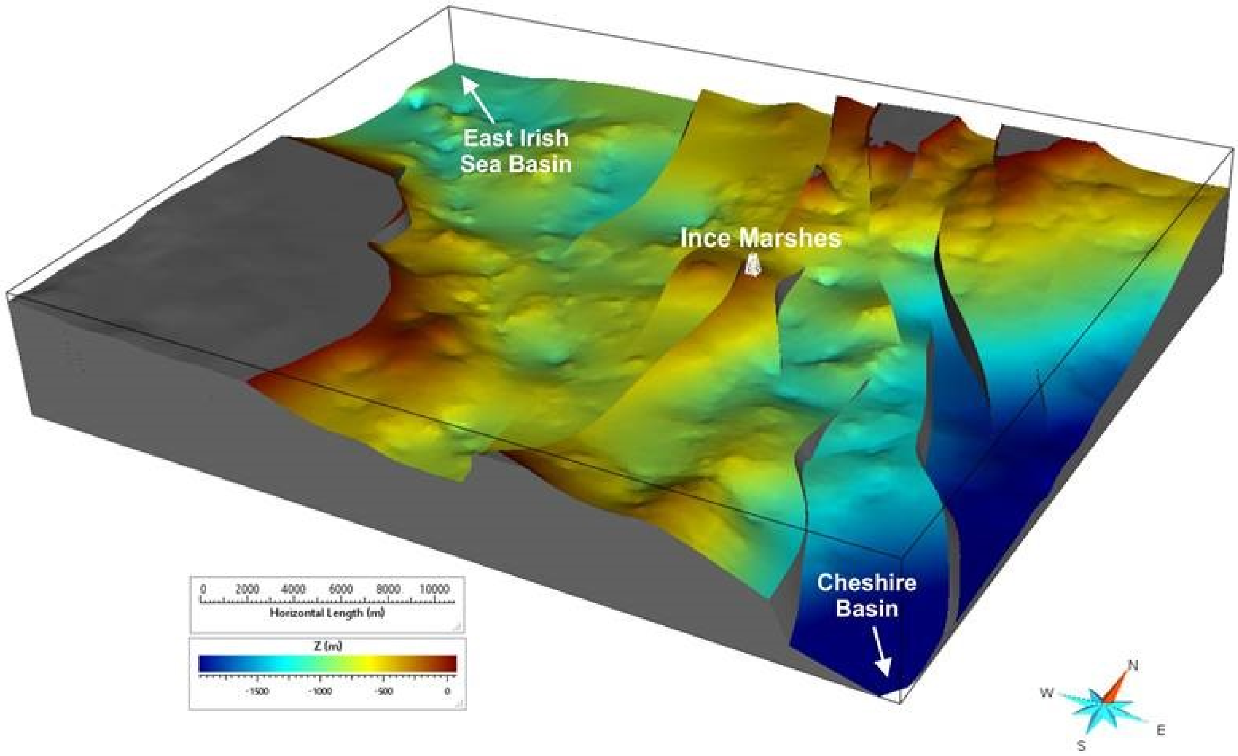

Figure 2 **Ince Marshes, the East Irish Sea and Cheshire basins modelled on the top of the Variscan unconformity. Colour coding indicates depth below surface: yellow is shallow; blue is deep.**

1.3 AVAILABILITY OF HIGH QUALITY GEOSCIENCE DATA

A key rationale for developing the Cheshire Energy Research Field Site (CERFS) is that there is extensive geological data already available for this area. This includes good quality 3D seismic survey data and extensive 2D seismic from the oil and coal industries (available from UKOGL). The geology has been directly sampled by exploration and appraisal wells for coal, coal bed methane, conventional oil and gas, and unconventional gas, including some high quality geophysical log suites. Much of this data is available to view, and some for download, on the BGS website. Such a quality, variety and density of data is available in only a few locations in northern England and this provides an excellent basis for further research at Ince Marshes.

1.4 SCOPE OF THE FACILITY

The Cheshire Energy Research Field Site spans over 20 square kilometres of Cheshire. Its main focus is around 50 purpose-drilled boreholes of between 50 and 1200 metres depth - the total drilled length of all boreholes will exceed 8000 metres. Over 1800 state-of-the-art sensors will be installed that will track seismicity, changes to groundwater flow and quality, temperature and hydraulic properties. These will provide data from the surface to 1200 metres depth and this will be streamed online in real-time allowing wide public observation of Cheshire's subsurface.

Almost 3000 metres of rock core will be sampled from these boreholes and scanned with state-of-the-art core scanners (recently installed at BGS's headquarters in Keyworth) to characterise its physical and geochemical properties. Rock core and scan data will then be made available to the research community for sampling and analysis. In addition, researchers will be able to request samples of core material that have been preserved immediately after recovery for biological, physical and geochemical analyses. All project data will made available online free of charge after any required quality checks have been completed.

From 2020 the Cheshire Energy Research Field Site will be open to researchers for field experiments. Researchers will have access to both the borehole arrays and data from £2m worth of installed instrumentation. They will also be able to deploy their own equipment. The vision is to encourage international scientists to focus their research efforts in this area by creating a volume of rock characterised to the highest standards. This will support world-leading science, creating a step-change in geological and process understanding.

BGS will provide access to scientific facilities at the Cheshire observatory. It is also envisaged that laboratory and welfare facilities, including a restaurant, will be available as workspaces at the nearby Thornton Science Park. At BGS Keyworth there will be the opportunity to sample and analyse core material and work with the new core scanning laboratory.

Finally, an innovative web portal is being developed to meet the needs of the public and the research community. This will include a state-of-the-art interactive 3D geological model to visualise the research facility and showcase the power of the data being generated to support scientific understanding. The portal will also provide access to an extensive archive of data from the installation and operational phases.

Figure 3 View over Ince Marshes. Image © Peter Cocoran

2 Geological and Hydrogeological Context

2.1 SITE LOCATION

2.1.1 Current Land Use and Made ground

Much of the area is artificially drained reclaimed land, close to the River Mersey and the Manchester Ship Canal. The area is flat, much of it is only slightly above sea-level, less 10 metres OD), reaching around 26 mOD in the Ince–Elton area.

The area includes large areas of present and historic industrial development, agriculture, transport infrastructure, urbanisation and residential development. Potential sources of anthropogenic groundwater contamination include the Stanlow oil refinery and historic landfill sites (neither of these will be sampled directly by CERFS drilling).

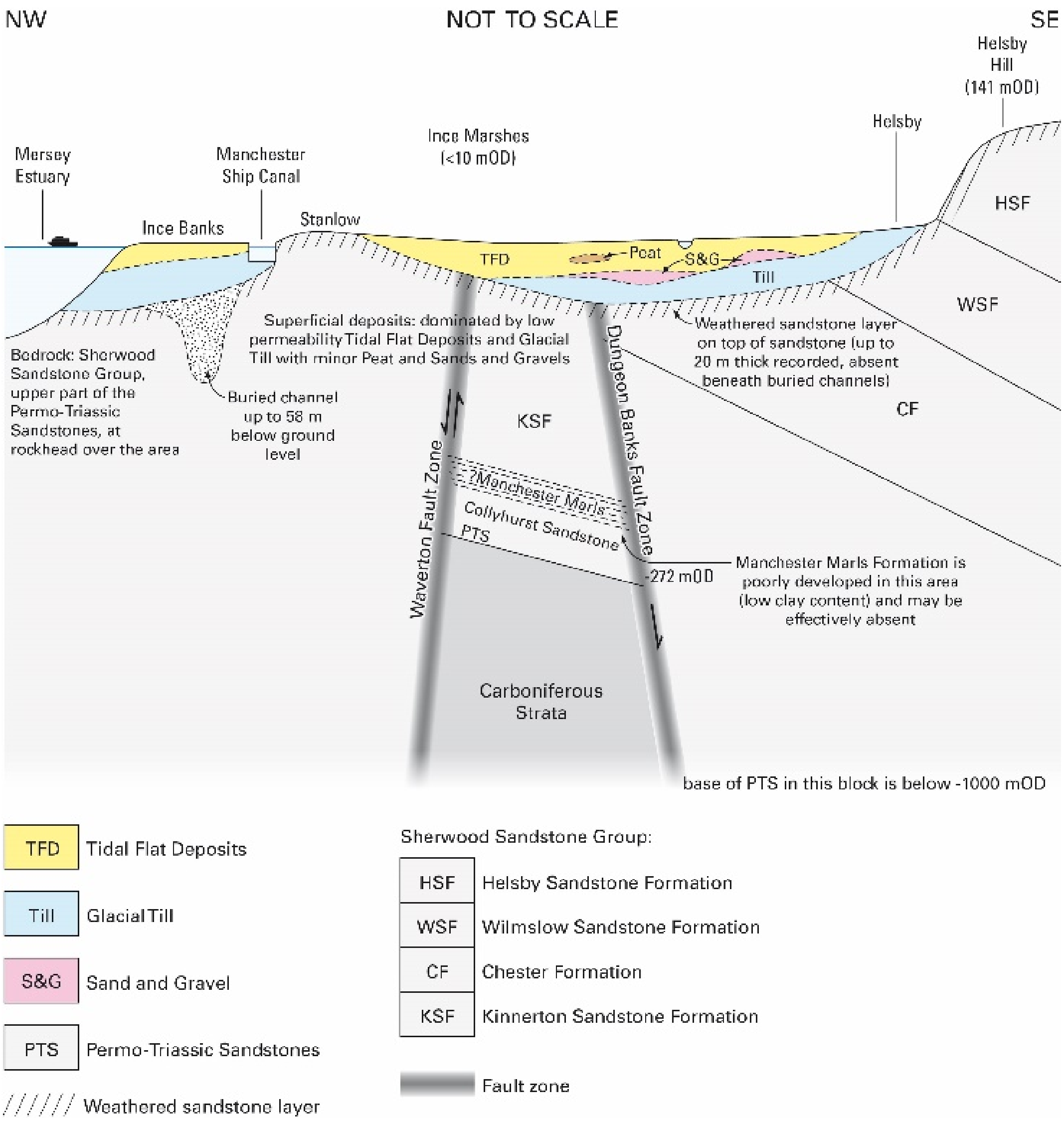

Figure 4 A diagrammatic cross-section of the geology of the Ince Marshes area including, anthropogenic, superficial, and bedrock geology

2.2 QUATERNARY GEOLOGY

The research site is located on estuarine marshes and tidal flats on the southern bank of the Mersey estuary. It is covered by Quaternary-age superficial deposits of variable thickness up to 60 metres deep, although these are absent beneath parts of Ince and Elton. The upper surface of the bedrock was deeply incised during the Quaternary, with thicker accumulations of alluvium deposits infilling a series of broadly north-trending buried channels. These follow the modern north-flowing tributaries of the River Mersey - the River Gowy and Mill Brook to the west and the Hornsmill/ Peckmill Brook to the east. The extent at depth of these channels is very difficult to prove without drilling as they are hard or impossible to distinguish using surface geophysical techniques. The Quaternary sequence typically comprises unconsolidated sand, silt and clay and may include lenses of peat or organic-rich muds. Peat and blown sand are also present.

The Quaternary deposits overlie a complex sequence of glacial deposits principally comprising till (boulder clay), with lenses of glacio-fluvial sand and gravel and glacio-lacustrine clay. The glacial deposits are complex, varying laterally and vertically across short distances, making geological interpretation difficult in areas where borehole data are sparse or absent.

Permo-Triassic sandstones are present at rockhead over most of the area, with a thick, weathered zone reaching a maximum thickness of at least 20 metres.

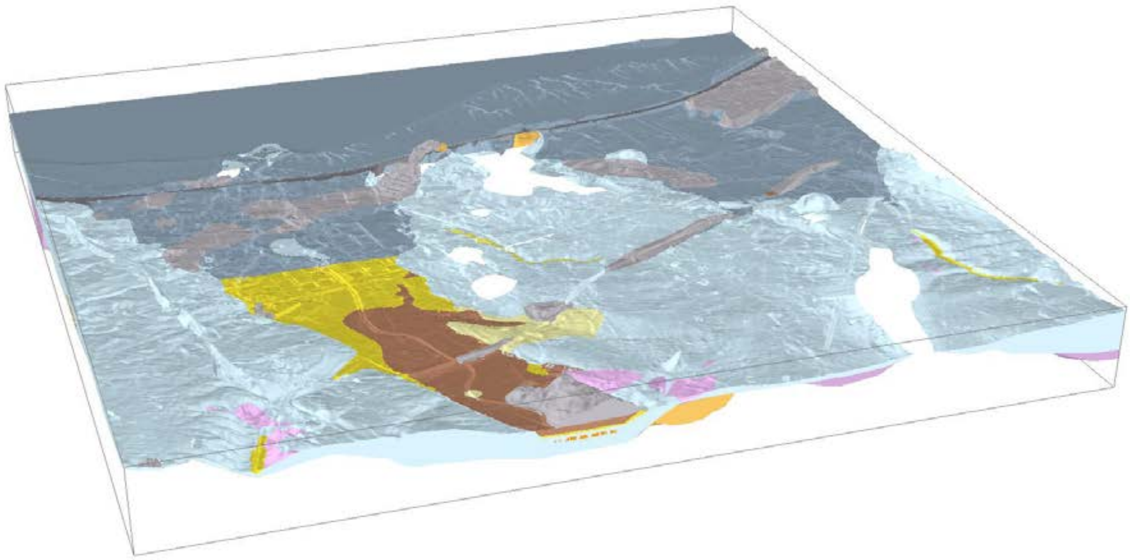

Figure 5 Lithoframe viewer model of the Quaternary deposits in the area around Ince Marshes

Further information is available in Burke et al (2016); Lee and Hough (2017) and the BGS Quaternary 3D model.

2.2.1 Hydrogeology of the superficial deposits

The variable composition and thickness of the Quaternary superficial deposits affects the hydrogeological regime, with low permeability tidal-flats and glacial till dominating because of their lateral extent. These deposits are expected to be saturated within a few metres of the ground surface, with the water level being strongly influenced by human induced drainage. More permeable deposits, such as glaciofluvial sands and gravels, tend to be present in lenses of limited lateral extent and surrounded by lower-permeability deposits, which limit recharge or discharge. Therefore natural groundwater flow will be minimal within the superficial deposits, with the exception of buried channels. Buried channels are up to tens of metres deep and occasionally up to hundreds of metres wide, infilled with glacial deposits comprising mainly sands, gravels, clays and silts. Depending on the composition of the infill, these may influence groundwater flow in the area.

2.3 BEDROCK AND STRUCTURAL SETTING

The Cheshire Energy Research Field Site is located on the northern margin of the Cheshire Basin. Made ground and a variable thickness of Quaternary deposits unconformably overlay faulted Permo-Triassic sandstone bedrock, which varies in thickness from approximately 250 metres to over 1000 metres. This comprises the Triassic Sherwood Sandstone Group, which is underlain in some locations by the Permian Collyhurst Sandstone Formation and/or the Manchester Marl Formation. Below the Permo-Triassic succession are older Carboniferous strata, with deep boreholes proving sedimentary rocks of the Warwickshire Group, Coal Measures, Millstone Grit and Craven Group at depth.

Analysis of 2D seismic-reflection data indicates that the bedrock structure is characterised by a north-trending horst block that is 1–2 kilometres wide in the Thornton area (Figure 6). The horst is defined by the Waverton fault zone to the west, and the Dungeon Banks fault zone to the east. Evidence from deep boreholes sunk for hydrocarbon exploration gives information on bedrock stratigraphy in the area. The Ince Marshes 1 borehole proves the succession on the horst, while the succession in the graben to the east is proved by the Kemira 1 borehole (Table 1).

Table 1: Stratigraphic depths on the horst and eastern graben

Stratigraphy(depths quoted in metres to base of unit)	Bedrock geology: horst, as proved by the Ince Marshes 1 borehole	Bedrock geology: eastern graben, as proved by the Kemira 1 borehole
Permo-Triassic	272	1042
Carboniferous Warwickshire Group	331	1221
Carboniferous Pennine Coal Measures Group	945	1438 (terminal depth)
Carboniferous Millstone Grit Group	1577 (terminal depth)	Not proved

2.3.1 Sherwood Sandstone Geology

The Sherwood Sandstone Group typically comprises red and grey fine- to medium-grained sandstone with rare pebbles. Deformation bands (zones of grain-size reduction formed in response to stress) are developed locally. The upper part of the bedrock has locally been weathered to an uncemented sand and gravel to a depth of 10 - 20 metres. Further information is available from Hannis and Gent (2017) and Fellgett et al. (2017).

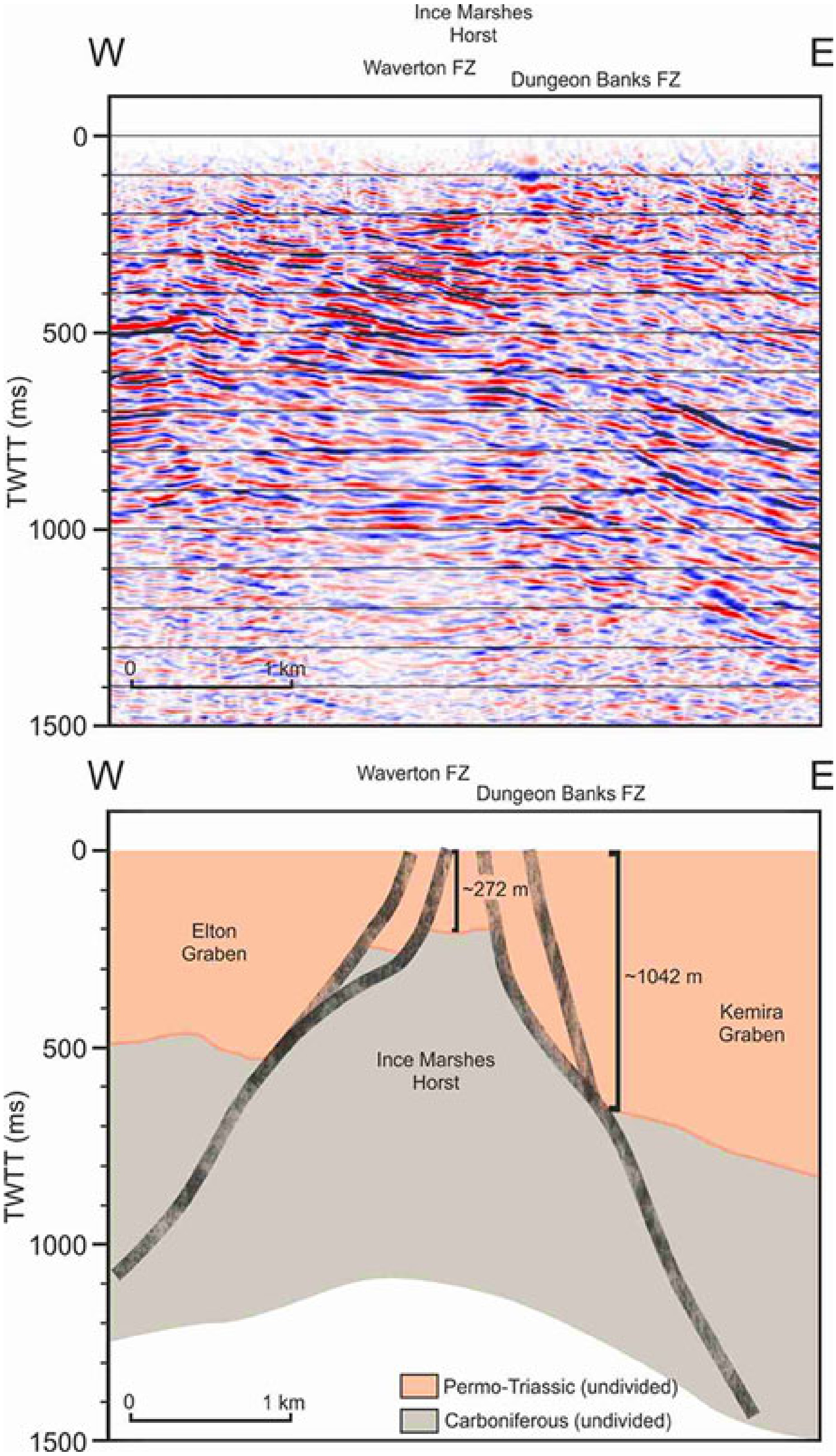

Figure 6 General structure of the Ince Marshes area, based on interpretation of seismic-reflection line SC-83-128V, illustrating the Ince Marshes horst structure defined by the Waverton fault zone to the west and Dungeon Banks fault zone to the east. FZ = fault zone. (Seismic data courtesy of UKOGL).

2.4 HYDROGEOLOGY OF THE BEDROCK

The Sherwood Sandstone Group is a principal aquifer. Groundwater abstraction is important in this region for public water supply, for example at Plemstall 5 kilometres south of Elton, and also industry and agriculture. A key feature of this aquifer is slow response to change, with observation wells showing a damped response to recharge and abstraction. Groundwater levels have been modified over time by large abstractions

The Permo-Triassic sandstones have moderate matrix permeability with fractures providing secondary permeability. The hydraulic conductivity is highly anisotropic, with considerably higher horizontal hydraulic conductivity than vertical, due mainly to the presence of marl horizons within the sandstones. Bulk permeability declines with increasing depth and salinity increases; thus the effective aquifer is considered to be about 200 metres thick. The aquifer has high storativity, which accounts for its slow response to perturbations (e.g. abstraction) compared to other UK aquifers.

The regional groundwater head gradient suggests flow in a west to north-west direction from the main recharge area in the east (the higher ground of the Mid-Cheshire Ridge) towards Ince Marshes and the Mersey Estuary. Faulting can affect the Permo-Triassic sandstone aquifer and groundwater flow in a range of ways, with faults sometimes acting as barriers to flow, or having a high permeability forming a preferential flow path. These are documented regionally, but the behaviour of the groundwater flow in the vicinity of the faults near the proposed site is not known.

The Sherwood Sandstone aquifer is mostly confined by low-permeability superficial deposits and the piezometric surface is above the top of the sandstone but below ground level. The hydraulic gradient is very low, and groundwater flow is expected to be very slow. A schematic cross section from the area is shown in Figure 7.

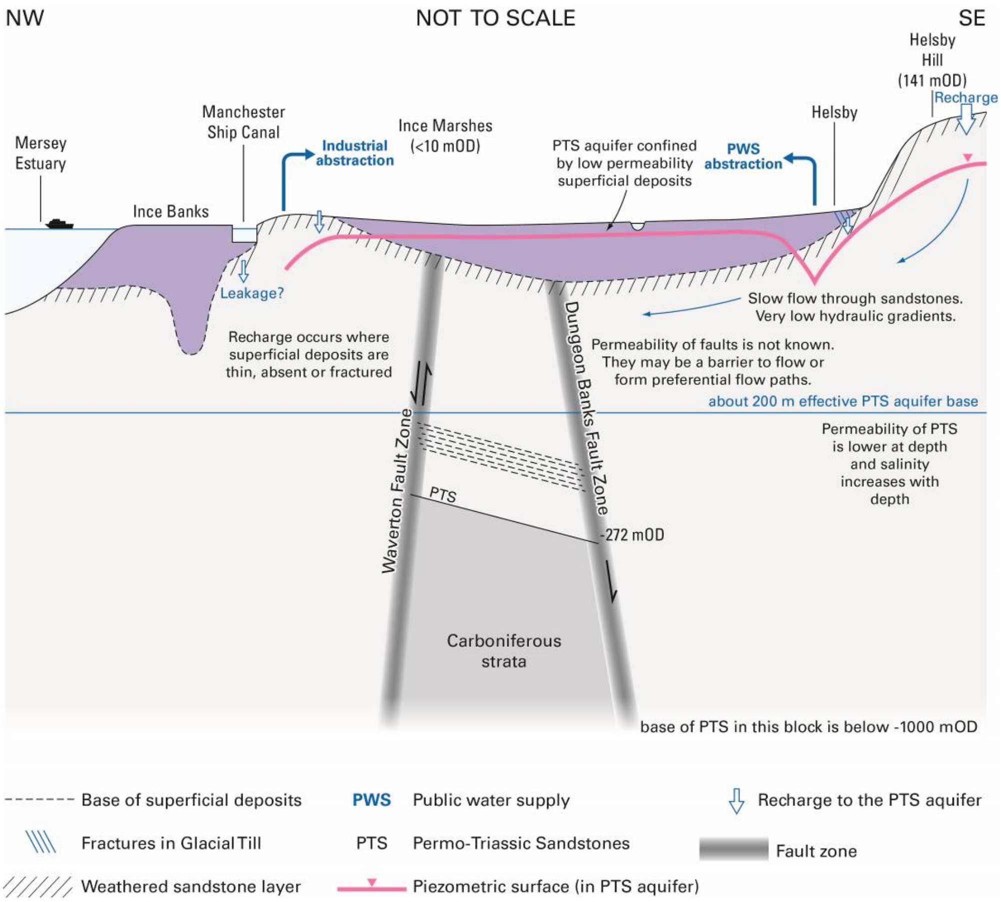

Figure 7 Schematic cross-section identifying key hydrogeological features of the Permo-Triassic sandstone aquifer in the Ince Marshes area.

2.5 HYDROCHEMISTRY

The natural hydrochemistry of the Sherwood Sandstone aquifer, where measured, is dominated by natural salts, and gives an insight into geological processes.

The Sherwood Sandstone aquifer regionally has zoned salinity; saline palaeo-waters are found at depth with fresh waters at the surface. Saline palaeo-waters are thought to result from halite dissolution and ponding of the resulting saline water during an interglacial (55,000 to 50,000 years ago). The saline water was then pushed to depth due to sea-level fall and refreezing of the ground.

Past and present land use have had considerable effects on the groundwater chemistry. Inundation by abstraction-related marine salinity is seen close to the Mersey Estuary within the upper aquifer, especially around the Stanlow oil refinery. A similar zonation is expected for the redox conditions of the aquifer and associated redox-sensitive hydrochemical parameters. Waters close to the surface are found to be oxic, with low concentrations of dissolved redox-sensitive ions such as iron and manganese, however, deeper groundwaters are reducing with high iron and manganese. The depth of the zones will be variable within the different areas. Faulting will affect zonation with low-permeability faults restricting water movement; this may result in saline palaeo-waters being trapped within faulted blocks.

The historical and recent industrial activity in the area is a significant source of contamination of groundwater in the made ground, superficial deposits and the sandstone. Historical landfill sites used by industry including the refinery and the former Ince power station were often unlined and represent possible point sources of contamination. Run-off and effluent from historical industrial activity along the Mersey's banks flowed into the Mersey Estuary and the Manchester Ship Canal. Although the water quality within the estuary and canal's surface waters has improved, their sediments are still highly contaminated and are a potential source of contamination of surface water and groundwaters, especially where dredged material has been deposited locally on the land surface.

Nitrate contamination is also a widespread issue within the Permo-Triassic sandstone aquifer. This is believed to be mostly agricultural in origin but leaking sewers may also contribute.

For more information on the hydrochemistry of the area see Griffiths et al, 2002.

3 Research infrastructure

3.1 OVERVIEW OF SCIENCE INFRASTRUCTURE

The Cheshire Energy Research Field Site research infrastructure will comprise of four borehole-based experimental facilities, or arrays, where science can be undertaken:

- Array 1 Groundwater baseline
- Array 2 Seismic Baseline
- Array 3 Deep well
- Array 4 Multiscale array

The infrastructure also includes the following science installations:

- Ground motion sensors
- Air quality monitoring station

Sections 3.2 to 3.5 provide an overview of the infrastructure and instrumentation available for science with a summary of the information for each array available in the document annexes.

3.2 ARRAY 1 GROUNDWATER BASELINE

3.2.1 Overview

Array 1 provides groundwater baseline data allowing researchers to study and understand the regional groundwater regime. The array and its associated monitoring will allow scientists to consider the temporal and spatial variability across the study area. The aim of the array is to:

- Improve scientific understanding of the subsurface and near-surface environment
- Provide the public with easily accessible and understandable evidence and information on aquifer conditions
- Establish a long-term archive of baseline groundwater data to monitor environmental change resulting directly or indirectly from anthropogenic influences
- Facilitate the development of new sensor technologies for environmental monitoring.

3.2.2 Locations

The groundwater baseline array comprises clusters of boreholes at nine locations across the facility area, which measures some 4 by 5 kilometres. Three locations are to the west of the Dungeon Banks Fault, three are on the horst block and three are to the east of the Waverton Fault. This distribution of boreholes is designed to allow groundwater flow and geochemistry to be studied within and between each fault block.

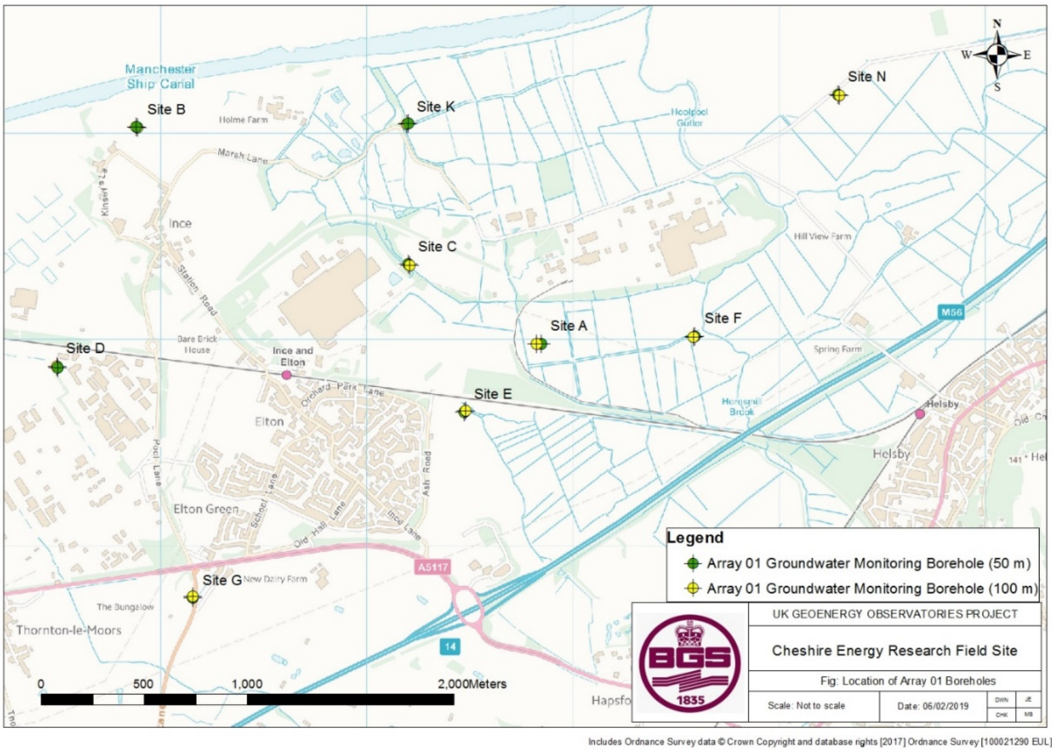

Figure 8 Array 1 Groundwater baseline monitoring locations. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved 2019. Ordnance Survey [100021290 EUL].Created using ArcGIS. Copyright © Esri. All rights reserved.

3.2.3 Infrastructure

All groundwater boreholes are anticipated to penetrate through the Quaternary deposits and terminate in the Sherwood Sandstone. At each of the nine locations there will be a pair of groundwater boreholes screened at different depths within the Sherwood Sandstone. One borehole will be 50 metres deep, have a minimum diameter of 216 mm and a 6 metre screened interval near its base. The other will be 100 metres deep, have a minimum diameter of 216 mm and be cased to ca 50m., with the lower 50-100m left uncased (formation competence permitting) to provide direct access to the formation for hydraulic testing.

The boreholes are available for the deployment of groundwater equipment and are equipped with a box above the borehole providing anchors, which can be used to hang equipment. Some locations will also be fitted with cabinets where subsurface sensors and data transmitting equipment can be stored.

3.2.4 Scientific instrumentation

All groundwater baseline boreholes have been designed to allow for the installation of scientific instrumentation including, for example:

- Multi-parameter water quality probes
- Pressure transducers
- Submersible sampling and high flow pumps

3.2.5 Scientific data acquisition

CERFS will deliver the following data from the groundwater baseline boreholes:

- Hydraulic head – measured via pressure transducers and manual depth measurements.
- Aquifer properties – a series of hydraulic tests, including pump tests and falling head tests will be undertaken
- Groundwater sampling – a groundwater sampling campaign will collect and analyse samples from the boreholes. Sampling will be undertaken bimonthly until a static baseline is obtained and will continue long-term, though reduce in frequency. Analysis will include on-site measurements of pH, Oxidation Reduction Potential (ORP), dissolved oxygen and electrical conductance.
- Samples will be obtained and analysed for: major ions (ion chromatography), a broad suite of trace elements (ICP-MS), dissolved organic carbon (TOC analyser), stable isotopes of water (δ18O, δ2H), TDIC, stable isotopes of methane (δ13C, δ2H), dissolved gases (CH4, CO2, O2, radon, noble gases), organic compounds (GC-MS/LC-MS), groundwater 'age' indicators/ environmental tracers (e.g. CFCs, SF6) and naturally occurring radioactive material (NORM; uranium and thorium decay series).
- Continuously monitored groundwater parameters – A subset of the groundwater boreholes will be equipped with sensor probes that monitor groundwater quality and head at 15 minute intervals. Groundwater parameters measured by these probes may include electrical conductivity, methane, BTEX, PAHs, temperature and barometric pressure. At selected locations this data will be telemetered from the site in real-time and be available via the online data portal.
- Geological core data
- Geophysical borehole logging
- All data collected at the site will be made available openly to researchers, including future data produced by the science community.

3.2.6 Intended Sampling regime

Full operational details including frequency of sampling have yet to be finalised, details of intended analytical proposals are incorporated in Appendix 3A as guidance though are subject to revision.

Sampling programmes will typically be undertaken at an initial monthly interval, moving over time to a quarterly cycle with each sampling campaign taking approximately 1 week to complete.

3.3 ARRAY 2 SEISMIC

3.3.1 Overview

Array 2 provides a seismic monitoring network that will improve understanding of the seismic activity within the Cheshire Energy Research Field Site area. The data will form the natural baseline against which future seismic activity will be compared and contrasted. The network will be one of the highest resolution seismic monitoring arrays in the world. It aims to detect earthquakes of -0.6 to -1.0 magnitude - this type of quake is 1000 times smaller than a quake someone is likely to feel.

3.3.2 Locations

The baseline seismic monitoring array comprises instrumentation at ten locations and at an average spacing of 1 kilometre, across an area measuring approximately 4 by 4 kilometres. The area is centred on the defining geological structure of the area and is designed for optimal detection of seismicity on the two main faults. The seismic boreholes are anticipated to penetrate through the Quaternary deposits and terminate in the Sherwood Sandstone Group.

Due to local infrastructure including windfarms, motorways, railways and factories that produce background noise, the seismic monitoring network will be installed in boreholes at a depth of at least 200 metres to reduce the impact of ambient noise on the seismic response.

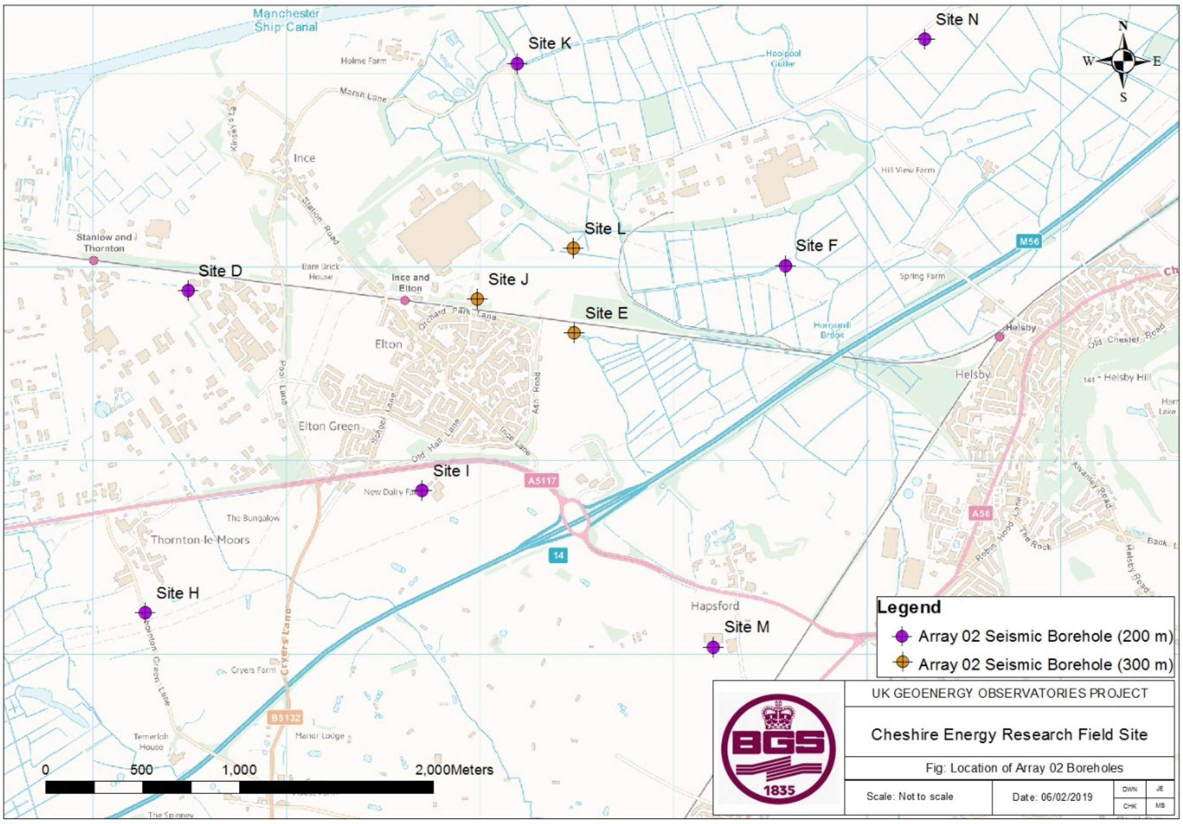

Figure 9 Array 2 Seismic baseline monitoring locations. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved 2019. Ordnance Survey [100021290 EUL]. Created using ArcGIS. Copyright © Esri. All rights reserved.

3.3.3 Infrastructure

The 10 boreholes of Array 2 are as follows:

- Three boreholes to a depth of 300 metres. These are equipped with two seismometers, one at 300 metres and one at 200 metres. Up to three 300 metre deep boreholes will also be equipped with acoustic fibre optic from surface to total depth.
- Seven boreholes to a depth of 200 metres. These are equipped with one seismometer each.

Note: A further seismometer (part of Array 3) will be installed in a 1200 metre borehole of terminating in the Millstone Grit Group.

3.3.4 Scientific instrumentation

The seismometers are Guralp Radian broadband seismometers that record 3-component acceleration data at 1000 Hz, with a sensitivity of 3000 V/m/s. The seismometers are lowered into the boreholes via a cable and are backfilled with sand, or mechanically held against the borehole wall with a clamp to ensure that the instrument has a good connection with the rock mass. The seismic data are logged at the surface and telemetered in real-time to the online data portal.

In the seismic boreholes fibre optic cable will be installed (as well as in other arrays). This is a leading edge technology that enables seismic data to be collected by firing a laser beam through the fibre optic cable and monitoring the backscattered light returned.

To protect the expensive seismic instrumentation and in particular the fibre optic cables, these boreholes will not generally be available for the deployment of other scientific equipment.

3.3.5 Scientific data acquisition

The following data will be available from the seismic array:

- Continuous seismographs
- Geophysical borehole logging
- Geological core and cuttings

All data collected at the site will be made openly available to researchers, including data generated by the science community from information provided by this array.

3.4 ARRAY 3 DEEP WELL

3.4.1 Overview

Array 3 comprises a single 1200 metre deep borehole. It will characterise the broad geological succession including Permo-Triassic sandstones overlying Carboniferous Warwickshire Group, Pennine Coal Measures Group, terminating in the strata of the Millstone Grit Group. The borehole trajectory is expected to cross-cut a major fault and so there is uncertainty with regard to the exact sequence of geological units that will be encountered during drilling. Collectively these rocks represent potential barriers to vertical fluid flow, which is an important consideration in the development of subsurface energy resources such as coal bed methane (currently extracted 20 kilometres away near Warrington).

The Array 3 borehole will terminate in the Carboniferous Millstone Grit at 1200 metres and have a diameter of between 100 and 150 mm. The borehole will be cored either from the surface or ca. 550 metres (dependent on the drilling technology) to terminal depth and will be cased throughout the Permo-Triassic succession. Where cased, the borehole will be completed with fibre optic cable installed behind the casing for high resolution measurement of temperature and vibration.

3.4.2 Locations

There will be one deep well located near to the centre of the study area at the location of the main array (where Array 4 is also located). The exact specification of the surrounding Array 4 wells will be determined by the findings from the Array 3 well, particularly the fault geometry.

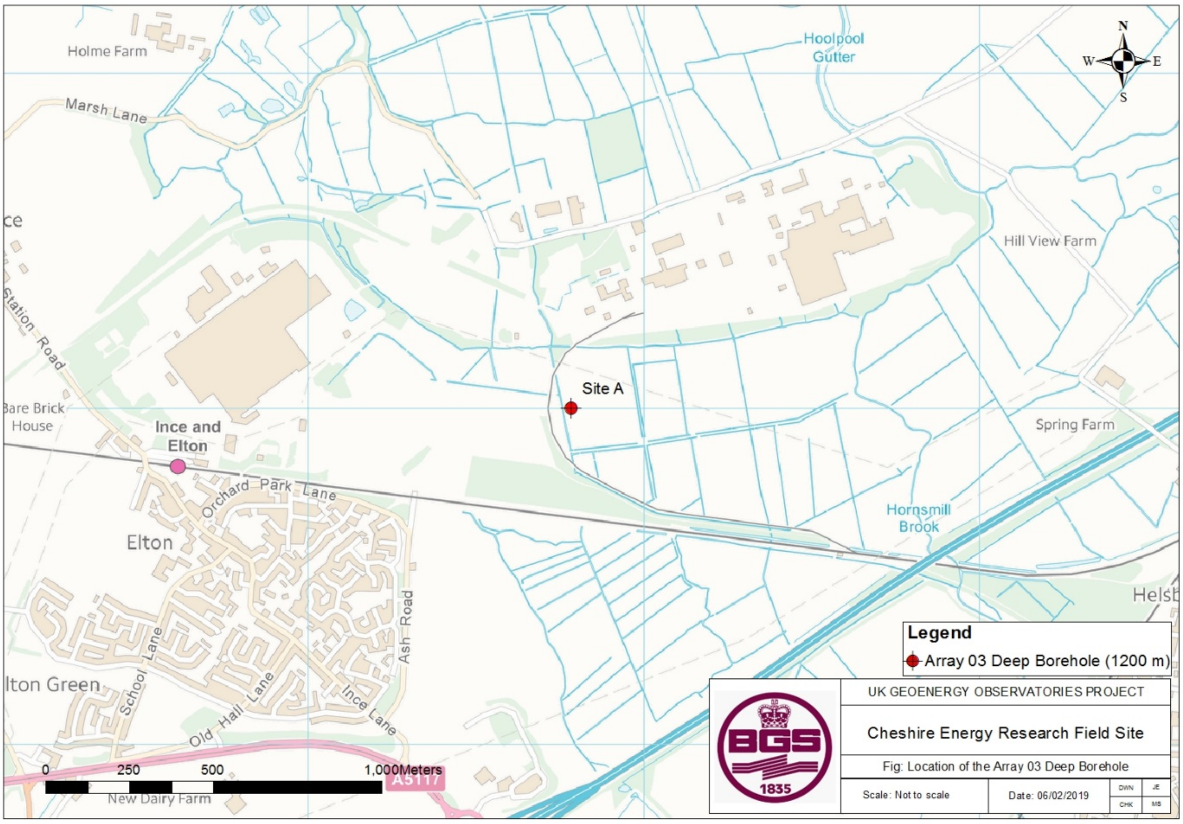

Figure 10 Location of Array 3 Deep borehole. Array 4 is immediately adjacent. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved 2019. Ordnance Survey [100021290 EUL]. Created using ArcGIS. Copyright © Esri. All rights reserved.

3.4.3 Infrastructure

A seismometer will be installed, together with geo-electric cabling and fibre-optic cabling. The borehole will then be back-filled and sealed with engineering cement to avoid the need to maintain such a deep borehole for the duration of the project.

3.4.4 Scientific instrumentation

At the terminal depth of the borehole a Guralp Radian broadband seismometer (the same type as described in Section 3.3.4) will be installed. The seismic data will be logged at the surface and telemetered in real-time to the online data portal.

Fibre optic cable, for use in Distributed Temperature Sensing and Distributed Acoustic Sensing will be installed alongside the borehole casing. The fibre optic cable allows for a continuous temperature profile or seismic activity to be measured along its length.

3.4.5 Scientific data acquisition

The deep borehole will yield the following data:

- Continuous seismographs
- Continuous vertical profiles of temperature and strain along the length of the fibre optic cable.
- Check shot survey
- Flow testing
- Geological core and cuttings
- Geophysical logging (see later)
- Physical and geochemical core scans (see later)
- Geochemical and microbiological characterisation of core material

All data, including core scan data, will be made available to researchers, including data generated by the science community from information provided by this array.

3.5 ARRAY 4 MULTISCALE ARRAY

3.5.1 Overview

Array 4 is designed to increase scientific understanding of the effects of geological heterogeneity at different scales on subsurface processes. The rock mass will be characterised in detail during the installation phase using the latest core scanning technologies and borehole logging tools. During the operational phase the array will be instrumented to support a range of experimental activities including:

- Hydrogeological characterisation via hydraulic tests (e.g. pumping tests, packer tests, slug tests) and tracer injection experiments (e.g. dilution tests, single-well injection-withdrawal tests, horizontal and vertical dipole tracer tests).
- Geophysical characterisation of formation properties using cross-borehole and surface-borehole 2D and 3D geoelectrical imaging technologies.
- Time-series imaging of fluid processes in the near surface including natural (e.g. near surface infiltration, fresh-saline water interface dynamics etc.) and induced changes (e.g. experimental – pumping/tracer tests).
- Integrated hydrogeological and hydro-geophysical experiments consisting of controlled and continuously monitored perturbations of the natural groundwater flow regime, subsurface temperature and hydrochemical composition of groundwater

3.5.2 Infrastructure

The design of Array 4 can be broken down into the following functional elements:

- **Dungeon Banks deep array**: 3 deep boreholes drilled to ca. 600m (dependent on the encountered geology) along a line perpendicular to the Dungeon Banks fault zone. The casings of these wells will be designed to provide access to the various fault zone structures that may be encountered, to enable their hydrogeological and hydrogeophysical characterisation

- **Thermal/ tomography array**: 20 boreholes drilled to 50 and 100m in the Dungeon Banks fault zone and completed with casing, screen and sensor cables. These will be installed in a grid pattern to support tracer migration experiments in the Sherwood Sandstone. Dependent on the fault zone width and geometry, some of these wells could intersect shallow fault structures.

- o One of the 100m wells in the DB shallow array will be completed for ground source heat research. A U-tube will be installed to permit recirculation of heat exchange fluids together with sensor cables to monitor gradients in subsurface temperature and electrical conductivity. The exact location of this well within the thermal/ tomography array will be decided during the installation phase when the location of the major fault structures has been confirmed. Currently it is anticipated that the well will be near the SE corner of the array to allow any heat migration to be monitored in wells to the north and west (the regional groundwater flow direction being W or NW)

3.5.3 Location

Array 4 will comprise a network of boreholes installed in faulted Permo- Triassic strata at relatively shallow depths (50-100m) and at greater depths (ca. 600m). The wells will be located within a relatively small area (ca. 200x 200m) and close to the 1200m Array 3 borehole to facilitate detailed geological, hydrogeological and hydrogeophysical characterisation of the subsurface (Figure 11).

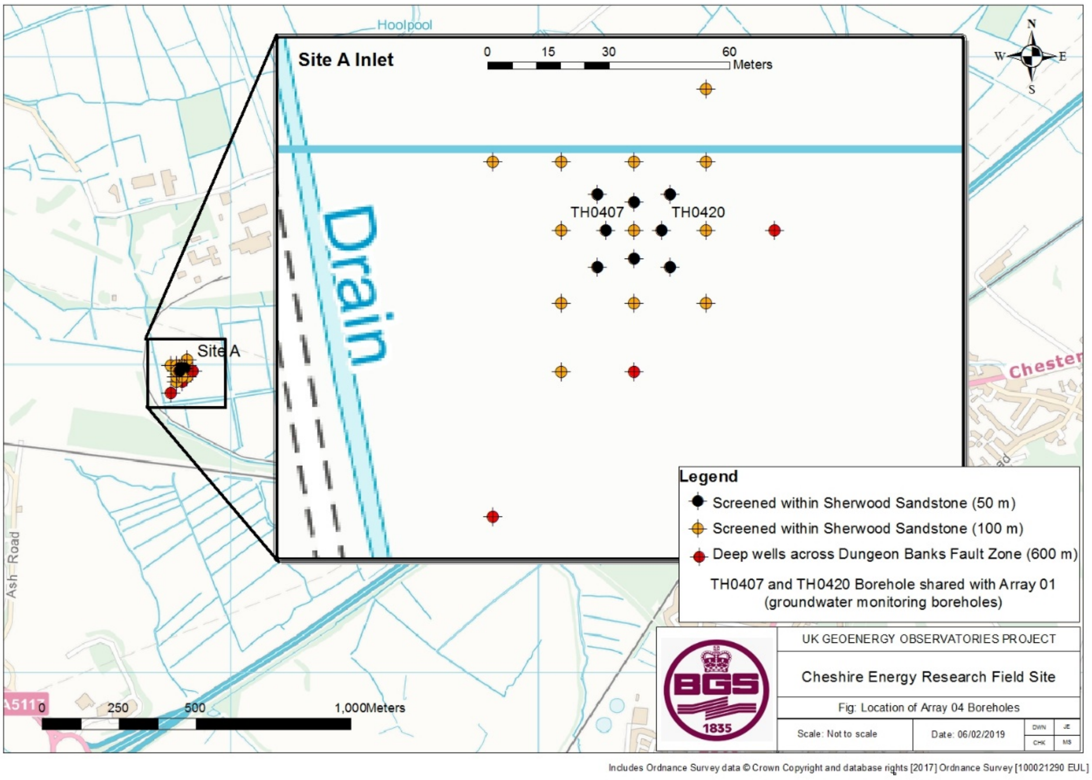

Figure 11 Close up location of Array 4, showing proximity to Array 3. Contains Ordnance Survey data © Crown copyright and database rights. All rights reserved 2019. Ordnance Survey [100021290 EUL] Created using ArcGIS. Copyright © Esri. All rights reserved.

3.5.4 Well designs

All boreholes are anticipated to penetrate the Quaternary deposits and Sherwood Sandstone Group (faulted). The 600 metre boreholes may also penetrate the Collyhurst Sandstone Formation, the Halesowen Formation and the Pennine Coal Measures. The depth of screen sections will be decided during drilling according to the formation properties- in general more permeable horizons will be targeted in view of their importance for aquifer flow and solute transport.

Fibre optic and electro resistivity cables installed into the boreholes will be laid in trenches and connected together in a data centre located at Site A. From this building, computing infrastructure will stream data to scientists working remotely. Scientists will largely be able to control this array and collect data remotely from their desktops.

3.5.4.1 GROUNDWATER MONITORING BOREHOLES IN THERMAL/ TOMOGRAPHY ARRAY

The eleven 100m boreholes will be completed with PVC casing and screen, with multiple screen sections to provide access to the aquifer at different depths. Outside of the casing, the boreholes will be instrumented with max. 80 electro-resistivity tomography sensors and a temperature-sensitive fibre optic cable. These boreholes will be positioned in a regular grid at a spacing of 25m.

The eight 50 m boreholes will be completed with PVC casing and screen, with multiple screen sections to provide access to the aquifer at different depths. Outside of the casing, the boreholes will be instrumented with max. 40 electro-resistivity tomography sensors spaced evenly with depth and a temperature-sensitive fibre optic cable. The boreholes will be positioned in a regular grid at a spacing of 10 m, nested within the 100 metre deep borehole grid

3.5.4.2 GROUND SOURCE HEAT RESEARCH BOREHOLE IN THERMAL/ TOMOGRAPHY ARRAY

A ground source heat research borehole will be installed in Array 4 to support the assessment of low enthalpy geothermal resource and the effect of heat addition and extraction on subsurface conditions. It will be completed as a Thermal Response Test (TRT) well according to a standard industry specification so that can be used by geothermal operators to calibrate equipment and understand the influence of subsurface conditions (e.g. GW flow) on thermal response. The design concept for this TRT well is shown in Figure 12.

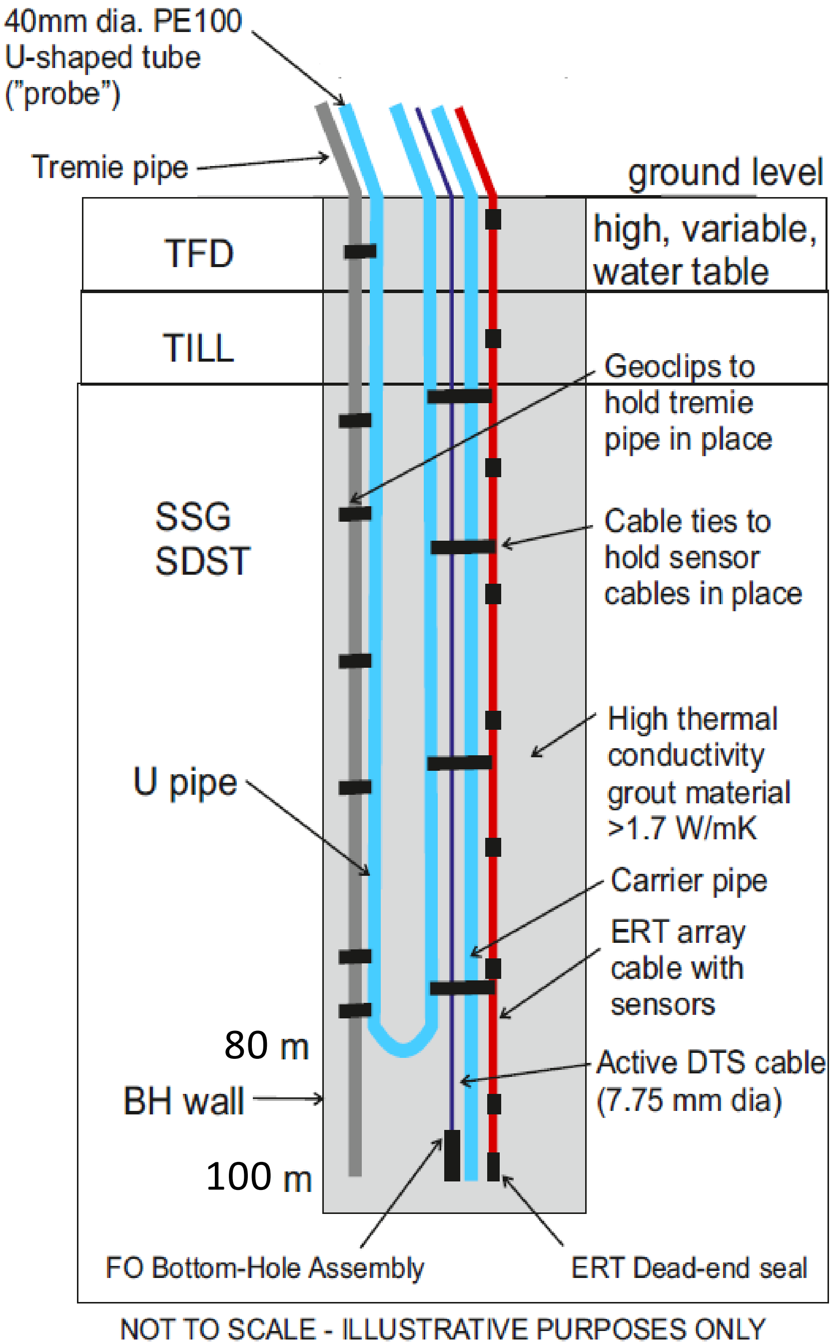

Figure 12: Schematic well design for Thermal Response Test (TRT) well showing positioning of DTS and ERT cables on outside of 40mm diameter PE100 U- shaped tube.

3.5.4.3 3 x ca. 600 metre boreholes in the Dungeon Banks deep array

The three 600m boreholes will be positioned along a line approximately perpendicular to the Dungeon Banks fault at a spacing of 10-50 metres. The two outer boreholes will incorporate an open section to provide direct access to fault structures. The middle borehole will be cased to permit the installation of max. 120 electro-resistivity tomography sensors and a temperature-sensitive fibre optic cable. The 600m well spacing, together with the permanent casing depth, base grout depth and open interval will depend on findings from the drilling of the 1200m Array 3 borehole. The design of the these boreholes, labelled A,B,C on Figure 14, is as follows:

Boreholes A, C

Electrically insulated steel casing will be installed into competent bedrock ca. 50m above the fault structures of interest. The casing will then be cemented into the annulus with DTS and ERT cables installed along the outside. The borehole will then be advanced by rotary coring through the cement plug and underlying fault zone structures to final depth. The borehole will be left open through the fault zone to provide access for research investigations, with a cement seal emplaced from final depth to below the fault zone to prevent any fluid migration from depth

Borehole B

Steel casing will be installed to the shallow competent bedrock. The borehole will then be advanced through underlying fault zone structures to final depth. A second electrically insulated steel casing will then be cemented into the annulus with DTS and ERT cables installed along the outside to final depth.

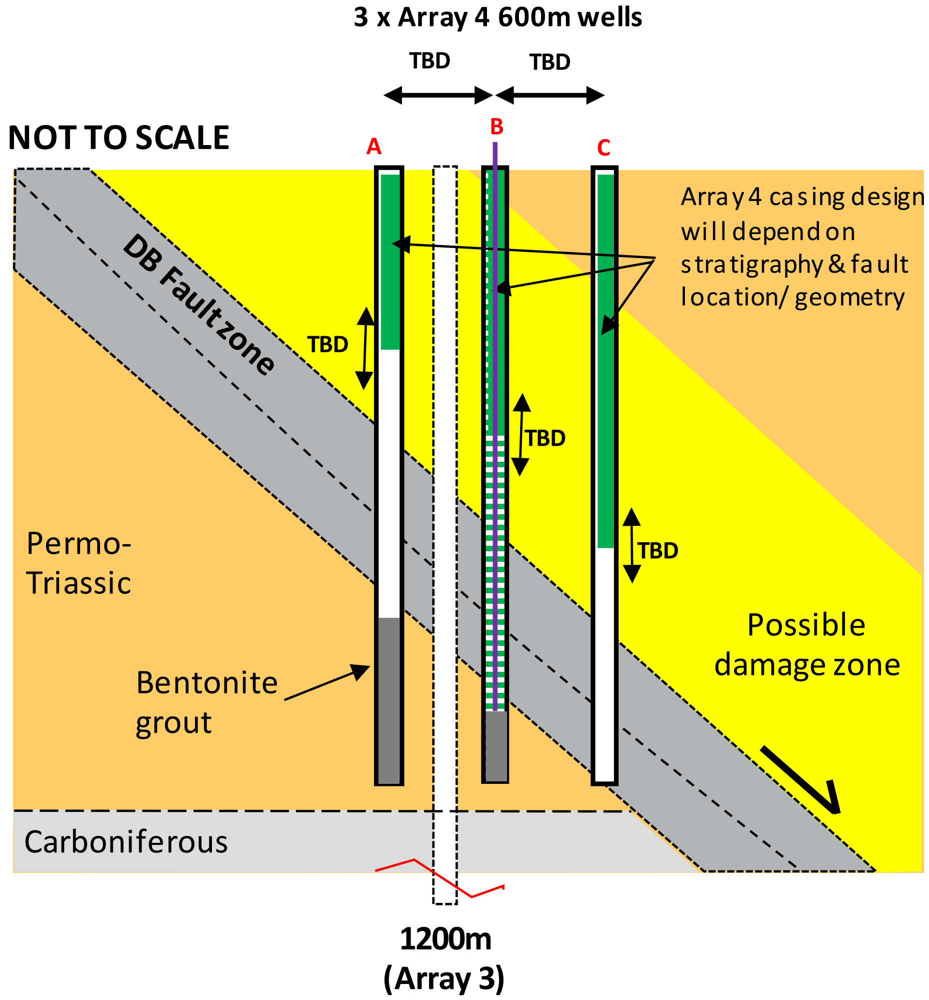

Figure 13. Design concept for 3 x 600m Array 4 boreholes: the middle 600m borehole is installed with a well casing/ screen instrumented with DTS & ERT cables to support online monitoring of fluid flow. Note that the 1200m array 3 borehole is located out of the plane of section

3.5.5 Scientific instrumentation

The Array 4 scientific instrumentation will comprise:

- Electrical Resistivity Tomography (ERT) sensors installed on the outside of the borehole casing, connected to a Proactive Infrastructure Monitoring and Evaluation (PRIME) instrument. The ERT sensors comprise metallic electrodes mounted on multi-core cables, with each cable supporting 40 discrete sensors. The sensors can be used to monitor temporal changes in the 3D distribution of electrical resistivity in the area of the array.
- Fibre optic cables for Distributed Temperature Sensing (DTS) installed on the outside of the borehole casing. Distributed temperature measurements are primarily required for calibration of ERT imaging data. One fibre optic cable will form a continuous loop down all boreholes of the array such that measurements can be made with the same DTS unit.

The array has been designed to allow for flexible deployment of borehole tools and instrumentation including, for example:

- Pressure transducers/loggers to monitor water level
- Submersible pumps, to collect groundwater samples and induce flow
- Multi-parameter groundwater monitoring probes

3.5.6 Scientific data acquisition

The following data types are anticipated from the construction and operation of Array 4:

- Wireline logs of geophysical properties
- Data generated from the logging and analysis of rock core (e.g. permeability, porosity, geochemistry, geomicrobiology)
- 3D resistivity data, which can highlight zones of saturation and be used to track injected tracers. Changes in the resistivity profile can also be monitored over time for 4-D characterisation.
- Formation flow and transport properties from hydraulic and tracer testing
- Time series data on groundwater elevation, temperature, geochemistry and geomicrobiology
- Seismic data
- Gas data

Data collected during array 4 construction and commissioning, including data generated by UKRI funded research projects (as per NERC data management policy), will be made available to the science community via the UKGEOS website.

3.6 GROUND MOTION

3.6.1 Overview

Ground motion monitoring in the Cheshire area is designed to detect the occurrence of any superficial instability (subsidence, uplift or stability) of the target area before, during, and following subsurface activities using Synthetic Aperture Radar (SAR) images, which have been acquired periodically since 1995.

The interferometric processing of the available SAR imagery (InSAR) has been designed to provide displacement measurements at different times with millimetre accuracy over an area of approximately 1,100 km^2.Two passive and one active inSAR reflector will be installed.

3.6.2 Infrastructure

To facilitate calibration and accuracy of the ground motion data, two types of radar reflectors will be installed: passive and active. Passive reflectors are large metal reflectors, usually trihedral in shape, with the open end of the reflector typically orientated towards the satellite line-of-sight. They return the back-scattered electromagnetic radiation, transmitted from the passing satellite, through a double bounce scattering reflection. Active reflectors provide a stronger response to an over passing satellite by increasing the amplitude of the received radar signal.

The installed reflectors provide a location where electromagnetic energy from the ground surface is backscattered and observable by satellite to provide the Synthetic Aperture Radar output. This strong scatterer on the terrain, measured through the Radar Cross Section parameter, facilitates the measurement of terrain deformation from SAR imagery especially where land cover lacks good radar scatterers (in this case marshy land).

Figure 144 Passive inSAR reflector

3.6.3 Data availability

The data generated from this facility includes:

- InSAR results of the average ground motion and relative time-series
- Geological interpretation of the InSAR data in order to identify the extent and origin of any possible ground movement.

All data collected at the site will be made available to researchers, including future data produced by the science community that may utilise this array.

3.7 AIR QUALITY

Air quality monitoring will be undertaken during facility operation, however at the time of writing details of the planned monitoring infrastructure are not yet available beyond the summary provided in Table 2. Air quality monitoring data will be made available to researchers, including data subsequently generated by the science community from information provided.

Table 2: Analytical outputs from air monitoring programme

Proposed Instrumentation	Analytical Measurements
Teledyne UP200 NOx analyzer	Nitrogen Oxides
Thermo Scientific Model 49i Ozone Analyzer	Ozone
Fidas 200 particulate matter monitoring system	Particulates
Thermo Scientific Model 450i Hydrogen Sulfide and Sulfur Dioxide Analyzer	Hydrogen Sulphide
To be confirmed	Methane / CO_2
Anemometer	Wind speed
Met station	Weather conditions

4 Physical sample collection and related data acquisition

4.1 OVERVIEW

It is envisaged that a large amount of physical samples and data will be collected during drilling and immediately post drilling. This section reviews the types of samples and data that will be acquired by the UKGEOS programme. Under the terms of the NERC data policy all samples and data that derived from them must be archived within the relevant data repository. The NERC National Geoscience Data Centres (NGDC) and Nation Geological Repository are the designated data centres for deposition of earth science digital data, and physical samples respectively. Both facilities are located at the British Geological Survey at Keyworth.

The data policy states that publicly funded data must be made openly available. However the policy allows of a moratorium period with unique access for scientists to undertake their research of up to 2 years post acquisition to complete research. After that moratorium period all samples and derived data will be openly available to all scientists. All digital data will be added to the UKGEOS website; data portal as fast as is proactively possible. Digital object identifiers (DOIs) will be issued to some of the data to allow for the tracking of outputs. Scientists that are free to publish this research but this must be on a journal which complies with the UK's open-access publication rules. Thereafter materials and the data therefrom will be available to all researchers who wish to undertake research relating to UKGEOS.

4.2 DRILLING DATA

During drilling, a wide range of operational data will be collected which will vary between arrays. A maximal set may include: driller's logs, leak-off test, drilling parameters, drill fluid logging and when complete, a well deviation survey.

4.3 CORE MATERIAL

Core material will be the primary resource for characterising the geology across the study area. The focus on core recovery is acquiring representative core from all encountered stratigraphic sections. This will include: the Quaternary, Permo-Triassic sandstones and underlying Carboniferous succession. The expected stratigraphy of the Carboniferous section consists of: the Warwickshire Group, Pennine Coal Measures Group and Millstone Grit Group.

In total, core will be retrieved from:

- Array 1 - 5 x 100 metres deep boreholes
- Array 2 - 4 x 200 metres deep boreholes
- Array 3 - 1 x 1200 metres deep borehole
- Array 4 - 1 x 600 metres borehole (includes core taken directly through the fault zone) and 3 x 100 metres boreholes.

The core will be sampled for microbiological analysis on site and then returned to BGS Keyworth. To facilitate biological sampling, tracers will be added to drilling fluid to assess contamination of samples. Fluorescent microspheres or other chemical tracers will be used for the assessment of infiltration of drill mud into the sample core.

The core will be logged for lithology and fractures, and described and interpreted. This will provide detailed insight into the stratigraphic evolution of the area and the depositional environments resulting in the lithologies and fluids represented in the subsurface.

Where possible, core will be scanned using the full suite of core scanning equipment documented in the annex below. Physical core will be analysed for a wide range of microbiological, geochemical and geomechanical properties. The core will be made available for researchers to undertake further sampling and analysis. All data will be available openly.

The core material will be stored in the NGR, where it will be available through normal procedures for researchers to view and undertake further sampling/ research.

The core acquired while drilling the infrastructure is the primary dataset for the first stage of the project. The only way to directly investigate the subsurface is by analysing core material, and the fluids contained therein, and the only chance to acquire core from these boreholes is during their drilling.

At the Cheshire Energy Research Field Site, the focus is on acquiring representative core from all encountered stratigraphic sections across the footprint of the CERFS site. Many CERFS sites will prove Quaternary successions and although all boreholes prove Permo-Triassic sandstones (which are a principal aquifer in this area), boreholes associated with Site A, including Array 3 and the deeper boreholes in Array 4, will also prove parts of the underlying Carboniferous succession including the Warwickshire Group, Coal Measures and Millstone Grit groups.

The provisional coring plan for bedrock and superficials is detailed in Tables 3 and 4, respectively.

Table 3 Summary of CERFS rock core acquisition

Core Acquisition		
7 x 100m	Groundwater baseline boreholes	Array 1
6 x 200m	Seismic boreholes, plus the upper 50 m of one 300 m deep seismic borehole (for retrieval of Quaternary material only)	Array 2
1 x 1200m	Deep borehole, from 0 - or as close as practicable - to TD	Array 3
1 x 600m	1 x 600m + 2 x deepest 200m	Array 4
3 x 100m	From the multi-scalar array	Array 4
Total rock core	**4000m (planned)**	

Table 4 Summary of CERFS superficials core acquisition

Superficial Core Acquisition		
c. 2 x 24m – to top bedrock	Baseline Groundwater	Array 1
c. 2 x 30m – to top bedrock	Baseline Groundwater	Array 1
c. 2 x 34m – to top bedrock	Baseline Seismic	Array 2
c. 2 x 21m – to top bedrock	Baseline Seismic	Array 2
c. 2 x 21m – to top bedrock	Baseline Groundwater	Array 1
c. 2 x 12m – to top bedrock	Deep well (at Site A)	Array 3
Total superficials core	**284m (planned)**	

Rock core will be processed in Keyworth to generate sedimentological, fracture and engineering logs, which will then be correlated with associated down-hole geophysical logs (including image logs), and geochemical and geophysical data.

4.3.1 Basis of bedrock core acquisition

The core recovery plan has been developed taking into account the need to recover representative material from major structural and stratigraphic features. The stored core will be preserved at the National Geological Repository at BGS Keyworth as a resource for future research.

The stratigraphic range is given by Permo-Trias boreholes TH0401, TH402 and TH403 (i.e. the ca. 600m wells in Array 04) and TH0301, which is prognosed to give the complete stratigraphy in the central part of the site from Permo-Trias to Millstone Grit;

Additional Permo-Trias stratigraphy is given by:

TH0101, TH0212, TH0107, TH0209, TH0216 (Horst block; younging southwards), with information in the Kemira Graben given by TH0104 (Site N) and TH0125 (Site F). TH0128 (Site G), TH0202 (Site K) and TH0116 (Site D) are located in the Elton Graben. TH0122 Site E is located in the central area of borehole arrays, located immediately to the west of the Dungeon Banks Fault Zone.

Structural features within the Dungeon Banks Fault Zone are given by (in addition to TH0403):

TH0405 Site A 100m well, TH0412 (100m well) and TH0415 (100m well). These boreholes give a broadly east-west profile through the lower part of the Dungeon Banks Fault Zone.

Detail on the composition within the Proto-Hornsmill Channel is anticipated to be gained from locations:

TH0104 (Site N), TH0125 (Site F), Site A, TH0122 Site E, TH0216 Site M, which together give a series of data points extending from the offshore to onshore expression of the mapped position of the channel. Other cored locations will give information on the intra-channel high in the area around Holme Farm in the north to Hapsford in the south.

Spatially, the cored boreholes are spread across the entire site, and importantly include provings within both the Kemira and Elton grabens, which are anticipated to inform the deep geological model for these areas of poor near-surface seismic reflection data. The borehole core retrieved will allow the near-surface interpretation of the ground model to be improved, especially in areas where the near-surface seismic imaging is poor. Along with other legacy core material held by BGS, and downhole logs generated by this project and others held by BGS, it is anticipated that it will be possible to identify, to at least Formation level, the near-surface sandstone units within the Sherwood Sandstone Group and older Permo-Triassic sandstones.

4.3.2 Depositional Control

The core will be described and interpreted to provide detailed insight into the stratigraphic evolution of the area and the depositional environments resulting in the lithologies and fluids represented in the subsurface.

4.3.3 Structural control

The core will provide data on the geometry, character and properties of the Dungeon Banks Fault Zone, in the area of Site A specifically, and variations within the shallow Permo-Triassic in general, across the area of investigation.

4.3.4 Geomicrobiology

Microbiological sampling requires a network of boreholes to understand spatial variation and connectivity. Samples will be taken from all horizons, ideally with samples from each horizon including different boreholes to explore spatial variation of microbial communities. Where possible, sampling will be carried out in boreholes fitted with in situ chemical sensors and those with the capability for in- situ perturbation experiments.

4.3.5 Approach to uncored sections in boreholes

For boreholes where core is acquired, a wider range of logging tools will be run to a higher resolution. Where no core is obtained from boreholes basic wireline logs will be obtained from the deepest borehole or one of the deepest boreholes at the site.

Additionally, 50 g of bagged and labelled cuttings will be collected at 1 m intervals of any uncored section of Array 03 or at the request of the BGS geologist / BGS Technical Manager.

Cuttings (50 g of bagged and labelled cuttings) at 1 m intervals will also be collected from Site J (TH0210) and Site L (TH0214), as these sites are not in the coring plan.

4.3.6 Basis of superficials core acquisition.

Sampling locations have been identified that:

- Characterise the Quaternary deposits– to help understand potential flow paths and infiltration paths to bedrock
- Supply material to analyse in order to improve the shallow geophysical and conceptual site models (CSM), allowing geology and physical properties to be correlated and interpolated between boreholes
- Supply material to investigate Carbon-cycling in the near surface
- Supply material to analyse Palaeoenvironmental reconstructions
- Supply material to analyse Aromatic hydrocarbons in the near surface – including contaminants in estuarine environments

To satisfy these objectives, six locations for sample retrieval have been identified from CERFS sites A-N. Sites have been identified that are located near to lines of shallow geophysical investigation that was carried out during 2018 (gravity, seismic reflection, passive seismic, ERT).

Unconsolidated material from the Hornsmill Channel will be retrieved from Site F (TH0126) in sealed liners that will be refrigerated at site. Approximately 25 m of samples are anticipated.

Additional sediment core samples will be retrieved from sites A, N, K, L and C. The wells will be cored as twin sets at each location i.e. cored twice in close proximity. One core will be available for destructive testing by the BGS and research associates to generate a digital dataset, with the second twin core retained for future research projects.

In priority order, the following sites have been identified for superficials core collection (Figure 15):

Site A (data may be forthcoming at Site A from geotechnical site investigation): located on western end of south-east shallow geophysical line. Site A is anticipated to prove ~12 m of Tidal Flat deposits/Peat overlying 5 m of Glaciofluvial Sand and Gravel on ~7m Till (24 m Quaternary Deposits in total). This area is on the western end of the shallow geophysical line and core retrieved from this location would allow validation and calibration of derived physical property models and methods, knowledge of the ground conditions and risks (e.g. soft wet ground, running sand, sub-artesian groundwater, surface flooding) at this deep drilling site. This site may also have a borehole heat exchanger installed for thermal response tensing (TRT) and a ground source heat pump (GSHP) for heating the above ground infrastructure. Samples collected from this location will enable engineering geology and physical property testing, including lab thermal conductivity and diffusivity testing, to be performed to improve/confirm the GSHP system design, reduce uncertainty in interpretation of monitoring data (A-DTS, ERT). Coring at this site will add significant scientific value and will enable meaningful parameterisation of thermo-hydrological-mechanical models and conceptual site models that will be developed over the 15-year lifetime of the project.

Site C: located near western end of central west shallow geophysical line (note- Made Ground may be associated with this site). Site C is anticipated to prove ~4 m Made Ground overlying ~3 m Tidal Flat deposits resting on ~5 m Till (~12 m Quaternary Deposits / Made Ground in total). Core sample will enable validation and calibration of the shallow geophysics and improves methods for subsurface attribution.

Site F: located on the eastern end of south-east shallow geophysical line. Site F is anticipated to prove ~9 m of Tidal Flat deposits/Peat resting on ~21 m of Till (~30 m Quaternary Deposits in total). Core sample will enable validation and calibration of the shallow geophysics and improves methods for subsurface attribution. Continuous Dynamic cone penetration test profiles at these sites (off set from the holes by 2-3 m) would also be useful to characterise the strength/stiffness profile of the ground.

Site K: located on the western end of northern shallow geophysical line. Site K is anticipated to prove ~11 m Tidal Flat deposits resting on ~10 m Till (~21 m Quaternary Deposits in total). Core sample will enable validation and calibration of the shallow geophysics and improves methods for subsurface attribution.

Site L: located on western end of south-west shallow geophysical line (note- Made Ground may be associated with this site). Site L is anticipated to prove ~4 m Made Ground overlying ~8 m Tidal Flat deposits resting on ~~9 m Till (21 m Quaternary Deposits / Made Ground in total). Core sample will enable validation and calibration of the shallow geophysics and improves methods for subsurface attribution.

Site N: located on the eastern end of central east shallow geophysical line. Site N is anticipated to prove ~4 m of Tidal Flat deposits/Peat overlying ~30 m of Till (~34 m Quaternary Deposits in total).

Collectively, sites L-A-F-N give a transect into the estimated position of the proto-Hornsmill buried channel feature and will help define its depth, geometry and infill, and hence its permeability and the groundwater regime.

4.3.7 Target intervals for wireline rock core recovery

The target intervals for CERFS core recovery, together with summary borehole data, are presented in Table 5 below.

Table 5 Details of boreholes for wireline coring

Site	Array	Use	Asset Code	Hole Depth	Cored interval top (m)	Cored interval base (m)	Core acquired (m)	Comments
B	1	Baseline Groundwater	TH0101	100	0	100	100	
C	1	Baseline Groundwater	TH0107	100	0	100	100	
D	1	Baseline Groundwater	TH0116	100	0	100	100	
E	1	Baseline Groundwater	TH0122	100	0	100	100	
F	1	Baseline Groundwater	TH0125	100	0	100	100	
G	2	Baseline Groundwater	TH0128	100	0	100	100	
H	2	Baseline Seismic	TH0202	200	0	200	200	
I	2	Baseline Seismic	TH0209	200	0	200	200	
J	2	Baseline Seismic	TH0210	300	0	0	0	
K	2	Baseline Seismic	TH0212	200	0	200	200	
L	2	Baseline Seismic	TH0214	300	0	~50	~50	
M	2	Baseline Seismic	TH0216	200	0	200	200	
N	1	Baseline Groundwater	TH0104	100	0	100	100	
A	3	Deep Well	TH0301	1200	0	1200	1200	
A	4	Multiscale	TH0401	600	0	600	600	Core interval will be dictated by actual fault geometry
A	4	Multiscale	TH0402	600	400	600	200	Core interval will be dictated by actual fault geometry
A	4	Multiscale	TH0403	600	400	600	200	Core interval will be dictated by actual fault geometry
A	4	Multiscale	TH0405	100	0	100	100	
A	4	Multiscale	TH0412	100	0	100	100	
A	4	Multiscale	TH0415	100	0	100	100	

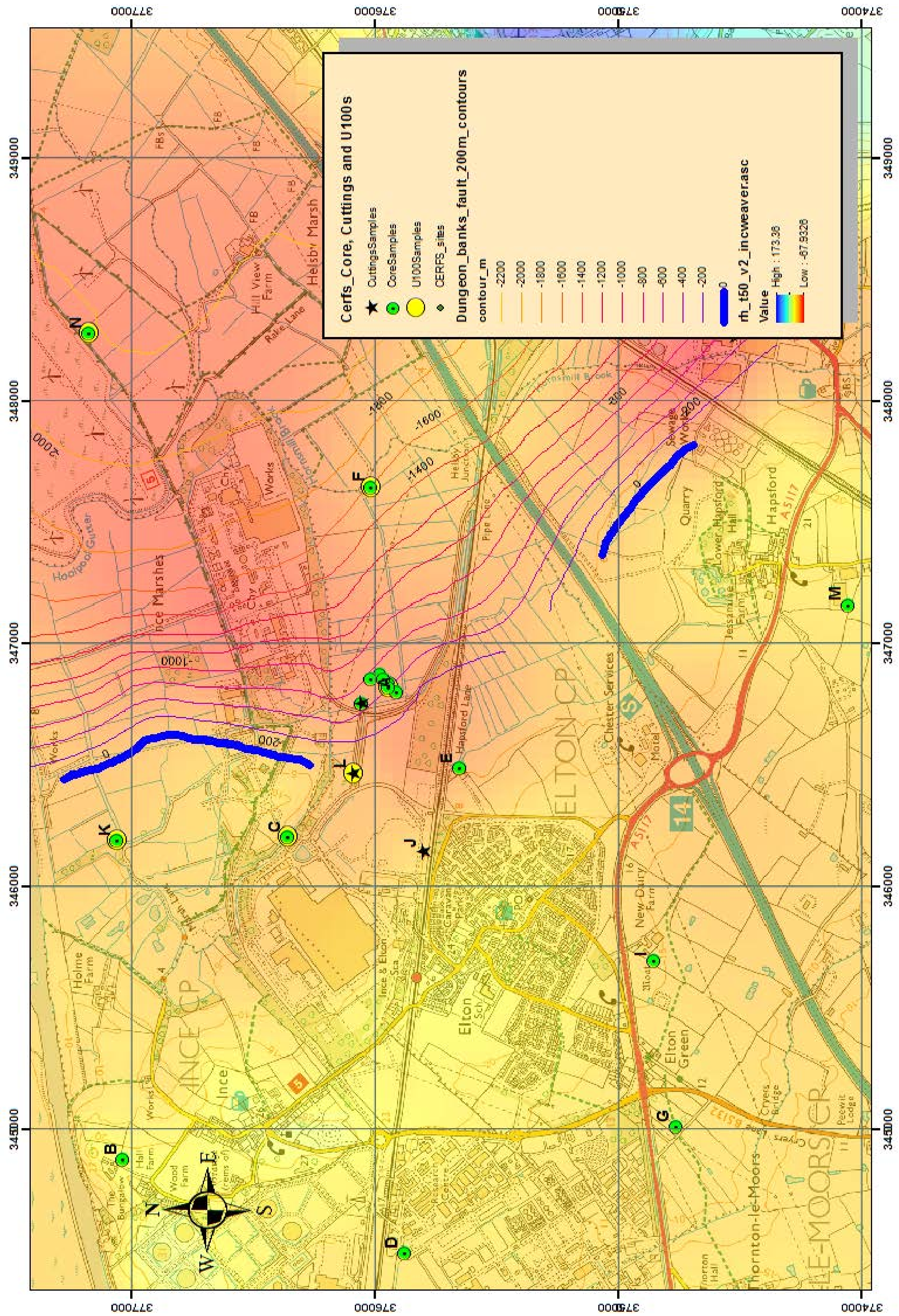

Figure 15 Proposed CERFS coring and sample retrieval locations

4.4 GEOPHYSICAL WIRELINE LOGGING

Geophysical logging will provide a framework for geological modelling of the study area. The geophysical log data will allow cross-hole stratigraphic correlation and thus structural correlation between the cored and drilled boreholes. A suite of geophysical logging techniques will be applied across the study area (outer array), with more detailed logging being undertaken in the deeper boreholes (inner array).

In the outer array, thirteen cased boreholes (3 x 100 metre, 7 x 200 metre and 3 x 300 metre) will be logged with gamma-ray and caliper tools to allow for stratigraphic correlation.

Within the inner array, the 1200 metre and 1 x 600 metre deep wells will be logged using a highly detailed logging suite. Logging tools will include temperature, spectral gamma ray, density/ neutron, Laterolog/ induction resistivity suite, full waveform sonic log and 4-arm caliper. In a small subset of wells borehole imaging tools will be run alongside ultrasonic imaging and cement bond logging. In addition, check shots will be undertaken. The logging programme in these wells will be of sufficiently high quality to facilitate a complete interpretation of this succession.

5 Data portal

5.1 OVERVIEW

The UK Geoenergy Observatories informatics platform ("UKGEOS data portal") will provide the infrastructure necessary to collect, transmit and store data from the field as well as provide researchers with the necessary tools to discover, access and process such data. It will:

- allow data (real-time or otherwise) collected in the field to be streamed back to scientists and/or web portals
- store scientific data in bespoke databases
- facilitate re-use and sharing of scientific data between scientists
- allow for expansion as demand requires (e.g. allowing data from new experiments to be streamed to the portal)
- be supported long-term by BGS data and system management
- provide access to new facilities such as a suite of state-of-the-art core scanners.

5.2 ACCESS TO NEAR REAL-TIME ENVIRONMENTAL BASELINE DATA

The informatics platform will initially be used to transmit near real-time data from environmental monitoring sensors to scientists, businesses and the public through web-based delivery channels. These data will characterise the subsurface around the research facility.

Once research commences, scientists will be able to use this infrastructure to transmit continuous data from their experiments back to the laboratory. Data will be presented publicly via dedicated data portals, providing audience-tailored views including spatial and temporal visualisations as well as search, query and download tools. The portals will be developed in advance of the baseline monitoring taking place so that they can be launched as soon as data streams from the field go live. Links to these new facilities will be published on the BGS website and in other appropriate communication channels.

Appendix 1: Working at UKGEOS

OVERVIEW

The UKGEOS Cheshire Energy Research Field Site is open to researchers from the UK and internationally. It will welcome researchers both from academia and from industry. In addition to the observatory described above, the facility offers a range of welfare and science facilities. These are described below.

WELFARE FACILITIES

Whilst working at the Cheshire Energy Research Field Site, researchers will have access to facilities at Chester University's Thornton Science Park. These facilities include wash facilities, restaurant, office space and connection to the internet and the JANET network.

The site is nearby the villages of Elton and Helsby and to the town of Frodsham. Hotel accommodation is available nearby

SCIENCE FACILITIES

Field site laboratory space

Whilst working at the Cheshire Energy Research Field Site, researchers will have access to laboratory and office space at Thornton Science Park (TSP). The laboratory will be equipped with benches, power and water and will provide space where researchers can undertake sample preparation and analysis and prepare and calibrate instruments and other equipment for the field. Laboratory spaces are available to hire directly from TSP.

Core viewing facilities

Core examination laboratories are available at BGS Keyworth.

Appendix 2: Core scanning facilities

A new, state-of the art, core scanning facility funded by the UK Geoenergy Observatories programme is available as part of the National Geological Repository (NGR) at Keyworth, Nottingham, UK. The NGR Core Scanning Facility hosts several high-resolution core scanners that allow whole, split, or slabbed rock and sediment cores to be, continuously and non-destructively, scanned before being further processed.

Core scanning provides detailed information on the geophysical, mineralogical, and geochemical characteristics of the core, records core quality and fundamental variations along the core, and allows multiple imaging techniques including high-definition optical, near-infrared (NIR), ultraviolet (UV), and X-radiographic images to be taken.

The following core scanning facilities are available:

X-ray tomography – X-ray computed tomography visualises and records internal structures present within the core to determine core quality, structural features, heterogeneity and fracture networks. The rotating source-detector assembly scans in multiple orientation, producing both 2D radiographic core images (“slices”) and 3D reconstructions. A digital rock software package will help users to visualize, process, and rapidly interpret the digital core imagery.

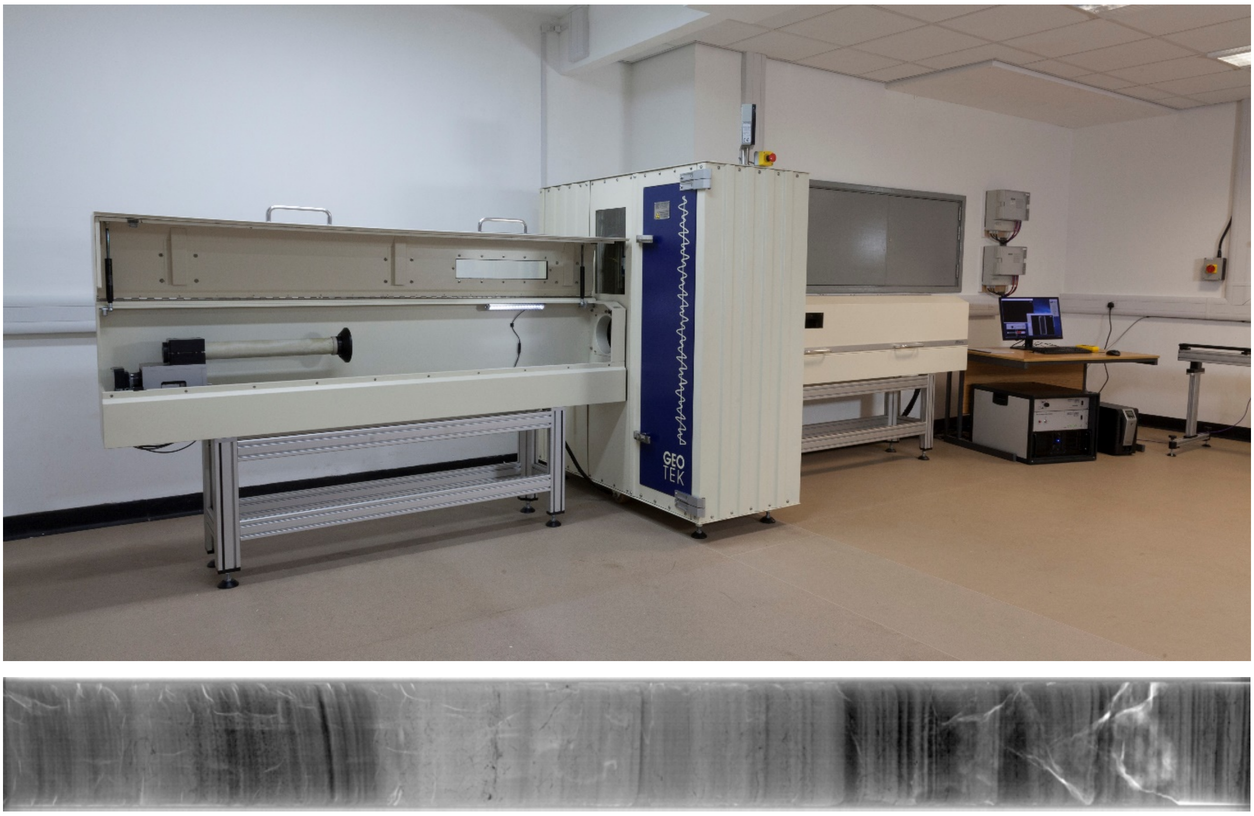

Figure 165 MSCL-RXCT core scanner and example 2D X-ray radiograph (Geotek MSCL – RXCT)

Geophysics and core imaging – Multi-sensor core logging providing ultra-high definition optical core images and geophysical analyses, including:

- bulk density, porosity, and/or P-wave velocity profiles

- core quality, heterogeneity, identification of sedimentary features and lithological variations (e.g., grain-size, texture, colour) and changes in composition
- core-log integration & correlation between boreholes

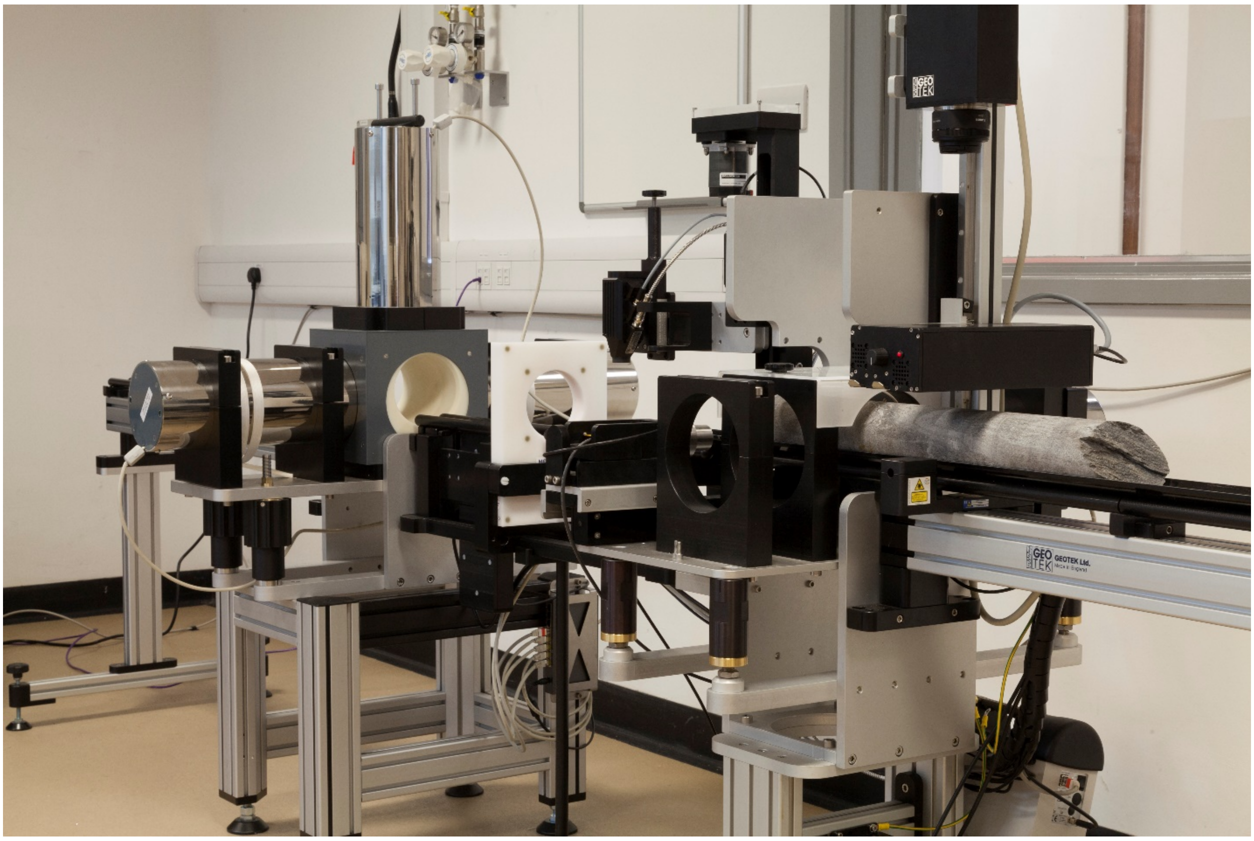

Figure 176 Multi-sensor core logging scanner (Geotek MSCL-S)

Two X-ray fluorescence scanners – These acquire elemental abundances and variations along core, and can produce 2D XRF maps. Additional colour linescan and UV imaging capabilities provide records of down-core textural/compositional variation. Both XRF core scanners are able to detect a wide range of elements (Mg to U at % and ppm levels) and allow high-spatial resolution scans, down to 0.1 mm. XRF scanning is a well-established, non-destructive method that allows:

- Characterisation of rock and sediment provenances
- Interpretation of mineralogy and matrix properties
- Identification and analysis of fundamental horizons (e.g., bed boundaries)
- Identification of potential element ratio proxies
- Core-to-core and/or core-to-log correlations.

Figure 187 X-ray fluorescence scanner (Geotek, MSCL-XYZ XRF)

Other Laboratory facilities

The British Geological Survey at Keyworth have the following facilities:

- Geochemistry labs
- Mineralogy, petrology and biostratigraphy
- Physical property labs

Methodology and eligibility for access to these facilities is still to be determined.

Appendix 3A: Array 1 Borehole Descriptions

Table 6 Array 1 Summary borehole metadata and planned sampling

Array 1: Sampling	Details
Scientific Objective:	Long-term baseline groundwater testing and sensor installation
No of Sites and boreholes per site	9 Sites each with both 1 x 100 m and 1 x 50 m borehole
Expected Lithostratigraphy at TD	50 m boreholes TD in Quaternary, 100 m TD in Sherwood Sandstone Group (Triassic)
Boreholes per site	1 x 100 m, 1 x 50 m boreholes
Likely borehole diameter	13 ½" nominal diameter
Casing Installed: 50 m boreholes	10 ¾" permanent steel casing (6-22 mbGL), 150 mm PVC screened between 43 to 49 mbGL
Casing Installed: 100 m boreholes	11 ¾" permeant steel casing (6-22 mbGL), 150 mm PVC screened between 90 to 99 mbGL
Expected end use	Boreholes remain open for future sampling
Samples available during drilling	Drill cutting collected sporadically
Cored Boreholes	5 X 100 m cored to sample superficial & Permo-Trias geology
Geophysical logs	5 x 100 m boreholes, Gamma-Ray - Caliper (Borehole diameter)
Geomicrobiology sampling	Standard geomicrobiology sampling protocol: 1 sample per 10 m of core in cored boreholes
Gas testing during drilling	Equipment
Fluid testing during drilling	None planned
Fluid Testing Post Drilling	None planned
Pump Testing	Long-term Pump testing
Permanently installed equipment	Automated & telemetered data logging in 6 boreholes

The array will provide environmental baseline data of the groundwater, ground motion and air quality across the study area. The purpose of the proposed groundwater array is to create a new groundwater monitoring network which will allow researchers to get an improved understanding of the groundwater processes within the Cheshire Energy Field Research Site (CERFS) area. These data will form the natural baseline against which future research activity will be compared.

BOREHOLE COMPONENTS OF ARRAY 1

The array consists of 18 boreholes at 9 separate locations in the broad vicinity of the village of Elton in Cheshire. This allows the sampling of the regional groundwater in the vicinity of the CERFS research site and also allows the stratigraphy and variability of the Permo-Triassic geology to be more completely understood.

Following completion of the drilling phase a series of pump tests will be undertaken at each borehole location. In addition these boreholes will also be instrumented with continuously recording sensor to allow the borehole steady-state conditions to be monitored remotely over an extended time interval. Combined with outputs from analytical groundwater geochemistry this will produce a laterally and temporally extensive baseline data set.

ABOVE-GROUND DATA ACQUISITION IN ARRAY 1

Interferometric synthetic-aperture radar (InSAR) ground motion equipment will also be installed across selected sites at the CERFS area. Equipment will be installed at the surface to continuously monitor deformation or shifts in rock mass in the subsurface. Air quality monitoring installations are included as part of the environmental baseline study for the CERFS area. These are designed by (and will be controlled by) Manchester/York Universities and NCAS[1]. These installations will include a range of sensors and instruments to monitor atmospheric gases.

SUBSURFACE DATA ACQUISITION IN ARRAY 1

The groundwater monitoring wells within this array allow an environmental baseline for groundwater quality to be produced. The baseline will detail various chemical and physical parameters and general groundwater quality through the collection of groundwater samples and continuous automated monitoring, using data loggers and groundwater quality sondes, over an extended period. The sondes will be purchased, installed and maintained by the UK Geoenergy Observatories capital funding.

The array is also designed to allow pumping tests to be undertaken during the operational phase of the wells. This will help to characterise how the groundwater flows and behaves across the region.

Table 7 Array 1 List of borehole codes and site locations (Cored boreholes in Bold)

Location	100 m BH	Cored	50 m BH
SITE A	TH0407		TH0420
SITE B	**TH0101**	TH0101	TH0102
SITE C	**TH0107**	TH0107	TH0108
SITE D	**TH0116**	TH0116	TH0117
SITE E	**TH0122**	TH0122	TH0123
SITE F	**TH0125**	TH0125	TH0126
SITE G	TH0128		TH0129
SITE K	TH0110		TH0111
SITE N	**TH0104**	TH0104	TH0105

Table 8 Array 1 planned hydrogeochemical sampling: summary of intended sample types

Sample Type	Treatment	Sample Container	Analysis Possible
FA 30 ml	Filtered acidified with HNO_3 to 1%	30 ml LDPE	ICP AES, Na, K, Ca, Mg, SO_4, Si, Al, B, Ba, Be, Cd, Co, Cr, Cu, Fe_{total}, La, Li, Mn, Ni, Mo, Pb, P_{total}, Sc, Sr, V, Y, Zn, Zr, As, Se, ICP MS suite
FUA 60 ml	Filtered, unacidified	60ml LDPE	Cl, F, Br, I, NO2, NO3, TON, NH_4 (SO_4, PO_4)
FUA 30 ml NH_4		30 ml LDPE	Ammonium
FUA 30 ml As			Arsenic
NPOC	Silver filtered, unacidified	14ml foil capped glass vial	Dissolved Organic Carbon
$\delta^{18}O$/ $\delta^{2}H$	Filtered, unacidified	60 ml HDPE	Oxygen and Deuterium
$\delta^{13}C$		100 ml HDPE	Carbon Isotopes
Dissolved gases	Unfiltered, unacidified	Gas Sampling Bomb	Dissolved gases
CFCs		Small Amber Bottle	CFCs
SF_6		Clear Glass Bottle	SF_6
SVOCs		1 x Green Bottle 2 x Glass Vials	SVOCs
NORM		1L Glass Amber Bottle	NORMS
Tritium		1L Glass Amber Bottle	Tritium (^{3}He)
S Isotopes		250 ml Nalgene	Sulphur Isotopes
Radon Daughters		Nalgene pots	Radon Daughters
Radon		60 ml HDPE	Radon (Rn) (Triathler)
Organic micropollutants		2 x 1 L PTFE Lined Bottles	GCMS/LCMS
PAHs		1 x 1 L PTFE Lined Bottles	PAHs
VOCs		1 x 250 ml plastic bottle	Chlorinated hydrocarbons, BTEX

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Table 9 Array 1 Non-geochemical sampling (Groundwater Baseline)

Type	Data Collection	Data Produced/Possible	Status
Pumping Tests	Step Drawdown	Well efficiency, critical pumping rate, optimum pumping rate	Operational details to be confirmed
	Constant Rate	Transmissivity (hence hydraulic conductivity), storage coefficient, aquifer response	
	Constant Head	Transmissivity (hence hydraulic conductivity)	
InSAR	Ground level monitoring	Baseline of ground level stability	Confirmed

Special sample handling procedures that will be adopted:

- One sample will be acidified in the field
- The majority of samples will be filtered
- Samples will be refrigerated in the field using ice packs/ice and kept in cold stores over the weekend before shipping to labs
- There is scope to keep some samples in the cold store for testing at a later date
- Further parameters need to be further examined including long-term storage requirements

Appendix 3B: Array 2 Borehole Descriptions

Table 10 Array 2 Summary borehole metadata and planned sampling

Array 2: Seismic Baseline	
Scientific Objective:	Seismic monitoring network that detects very small earthquakes (-0.6 to -1.0 Magnitude)
No of Sites	10 sites each with 1 borehole (some co-located with Array 1)
Expected Lithostratigraphy at TD	Sherwood Sandstone Group (Triassic)
Boreholes per site	1 per site: 7 x 200 m deep, 3 x 300m
Casing Installed	PVC casing
Expected end use	Seismometers / sensors installed in boreholes then sealed
Samples available during drilling	Drill cutting collected sporadically
Cored Boreholes	4 x 200 m boreholes also cored
Geophysical logs	3 x 300 m, 7 X 200 m boreholes: Gamma-Ray - Caliper (Borehole diameter)
Geomicrobiology sampling	Standard geomicrobiology sampling protocol: 1 sample per 10 m of core in cored boreholes
Gas testing during drilling	Boreholes not equipped for gas testing
Fluid testing during drilling	None planned
Fluid Testing Post Drilling	None planned
Pump Testing	None planned
Permanently installed equipment	10 seismometers installed in boreholes then sealed, 3 x DAS fibre optics

The purpose of the proposed seismic array is to establish a new seismic monitoring network which will allow researchers to get an improved understanding of the seismic activity within the Cheshire Energy Field Research Site (CERFS) area. These data will form the natural baseline against which future seismic activity will be compared and contrasted.

MONITORING COMPONENTS OF ARRAY 2

The baseline seismic monitoring array will consist of 13 seismic sensors in 10 boreholes with an average spacing of 1 km, along with three strings of fibre optic cables configured for distributed acoustic sensing (DAS). These are distributed across a 4km by 4km area, centred on the proposed zone of subsurface anthropogenic activities in the Ince Marshes area, and the defining geological structure of the area. An additional seismometer will be installed at the base of the "Deep Well" (Array 03). The components parts of the array are:

- 3 boreholes, each with a planned total depth (TD) of 300 metres dependent on drilling conditions. Each borehole will be instrumented with two seismometers, one at 200 metres and one at 300 metres depth. All of these 300 metre boreholes will have fibre optic cables installed on the outside of the casing, which will be used for Distributed Acoustic Sensing (DAS) applications.

- 7 boreholes, each with a planned total depth of 200 metre dependent on drilling conditions, instrumented with one seismometer at 200 metre.
- 1 seismometer to be installed at the base of the Array 3 1200 metre deep borehole.

Each seismometer (Guralp Radian broadband) will record 3-component acceleration data at 1000 Hz. This data will be transmitted in real time using Guralp's GCF protocol to be archived at the BGS. Complimentary metadata will be maintained as part of the archive. The installed fibre optic cables will provide the facilities for future DAS measurements/interrogation to take place. The DAS unit will be supplied externally, and will not be installed on site.

Table 11 Array 2 List of borehole codes and site locations (Cored borehole in Bold)

Location	200 m	300 m	Cored
SITE D	TH0204		
SITE E		TH0215	
SITE F	TH0218		
SITE H	**TH0202**		Yes
SITE I	**TH0209**		Yes
SITE J		TH0210	
SITE K	**TH0212**		Yes
SITE L		TH0214	
SITE M	**TH0216**		Yes
SITE N	TH0220		

Appendix 3C: Array 3 Borehole Description

Table 12 Array 3 Summary borehole metadata and planned sampling

Array 3: Deep Borehole	Description
Scientific Objective:	Drilling of Permo-Trias succession & fault, coring of Carboniferous succession and installed of seismic monitoring and geophysical equipment
No of Sites	1 (co-located with Array 4)
Expected Lithostratigraphy at TD	Carboniferous Millstone Grit Formation
Boreholes per site	1 x 1200 mbGL
Casing Installed	Conductor 0 -30 mBGL, Permanent steel Casing to 428 mbGL (to achieve complete zonal isolation for aquifers)
Expected end use	Long Term Seismic Monitoring
Samples available during drilling	Drill cutting collected sporadically
Cored Boreholes	Continuous coring for 428 -1200 m, likely 85 / 102 mm core diameter (TBC)
Geophysical logs: Run 1	0-425 M: Neutron-Density-Spectral Gamma Ray, P&S wave, Resistivity (+ potentially Cross-dipole sonic)
Borehole Imaging Run 1	0-425 M: High-resolution resistivity borehole imaging + inclinometry
Geophysical logs: Run 2	425 -1200 M: Neutron-Density-Spectral Gamma Ray, P&S wave, Resistivity (+ potentially Cross-diplole sonic) Casing Inspection Logs (Cement Bond Log / Ultrasonic Imager)
Borehole Imaging Run 2	425 -1200 M: High-resolution resistivity borehole imaging + inclinometry
Drilling parameters	Drilling data parameters & Extended leak-off test
Geomicrobiology sampling	Standard geomicrobiology sampling protocol: 1 sample per 10 m of core in cored boreholes
Gas testing during drilling	MFDT / RFT Pressurised fluid & gas sampling
Fluid testing during drilling	MFDT / RFT Pressurised fluid & gas sampling
Fluid Testing Post Drilling	None possible with borehole completion
Pump Testing	None possible with borehole completion
Permanently installed equipment	Guralp seismometer, DAS fibre optic cable & resistivity tomography to base casing

INTENDED PURPOSE OF ARRAY 3

The purpose of the proposed deep well is to characterise geological sequence in the area of the Ince Marshes horst block and is designed to allow long-term seismic monitoring of these formations for the life of the project from the Quaternary through to the Carboniferous Millstone Grit Group.

Within the CERFS, Array 3 gives the single opportunity to obtain information relating to the Carboniferous Millstone Grit, Coal Measures and lower part of the Warwickshire Group bedrock strata. These rocks represent potential barriers between exploration targets for PEDL licence holders in this and adjacent areas, although have been faulted over geological time; they have also been explored in the past for coal-bed methane. As such, characterisation of these rocks is considered important to a range of potential innovative geoenergy technologies that may form topics of research projects as part of the broader UK Geoenergy Observatory aims.

The array will generate a dataset of drilling data, wireline log data (including image logs) and core as well as gas and drilled cuttings data. In combination these will allow for detailed studies of rocks which are often poorly characterised as a foundation for future research. The data will be relevant to furthering understanding from this site, but also add value to existing datasets from the region, including other deep borehole core, downhole log data, and released 2D and (not-yet released) 3D seismic data .

The well will be drilled in proximity to Array 4 (Multiscale) and potentially can be co-opted to service multiscale experimentation. The Array 3 borehole will be drilled in advance of Array 4. Given that Array 4 is intended to operate as an experimental infrastructure, with the flow properties of the Dungeon Bank Fault system being a key research objective, ensuring that the infrastructure is appropriately located within these wells is a key consideration for Array 3. The Array 3 research objectives include:

- Characterising intact and faulted rock properties
- Identifying the location and orientation of the main Dungeon Banks Fault plane
- Quantifying the width of the fault damage zone and the types of deformation present
- Identifying whether any significant gas is present in the vicinity of this fault
- Assessing the likelihood of borehole collapse in the vicinity of the fault.
- Determining the offset on the fault and the depth to the top of the Pennine Coal Measures Group

COMPONENTS OF ARRAY 3

The array will consist of a single vertical borehole that will penetrate the Quaternary superficial deposits, the Permo-Triassic and some Carboniferous formations reaching total depth, estimated at 1200m (TD) in the upper part of the Carboniferous Millstone Grit. The Permo-Triassic succession will be open hole drilled and then logged using wireline geophysical logging tools. This section will then be fully cased through the lower bounding fault to achieve zonal aquifer isolation. Both electrical resistivity tomography and fibre optic cables will be permanently installed behind the casing. Following the completion of the drilling to TD, geophysical logging (including borehole imaging) and fluid / gas sampling of the total borehole section will be undertaken. On completion of these activities a single seismometer will be inserted at TD and the borehole backfilled with engineered cement.

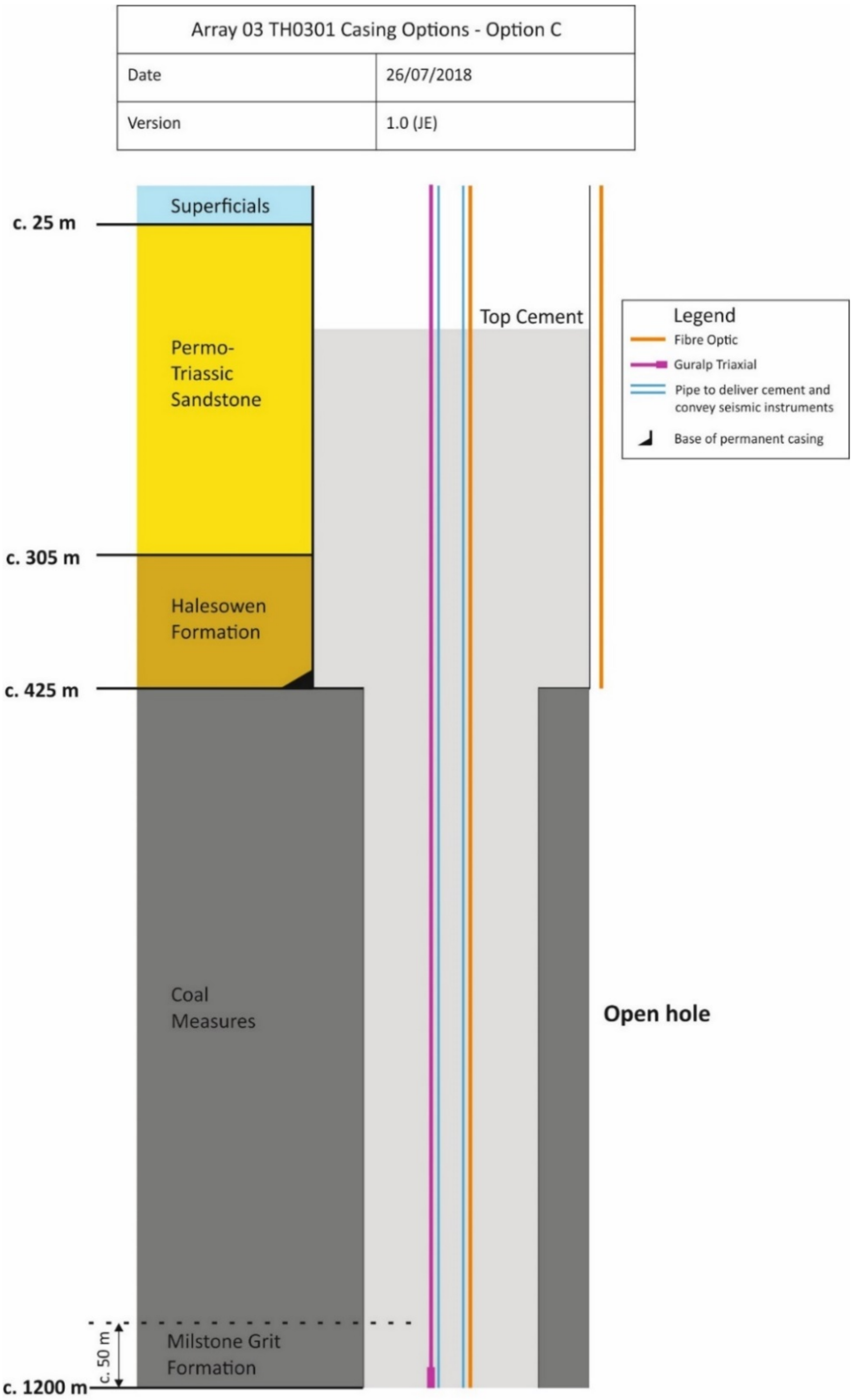
The components parts of the array are:

- A borehole approximately 1200m Total Depth (TD) in the Carboniferous Millstone Grit.
- Fibre Optic cable installed on outside of the casing(s) for Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS).
- A single seismometer installed in the base of the borehole for the detection of seismic activity.

DATA ACQUISITION IN ARRAY 3

Key data acquisition phases in this borehole, includes core recovery, geophysical wireline logging and borehole imaging. Pressurised fluid / gas samples will be acquired using wireline formation testing tools such as the Repeat Formation Tester and the Module Dynamics Tester. Depending upon the specific contractor and equipment used (to be confirmed) samples of specific intervals will be recovered at in-situ pressure allowing accurate quantification of the subsurface fluids and gas composition.

Figure 19 Array 3 Borehole construction / casing options and prognosis



Appendix 3D: Array 4 Borehole Descriptions

Table 13 Array 4 Summary borehole metadata and planned sampling

Array 4: Multi-scale array	Description
Scientific Objective:	Multi-scale experimental site for quantification of groundwater properties and geological characterisation of the Permo-Trias succession. This will include: identifying the location of the intersection of the Dungeon Bank Fault and the Role of faults as a barriers/pathways to fluid / gas migration
No of Sites	1
Expected Lithostratigraphy at TD	Quaternary / Triassic Sherwood Sandstone Group (SSG) for 50 m boreholes, SSG for 100 m boreholes, Upper Carboniferous (Warwickshire Group or Pennine Upper Coal Measures Group) for 600 m boreholes
Boreholes per site	8 x 50 m, 12 x 100 m, 3 X 600 m
Casing Installed	Steel casing installed in top section of 600 m boreholes
Expected end use	Multi-scale experimental site
Samples available during drilling	Drill cuttings collected sporadically
Cored Boreholes	1 x 600 m 3 x 100 m
Geophysical logs: Run 1	1 x 600 m well: near-oilfield log suite (Density-neutron-spectral-gamma, P&S wave sonic, resistivity, SP), 2x 600 m well : gamma ray -caliper (borehole diameter)
Borehole Imaging: Run 1	Medium-high resolution resistivity logging in core 600m well or acoustic imaging in 1 x 600 m boreholes
Geophysical logs: Run 2	1 x 600 m well: near-oilfield log suite (Density-neutron-spectral-gamma, P&S wave sonic, resistivity, SP), 2 x 600 m well : gamma ray -caliper (borehole diameter) + casing inspection tools (Cement bond long + ultrasonic imager)
Borehole Imaging: Run 2	Medium-high resolution resistivity logging in core 600m well or acoustic imaging in 1 x 600 m boreholes
Drilling parameters	Potentially recording of drilling parameters
Geomicrobiology sampling	Standard geomicrobiology sampling protocol: 1 sample per 10 m of core in cored boreholes
Gas testing during drilling	None Planned
Fluid testing during drilling	None Planned
Fluid Testing Post Drilling	Baseline conditions & after pressure injection experiments
Pump Testing	Multiple cycles planned for experimental array, details to be confirmed
Permanently installed equipment	Cross-borehole and surface-borehole 2D and 3D geoelectrical imaging (electric resistivity tomography) array; Time-lapse imaging of fluid processes in the near surface including natural and induced changes

COMPONENTS OF ARRAY 4

The multi-scale array will enable hydrogeological and hydrogeophysical characterisation of the rock mass from surface to experimental borehole depth. It will allow subsequent investigation of hydraulic, geophysical and geochemical processes at multiple scales (space and time), particularly in response to changes induced by controlled experiments.

Whilst drilling will be completed in Array 4 during the delivery phase of CERFS, this array is intended to continue to operate for an extended period allowing multiple future opportunities for the hydrogeology to be characterised by repeated hydrogeochemical and geophysical sampling.

DATA ACQUISITION IN ARRAY 4

Data, primarily wireline and core data, will be collected through the drilling and construction process. Electrical Resistivity Tomography (ERT) sensor cables as well as DAS / DTS fibre optic cables will be installed down the back of the casing. The metal casing will require electrical isolation from the lithology. The purpose of the fibre optic cables will be to obtain high resolution temperature data to help calibrate ERT electrical imaging data.

The well will be completed to allow future installation of various downhole probes, including but not limited to seismic, pressure and temperature sensors. Screened casing sections may be incorporated to provide hydraulic access to permeable geological units for future hydrogeological and hydrogeophysical experimentation.

Table 14 Array 4 List of borehole codes and site locations (Cored boreholes in Bold)

Location	50 m	100 m	Upto 600m	Cored
Site A			TH0401	
Site A			TH0402	
Site A			**TH0403**	Yes
Site A		TH0404		
Site A		**TH0405**		Yes
Site A		TH0406		
Site A		TH0407		
Site A		TH0408		
Site A		TH0409		
Site A		TH0410		
Site A		TH0411		
Site A		**TH0412**		Yes
Site A		TH0413		
Site A		TH0414		
Site A		**TH0415**		Yes
Site A	TH0416			
Site A	TH0417			
Site A	TH0418			
Site A	TH0419			
Site A	TH0420			
Site A	TH0421			
Site A	TH0422			
Site A	TH0423			

Repeated water sampling and pump testing is intended for Array 4 into the future but precise protocols are yet to be defined so sampling opportunities of these materials cannot be provided at this time.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi

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