Natural Environment Research Council (NERC)

‘Unlocking the Subsurface’ Scoping Workshop Report

14th July 2025 – Held virtually on MS Teams

Natural Environment Research Council

Executive Summary

The Natural Environment Research Council (NERC) is scoping a potential research and innovation opportunity aimed at **'Unlocking the Subsurface',** which would aim to deliver the understanding, evidence and tools needed to sustainably balance the increased demands on the subsurface for provision of resources, storage and infrastructure, and to responsibly optimise utilisation of the subsurface to deliver green growth and enhanced resilience and security in the context of clean energy, climate change and decarbonisation.

NERC organised a workshop bringing together an interdisciplinary group of academic and industry representatives to refine the scope of a potential strategic research programme in this area, to agree priority scientific challenges and consider the interventions needed to deliver the required outcomes. Background to the potential programme is outlined within this report, along with summaries of the key topics covered and discussions from the workshop.

The key findings from the workshop are:

- There is a need to expand our fundamental understanding of the subsurface to reduce uncertainties, characterise risk and enable the optimisation of multiple, often competing, subsurface uses.
- Significant opportunities exist to harness data analytics, modelling techniques and emerging technologies to improve the prediction, assessment, monitoring and evaluation of the subsurface.
- Integration of socio-economic, regulatory and public perception considerations, including risk communication and social license to operate throughout any research investment, will be key to ensuring long-term impact.
- Research and innovation (R&I) is needed for both onshore and offshore domains, and at all depths of the subsurface.
- To maximise benefit, any potential research programme in this area should have a strong UK regional/place-based approach, reflecting specific geological and societal context. Where appropriate, working or collaborating internationally could add further value.
- The UK possesses substantial infrastructure and legacy data, which in some cases is currently underutilised, that new subsurface research could capitalise on. Cross sector collaboration - including industry, academia, regulators and policymakers - can facilitate data sharing thus reducing the need for new data collection, enhance use of existing facilities and accelerate impact.
- The UK should invest in skills and training to remain at the forefront of subsurface research. Key gaps exist in hydrogeology, systems thinking in earth sciences, and computational geosciences (specifically the statistical skills needed to implement quantitative analysis techniques).
- To deliver maximum impact, a research and innovation programme in this area should be inherently interdisciplinary – bringing together engineering, social sciences and other disciplines to complement an environmental focus and address complex subsurface challenges holistically.

For the avoidance of doubt this document records the scoping process and views of those attending the workshop; it is not indicative of future positions or opportunities from NERC or UKRI (UK Research & Innovation).

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1. Background

1.1. Scientific Need

The subsurface is a multifunctional resource providing society and the economy with a range of services that are set to increase in variety and criticality over the coming decades. However, subsurface systems are complex, interconnected, and dynamic, resulting in a variety of feedback loops which can be difficult to track or predict.

Critical technologies and green growth sectors central to the clean energy and net zero transition are increasing the demand for subsurface resources (i.e. minerals; water; energy) and requirement for subsurface storage (i.e. carbon; energy) or disposal (i.e. radioactive waste), whilst population increases and densification are driving increased demand for subsurface infrastructure, including utilities, transport tunnels and building foundations. Concurrently, climate change is increasingly having an impact on the subsurface environment, either directly, or indirectly through anthropogenic demand on finite subsurface space for mitigation and adaptation measures.

Currently we lack the fundamental understanding, evidence and tools needed to balance and meet the increasing demands on the subsurface through responsible optimisation of subsurface usage to support green growth alongside enhanced resilience and security for the UK.

1.2. NERC 'Unlocking the Subsurface' programme concept

The Natural Environment Research Council (NERC) is scoping a potential research and innovation opportunity aimed at '**Unlocking the subsurface**.' Funding for this programme is not confirmed; however if secured, the programme would aim to deliver the understanding, evidence and tools needed to:

- sustainably balance the increased demands on the subsurface for provision of resources, storage and infrastructure, without compromising its' physical, structural and environmental integrity;
- responsibly optimise utilisation of the subsurface to its full potential for UK communities at local, regional and national scales to deliver green growth and enhanced resilience and security in the context of climate change and decarbonisation.

The programme would be expected to deliver the following outcomes:

- **Building evidence and understanding of what works where,** in terms of the potential interdependencies and interactions of different subsurface usage scenarios, and **how to overcome barriers to exploring and developing new opportunities** (practices and technologies) that have real world impact to support economic growth, achieve environmental goals and increase security across the UK
- **Creating world-leading capability, capacity and partnerships** that results in mobilisation, data-sharing, advancing knowledge, and skills, that have long term legacy
- **Developing innovative place-based** tools and methods that can be scaled up across the UK to increase resilience and efficiently utilise the subsurface to its **full potential for UK communities** at local, regional and national scales
- **Embedding research into policy and industry** through partnership, resulting in evidence-based policy, regulation, standards and permitting for subsurface usage
- **Developing tools, technologies & frameworks** to support more effective and efficient prediction, assessment, monitoring and evaluation of the subsurface

The focus of this potential programme is on research and innovation that is applicable to the sustainable utilisation, optimisation and management of multiple subsurface technologies &

sectors. Research that is only specific to a particular single technology or sector (e.g. geothermal; carbon capture, usage and storage (CCUS); minerals extraction) is out of scope.

2. Scoping Process

This programme idea has been informed by the Go Science foresight study on Future of the Subsurface, alongside previous activities such as the US-UK Workshop on Transformation in Urban Underground Infrastructure, and will address the three key priorities at the heart of NERC's recently published Forward Look: Driving Green Growth; Strengthening Environmental Security; and Enabling Responsible Innovation.

To seek input to further refine the scope of this potential programme, NERC has engaged widely across relevant policy, academic and industry stakeholders through 3 activities:

a) policy survey
b) community input through 'Well Sorted'
c) research and innovation scoping workshop

2.1. Policy survey

NERC sought the views of key government and regulatory stakeholders via a short survey and subsequent follow up conversations, to inform development of the potential programme idea and refine the anticipated programme outcomes and impacts to ensure these align with policy and regulatory needs. The consultation shaped the expected outcomes (outlined in Section 1.2) and identified the following R&I needs to support policy, regulation and decision-making for the subsurface:

- Understanding subsurface risks, trade-offs and interdependencies (including surface-subsurface interactions)
- Enabling data, tools and technology
- Partnership working

2.2. Community input

NERC gathered the views of our academic and industry communities using the 'Well Sorted' tool to ask for responses to the question: **"What are the key knowledge gaps that, if addressed by research and innovation, will deliver a significant step change in optimising the use of the subsurface?"**

A total of 77 responses were received from 41 individuals. Prior to the workshop, invited participants used the Well Sorted platform to group submitted ideas in ways that made sense to them. Well Sorted then combined all participants' groupings to generate an overall structure, consisting of 9 groups of ideas (see Annex A for Well Sorted outputs). Building on this, NERC consolidated the groupings into 3 research and innovation theme areas and 3 cross-cutting themes relevant to all 3 research and innovation theme areas. These final groupings, illustrated in Figure 1, were used to inform the design of the workshop.

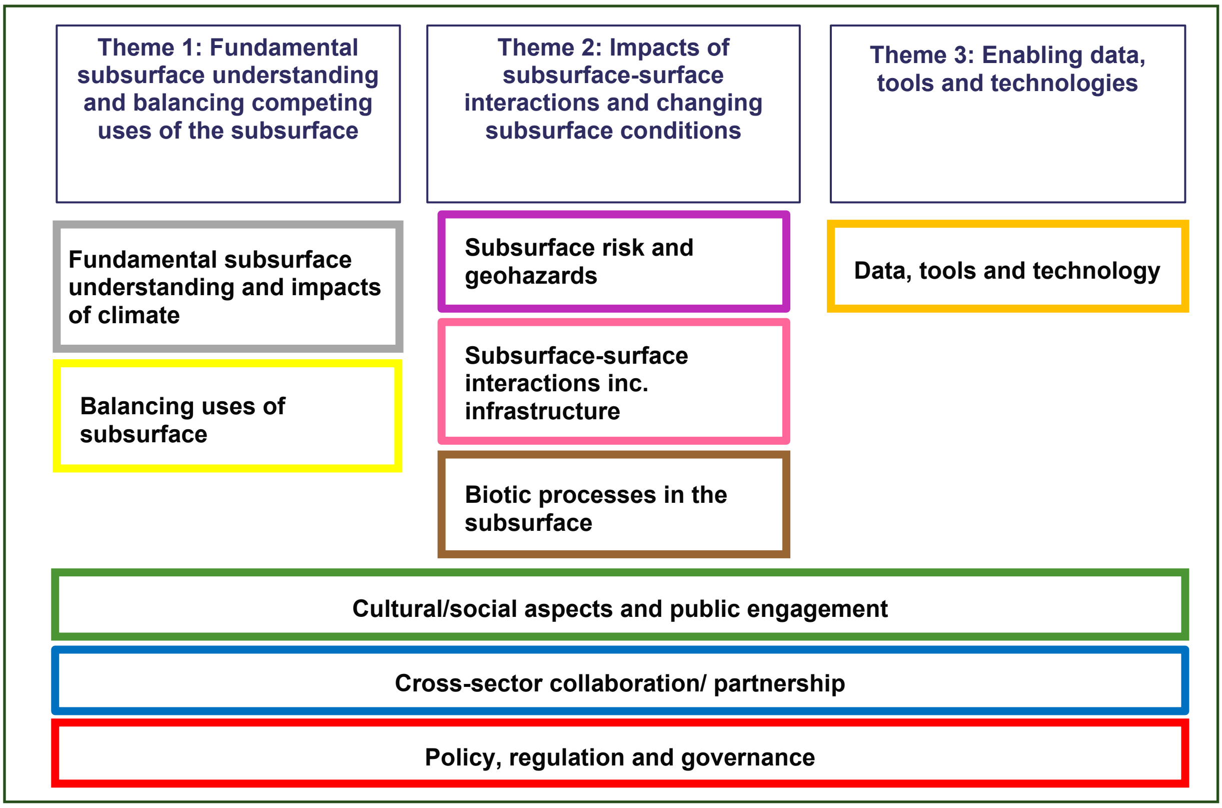

Figure 1 The nine groupings from Well Sorted, combined into 3 Research and Innovation themes and 3 cross-cutting themes. Colours relate to those in the Well Sorted groupings in Annex A. Note the above figure includes modification following discussion during the workshop.

3. Research and innovation scoping workshop

3.1. Workshop overview

NERC held an online workshop on 14 July 2025 to gain community perspectives to help refine the scope and identify the key priority research challenges that need to be addressed by a potential research and innovation programme around ‘Unlocking the Subsurface’ in order to deliver the intended outcomes (outlined in Section 1.2). There were 18 invited participants from across academia and industry (see Annex B). Participants were identified to ensure coverage of knowledge and expertise spanning the remit of this area, including earth resources, geomicrobiology, seismology, geophysics, hydrogeology, geochemistry, climate change and geological hazards, sustainable energy, sensing/imaging the subsurface, digital technology development, artificial intelligence (AI), ground and environmental engineering and social science. Participants were asked to act as representatives for their communities and provide input in the broadest sense.

The workshop was chaired by Professor Mike Kendall (University of Oxford) with four members of NERC staff acting as facilitators. Four UKRI colleagues (from the Engineering and Physical Sciences Research Council (EPSRC), the Economic and Social Research Council (ESRC) and Innovate UK) were also in attendance.

3.2. Workshop objectives

The objectives of the workshop were:

- To define the scope of a potential NERC/UKRI strategic research programme

- To discuss and agree the priority key scientific challenges and research questions to inform the science plan that will underpin the case for investment for consideration by UKRI-NERC
- To understand the data, tools and infrastructure, as well as skills and training needs, to support research in this area.
- To consider potential programme implementation pathways and scalable investment options

3.3. Session 1: Priority Research Areas and Challenges

Following the grouping of the ideas submitted to the 'Well Sorted' survey, NERC identified three emerging research and innovation themes (see bullet points below) underpinned by three cross cutting themes (see Figure 1):

- Fundamental subsurface understanding and balancing competing uses of the subsurface
- Impacts of subsurface-surface interactions and changing subsurface conditions
- Enabling data, tools and technologies

Participants were split into two breakout groups to discuss and agree three priority research areas or challenges that need to be addressed to move the field forward for each of the above three themes. The identified priority research areas/challenges are summarised below.

Theme 1: Fundamental subsurface understanding and balancing competing uses of the subsurface

Key research and innovation needs identified to improve fundamental understanding of the subsurface include:

- Enhanced understanding and predictive capability of subsurface fluid flow and fluid/rock interactions across all depths, including reactive transport in anthropogenically modified environments. This includes the development of improved methods to monitor, model and predict the movement of contained substances within the subsurface.
- Improved measurement, imaging and sensing in the subsurface to enable accurate prediction & characterisation of subsurface geology (i.e. porosity and heterogeneity) at all depths, including the deep crystalline basement (which is critical for deep geothermal and managing induced seismicity).
- Improved understanding and prediction of subsurface responses to engineered perturbation across diverse geological settings to inform the development of appropriate monitoring and measurement approaches tailored to specific subsurface applications. This includes characterisation of baseline subsurface conditions and subsurface responses (i.e. rock mass integrity; microbiology; seismicity) to engineered cyclicity (i.e. often strongly coupled cycles of stress, fluid pressure and chemistry), and how subsurface responses interact with and impact on subsurface infrastructures and technologies.
- Increased understanding of the interactions within and between the deep (beyond kilometre scale), shallow (10s of metres to kilometre scale), and near- subsurface zones (critical zone, up to 10s of metres), and how interventions or perturbations in one zone influences the geological, chemical and microbiological processes across all zones across spatial and temporal scales.
- Development of cohesive upscaling methodologies for process understanding from nano- and lab-scale to field scale, including identifying and characterizing the

dominant processes at each scale, to enable fully coupled thermal-hydraulic-mechanical-chemical-biological (THMCB) process models. Benchmarking through fundamental process experiments and field measurements is essential to constrain model uncertainties and enhance predictive capability.

Key research and innovation needs identified in relation to balancing competing uses of the subsurface include:

- Improved understanding of the geological settings and/or subsurface conditions that provide opportunities for coupling and co-location of different subsurface uses/technologies (for example geothermal heat and mineral extraction), including coupling/integration with existing subsurface and surface uses. This requires understanding of interactions between different subsurface applications/technologies.
- Understanding of opportunities for application of circular economy practices to the use of the subsurface, including re-use/sharing of assets, identification of useful by-products from subsurface technologies/applications, linking resource supply to demand and driving behavioural change to reduce consumption.

Theme 2: Impacts of subsurface-surface interactions and changing subsurface conditions

Key research and innovation needs identified relating to subsurface-surface interactions include:

- Improved understanding and characterisation of fluxes (water, heat, gas, chemicals) between the surface, subsurface and atmosphere, and how these are likely to be impacted by and impact on different subsurface uses, particularly in the context of climate change. For example, surface water – groundwater interactions including in extremes such as flooding; impact of atmospheric changes on geological materials in the near subsurface.
- Understanding the wider environmental impacts and implications of deployment of different technologies/uses of the subsurface, including impacts on water demands, biota, pollution/contamination risk, hazard risks (e.g. from induced seismicity). Within this we also need to understand views of different stakeholder groups around acceptable levels of risk/impact, how to communicate risk and consideration of social 'license' to operate.

Key research and innovation needs identified relating to changing subsurface conditions include:

- Quantifying the impacts of climate change on the subsurface (e.g. clay shrink-swell; impacts on natural geology, hydrogeology, microbiota etc) and the implications of this for uses of the subsurface and geotechnical infrastructure.
- Understanding the impact of geological and multi hazards to delivery of subsurface infrastructure and uses of the subsurface, as well as the broader risks these hazards present to society and the economy Capturing data in the immediate aftermath of extreme events could provide useful insight into their effects on the subsurface
- Understanding risks of hazards due to anthropogenic perturbations of the subsurface and how these interact with co-located subsurface technologies/uses.
- Understanding of how interventions from the built environment and subsurface engineering works (including the need for maintenance) affect the quality of the subsurface and over longer time periods.

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Theme 3: Enabling data, tools and technologies

Key data, tools and technology needs identified related to unlocking the subsurface include:

- Data
    - Understanding of the data that is already available from different sources (i.e. satellite data) and how this can be brought together or used differently to provide additional value; in addition to identifying requirement for additional data collection.
    - Improved collation, sorting, integration, digitisation, sharing and use of data between different data sources, disciplines and stakeholders; this may require a central bespoke, well-curated database, or making better use of existing underpinning research infrastructure to curate data (e.g. the National Geoscience Data Centre (NGDC)) to ensure its accessibility and interoperability.
    - Tools to deal with data gaps, interrogate subsurface data, integrate different data types (e.g. statistical tools, AI interpretation techniques, machine learning)
- Tools
    - Development of accessible decision-support tools to facilitate inclusive decision-making
    - Accurate subsurface representation in models and methods to improve integration of different models including and beyond the subsurface (e.g. energy systems; land-use). This includes understanding model uncertainty, how to constrain it and how this varies dependent on the application, along with how to communicate uncertainty to stakeholders.
- Technologies
    - Development and implementation of minimally invasive, multiple purpose, subsurface investigation and monitoring techniques that will improve resolution and reduce uncertainty in measuring, visualising and monitoring the subsurface at all depths. This includes leveraging new technologies such as quantum sensing, fibre-based monitoring, automation/robotics, 4D geoelectrics, advanced laboratory technologies and smart sensors, and development of near surface geophysical tools suitable for imaging the subsurface particularly within urban areas.

3.4. Session 2: Scope and Prioritisation

Session 2 aimed to refine the scope of the potential programme by looking across the themes and research challenges identified in Session 1 and agreeing the key priorities to tackle where research and innovation can best add value.

The key discussion points arising from this session are summarised below.

- Participants noted the scope of the investment and areas that should be prioritised are strongly dependent on the drivers for the programme and whether a more fundamental or applied approach is taken. Participants developed 2 potential programme scopes reflecting each of these approaches:
    - Fundamental approach example: focus on understanding sub-surface fluids and their applications to different uses of the subsurface, including geothermal energy, mineral extraction, storage of CO_2, natural and engineered hydrogen, underground infrastructure.

This would require: better use of data; improved modelling of injectivity, stress changes, chemical reactions, fluid flow, prediction of geophysical attributes; improved sensing, monitoring and exploration; collaboration with industry, regulators and communities.

- Applied approach example: focus on understanding how multiple subsurface technologies can be deployed within a region to decarbonise and provide secure, sustainable energy.

  This would require: integrated datasets; integrated coupled models; upscaling; reducing uncertainties (e.g. associated with geomechanics, fluid flow, induced hazards, smart monitoring, geomicrobiology, and long term impact); working with industry, communities, regulators.

Following discussion, participants noted there were strong similarities and overlap between each of the proposed approaches. Based on the strategic drivers of delivering the fundamental understanding, evidence and tools needed to balance and meet the increasing demands on the subsurface through responsible optimisation of subsurface usage to support green growth alongside enhanced resilience and security for the UK, in conjunction with the intended programme outcomes, they agreed the following key priority areas:

A) Improving fundamental understanding of the subsurface and how it can support multiple uses, to reduce uncertainties and enable the optimisation of subsurface use, including:

- Enhanced understanding of:
  - **the fundamental behaviour of fluid and rocks** under coupled thermo-poro-mechanical conditions
  - **geomechanical properties of the subsurface** including stresses, elastic and strength properties, permeability, faults and fractures, and how these impact and are impacted by different uses of the subsurface and changing subsurface conditions (including under climate change)
  - **chemical and bio-geochemical reactions** (including those mediated by microbiota) within the subsurface and how these impact on and are impacted by different uses of the subsurface and changing subsurface conditions (including under climate change)
  - **the relationships and interactions between the deep, shallow, and near-subsurface** including the impact of disturbance/perturbations/deployment of interventions and implications for subsurface applications
  - **the behaviour of stored materials & substances** and the storage efficiency and containment of materials in the subsurface including under changing subsurface conditions (including under climate change)
- **Identification of opportunities for deployment of multiple subsurface technologies/uses in support of decarbonisation, clean energy and green growth**, and the potential for colocation of different subsurface uses within a specific region or regions, including the interactions between different potential subsurface uses, impacts and risks for the wider subsurface and surface environments, and the socio-economic context.
- **Exploration of circular economy opportunities in subsurface applications**, including asset reuse, by-product valorisation and resource efficiency.
- **Integration of socio-economic, regulatory and public perception considerations**, including risk communication and social license to operate.
- **Understanding of fluxes (water, heat, gas, chemicals) between the subsurface, surface and atmosphere**, including assessment of the impacts of climate change and climate change induced hazards on the subsurface, and implications for different subsurface applications.

B) Harnessing data, models and emerging technologies to support more effective and efficient prediction, assessment, monitoring and evaluation of the subsurface or that supports understanding of the wider environmental impacts and interactions of different subsurface uses:

- **Development of integrated datasets**, including balancing the use of existing data with collecting new data; ensuring data interoperability and enabling AI/ML (machine learning)
- **Development of integrated, fully coupled models to accurately represent the subsurface and predict subsurface behaviour** including in response to engineered perturbations (e.g. cyclic stress, fluid pressure, chemical changes) and climatic variability; and how subsurface responses interact with and impact on subsurface infrastructure and technologies. This includes understanding of model uncertainty and how this needs to be constrained for different subsurface applications.
- **Cohesive upscaling of process understanding** from nano- and lab-scale to field scale, supported by benchmarking experiments and field data
- **Advancement of minimally invasive subsurface imaging, sensing and monitoring technologies**, tailored to different depths and geological settings, to improve characterisation and reduce uncertainty.

Scope:

- Participants agreed that the scope should include both onshore and offshore domains. Whilst interactions between the surface and deeper crust can be considered, the focus is on research challenges around the use of the consolidated subsurface nominally between depths of 10s of metres to kilometres below the critical zone. Areas of focus should be driven by the specific research questions and the subsurface uses/technologies being considered.
- Participants agreed that the programme should have a strong UK focus, but advocated the potential value in enabling international collaboration where appropriate.
- Participants noted the breadth of the areas prioritised and suggested that a programme could benefit from being more tightly focussed, for example on contribution of the subsurface to the energy transition and green growth.

3.5. Session 3: UK capability and requirements to deliver research

Session 3 explored whether the UK has the existing capabilities - such as data, tools, infrastructure and skills – needed to support the research priorities identified in Session 1 and 2, or whether any additional capabilities are needed. Participants highlighted existing assets that could be leveraged, as well as gaps that may potentially impact successful programme delivery.

Key discussion points are summarised below:

- Data and tools
    - Research should make better use of existing data collections and infrastructure such as the NGDC for the collation and sharing of subsurface data
    - Data availability varies across different depths and geological domains, and access to data can vary significantly depending on the ownership/management of different stakeholders.
    - Collaboration with a wide range of data holders/stakeholders (e.g. Environment Agency, National Grid, North Sea Transition Authority, The

Crown Estate, industry) to aid data sharing would reduce the need for new data collection and enable better use of existing data.

- Infrastructure
    - There are significant existing and potentially underutilised research facilities and infrastructure which subsurface research could capitalise on. This is more time and cost effective than developing new infrastructure. Existing infrastructure opportunities which could be used include:
        - National Buried Infrastructure Facility (NBIF)
        - UK Geoenergy Observatories (UKGEOS)
        - National Geological Repository (NGR)
        - Data & Analytics Facility for National Infrastructure (DAFNI)
        - The Alan Turing Institute (in terms of collaboration around geoscience data and AI)
        - Boulby Underground Laboratory (STFC)
        - Floods and Droughts Research Infrastructure (FDRI)
        - United Downs Deep Geothermal plant
        - Diamond Light Source (to help with characterisation)
        - NERC Environmental Omics Facility
        - NERC centres in Edinburgh (Field Spectroscopy Facility, Ion Micro-Probe Facility)
        - NERC Geophysical Equipment Facility including Seis-UK
        - National Environmental Isotope Facility (NEIF)
        - In addition to UK facilities, international opportunities could also potentially be explored (e.g. Denmark's SAFAtor - smart cables and fibre-optic sensing amphibious demonstrator)
    - Furthermore, the following potential gaps in terms of UK infrastructure available that could benefit this research area were identified:
        - Deep boreholes in understudied areas (either through the drilling of new boreholes in understudied areas of the UK or the repurposing of existing wells for scientific research).
        - Subsurface testbeds to test new technologies, processes, models and tools.
- Skills gaps and training needs:
    - Investment in skills and training at all levels is needed to ensure the UK remains at the forefront of subsurface research. Support for doctoral training for subsurface research was noted as a significant gap, with several relevant Centres for Doctoral Training having come to an end in recent years. Key areas highlighted where the UK should prioritise training included hydrogeology, systems thinking in earth sciences, and computational geosciences (specifically the statistical skills needed to implement quantitative analysis techniques).
    - There was acknowledgement that earth sciences departments across HEI's are currently struggling to recruit students and that dedicated funding to support Masters degrees could help to improve widening participation.
    - Participants suggested that secondments to/from other sectors across all career stages could help to cross fertilise ideas and generate solutions.

3.6. Session 4: Potential interventions to drive research and capitalise on the opportunity for innovation

Participants were asked to discuss and identify the most effective, scalable implementation pathways that would maximise the impact of research investment, whilst also ensuring effective stakeholder engagement and facilitating translation of research into impact.

- Programme structure, size and duration:
  - Participants broadly agreed that the programme required a central function (i.e. hub) to ensure cohesion across the programme, integrate knowledge, engage stakeholders, provide leadership and develop capacity. To enable the programme to be agile and responsive to emerging areas throughout its duration it was recommended that the central function could have a dedicated flexible fund.
  - Research grants should have a regional/place focus and be of sufficient scale (i.e. £3-4m) to fully consider the specific geological and social context within a given region or regions.
  - Funding for the hub and research projects should be staggered to ensure that the aims and deliverables of each of these components are complimentary, with the hub established first to support stakeholder engagement with research project development.
  - The research programme would benefit from all components being multi-institutional and multidisciplinary
  - The programme should be at least 5 years in duration
  - A complementary Doctoral Focal Award would help provide a feedstock of talent and ensure programme legacy
- Programme Partners:
  - Industry and policy support at a programme level will help ensure the programme has broad applicability. In addition, relevant policy, industry and public sector partners should be involved at a project level to help drive impact.
  - International partners on programme components should be allowed where clear benefit to the research is articulated, but should not be mandated.
- Incorporating Place:
  - Subsurface geology and consequently potential uses of the subsurface are inherently place based; research will therefore benefit from being place/regionally focussed. Any resulting funding opportunity would need to clearly outline requirements around the regional or place-based nature of projects to ensure clarity that applicant project teams do not have to be located within the region of focus; this will avoid introducing biases around institutions who could apply to the opportunity.
- Ensuring research is translated into impact
  - Additional targeted funding toward the end of the programme would help to accelerate progression of research outputs into impact (e.g. through commercialisation activities or working with industry) and could attract industry co-investment.

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4. Next steps

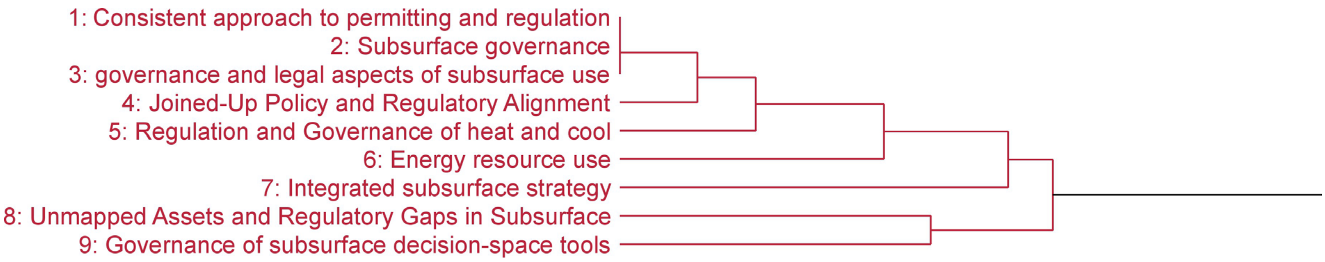
The outputs of the workshop will help NERC to refine the potential programme concept, scope and delivery mechanisms. NERC will continue to work with potential investment partners to explore R&I opportunities in this area. If you have any feedback or would like to discuss this area further, please contact: EarthEnergyResources@nerc.ukri.org

5. Annex A – Well Sorted ideas and grouping

NERC gathered the views of our academic and industry communities via an open survey using the 'Well Sorted' tool to ask for responses to the question: "What are the key knowledge gaps that, if addressed by research and innovation, will deliver a significant step change in optimising the use of the subsurface?".

Subsequently, those invited to attend the scoping workshop were asked to use the Well Sorted platform to group submitted ideas in ways that made sense to them. Well Sorted then combined all participants' groupings to generate an overall structure, consisting of 9 groups of ideas. The below tables present all responses received to the survey, structured into the 9 groupings. These ideas and groupings were shared with workshop participants in advance of the workshop, and were used to inform workshop discussions.

Raw Group Data: Red Group



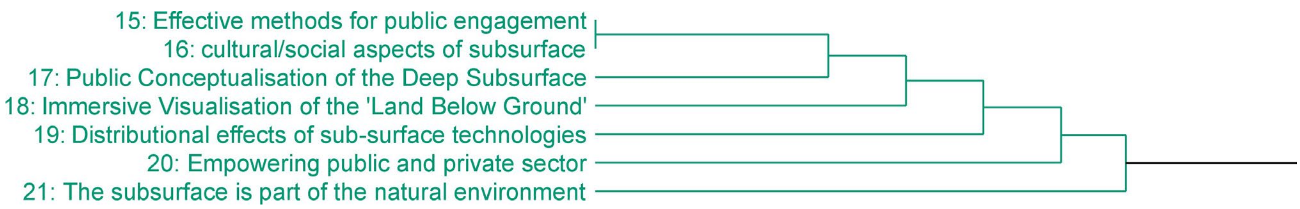
Colour	#	Title	Description
Red	1	Consistent approach to permitting and regulation	Different permitting standards could be applied to address very similar impacts associated with subsurface exploitation. Understanding the effects of these technologies will help ensure market confidence and support robust business cases for investment
	2	Subsurface governance	We must plan for optimal & sustainable use for different purposes, but uses are all regulated differently, e.g. rights for water or mineral extraction may be held by different people. Hence need to understand landscape and propose integrated approaches
	3	governance and legal aspects of subsurface use	There is a need to research governance and legal aspects of subsurface use. Currently it is highly fragmented (Grecksch, 2021) and could have serious implications for example for groundwater.
	4	Joined-Up Policy and Regulatory Alignment	Progress on subsurface use is often stalled by fragmented planning, regulation, and policy. We need frameworks that foster collaboration between researchers, planners, and regulators--especially environmental agencies--to enable timely, informed decisions

	5	Regulation and Governance of heat and cool	How can we adequately and cheaply monitor subsurface heat and cool and make that data available as a regulatory tool for Local Authorities and possibly the Environment Agency (and devolved equivalents) to manage and govern that resource
	6	Energy resource use	Do typical engineering companies, the EA, etc, sufficiently consider the full range of future subsurface uses related to energy resources? For example, geothermal. Do we have regulations, permitting processes that are fit-for-purpose?
	7	Integrated subsurface strategy	There is considerable work being done in relation to the subsurface but other this work is siloed within particular policy initiatives or areas of expertise. To fully understand the potential of the subsurface, an integrated strategy is needed.
	8	Unmapped Assets and Regulatory Gaps in Subsurface	Limited subsurface planning rules mean many subsurface assets remain unmapped, creating uncertainty and increasing risks. Improved regulation and mapping are needed to support safe, efficient, and coordinated subsurface development.
	9	Governance of subsurface decision-space tools	The geoscience community has capability to create a digital decision-space tool for the subsurface environment, but how would decision-makers use it, and who would be responsible for managing and maintaining it?

Raw Group Data: Blue Group

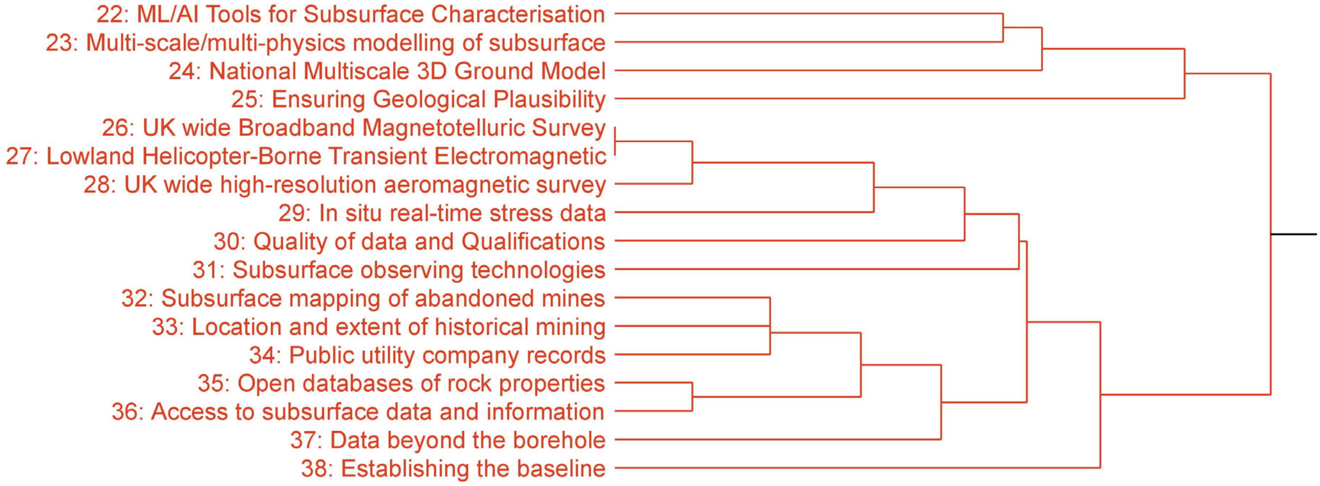
Colour	#	Title	Description
Blue	**10**	Open, cross-sector collaboration in research	Regulatory fragmentation, subsurface data gaps, and limited public awareness are some of the main challenges. There is a need for open, cross-sector collaboration in research.
	11	Need to bridge disciplines	Even within a particular sector (say energy), there is a need to bridge disciplines (and thus issues) such as geotechnical engineering, construction, regulation & policy, urban planning, consumer confidence.
	12	Potential for cross-sectoral innovation	As need to use subsurface space efficiently, we need to better understand the potential for collaboration and innovation between different sectors. What can be used in a multifunctional or circular way, what can be repurposed etc.
	13	Holistic subsurface understanding	Lack of integrated data on geology, groundwater, and subsurface assets hinders effective development. A holistic subsurface model is needed to support sustainable, informed decision-making and reduce environmental and operational risks.
	14	A systemic vision	How the subsurface is used/ managed today is based on historical legacy. Are we locked in not only the specific functions but also the paradigms that led to them? A systematic analysis to develop a vision what truly integrating the subsurface would mean.

Raw Group Data: Green Group



Colour	#	Title	Description
Green	15	Effective methods for public engagement	'Unlocking the subsurface' requires a social license. While there are studies on public perceptions of novel sub-surface technologies, there remains far less on effective methods for involving communities/publics in decision-making.
	16	cultural/social aspects of subsurface	Social Sciences and Humanities (and Arts) need to play a bigger role in subsurface research. Currently we are on track to repeat the same mistakes as above ground if we don't 'break' the engineering dominance in subsurface research.
	17	Public Conceptualisation of the Deep Subsurface	Psychologists stress the negative framing of geoenergy projects as 'tampering with the subsurface' weakens public acceptance and undermines social licence to operate, but what cognitive frames allow people to perceive the subsurface world more positively?
	18	Immersive Visualisation of the 'Land Below Ground'	Immersive visual environments offer lay audiences highly dynamic, multi-sensory experiences of the geological subsurface, allowing digital arts researchers to redefine scientific storytelling about our contested use of the land below ground
	19	Distributional effects of sub-surface technologies	Studies are required that explore the social impacts of these novel technologies, and their environmental impacts, and how these effects different societal groups (e.g. with respect to equity).
	20	Empowering public and private sector	What inhibits public and private sector actors from developing and using 3D subsurface decision-tools, and what is needed to empower them to harness the capability that geoscience offers?
	21	The subsurface is part of the natural environment	The subsurface is not treated with the same case as other environmental features like trees or water. What would it mean to truly integrate the subsurface into our understanding of nature? Would its use change? What does the public need to know to engage?

Raw Group Data: Orange Group

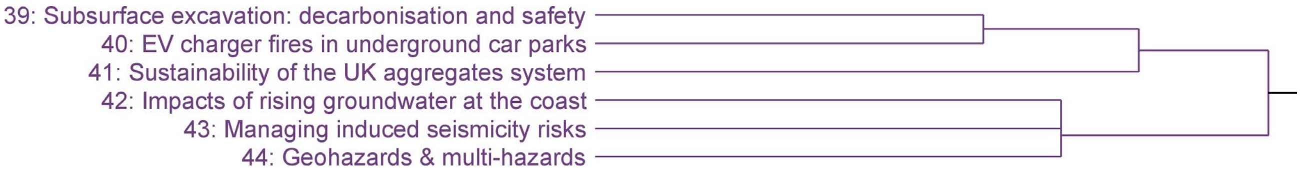


Colour	#	Title	Description
Orange	22	ML/AI Tools for Subsurface Characterisation	ML and AI has the potential to accelerate unlocking the subsurface allowing more opportunities to be generated, whilst adding better understanding of probability. At present this toolset is in its infancy - efforts are needed to fill this gap.
	23	Multi-scale/multi-physics modelling of subsurface	Large-scale subsurface phenomena (e.g. collapse) depend on micro-scale interactions (e.g. grain crushing). Different disciplines (engineering, geology, granular physics, hydrology) model these, but an integrated complex-systems approach is still missing.
	24	National Multiscale 3D Ground Model	Understanding natural subsurface conditions, especially within the top 300 meters, is crucial. 3D geological modelling creates a 'digital twin' of the subsurface, as seen in the Netherlands. This could be used to predict Interactions in the subsurface.
	25	Ensuring Geological Plausibility	Subsurface model generation is often inaccurate leading to poor outcomes. For example, whilst statistically valid, models can be geologically unrealistic. Regional geological context and adherence to rules needs to be baked-in to models to improve success
	26	UK wide Broadband Magnetotelluric Survey	Broadband magnetotelluric measurements provide a low-cost passive method for determining subsurface properties such as conductivity, temperature and water content in the upper 50m-5kms. A UK-wide survey would provide new data for geological applications.
	27	Lowland Helicopter-Borne Transient Electromagnetic	Visualizing subsurface structures and groundwater/gas movement is crucial for infrastructure and resources. Helicopter-borne TEM surveys, used in Denmark and other countries, could map UK subsurface pathways, mineral bodies, and groundwater.

	28	UK wide high-resolution aeromagnetic survey	A complete UK wide aeromagnetic surveying was last completed in 1960. A modern survey with improved positioning and quantum sensor technology would provide a huge long term return on investment for geological applications, similar to the Tellus project.
	29	In situ real-time stress data	Increasing demands on the subsurface require knowledge of the in situ stress state. We need real-time sensors measuring the in situ stress at depth at sites around the UK - boreholes, mines, and caves. This will decrease costs and increase safety.
	30	Quality of data and Qualifications	It's important that the individual who is gathering the initial data is appropriately qualified in drilling. Be that a BDA audited driller as example. Consultants often don't follow through with BS 22475 parts 2&3 devaluing the drilling.
	31	Subsurface observing technologies	Near-surface geophysics (applicable to imaging the Critical Zone) is a significantly under-resourced and under-researched area of science in the UK. However, these methods and technologies offer crucial insights into subsurface use across multiple sectors
	32	Subsurface mapping of abandoned mines	Abandoned mines offer potential for low-carbon heating and cooling, but long-term use relies on understanding mine geometry--often based on outdated miner drawings. Modern subsurface mapping technologies are needed to improve accuracy and system design.
	33	Location and extent of historical mining	The record of historic mining is poor and especially for non coal mining. Records of recent post 1873 mining was held by HSE but has now lost. In some areas records are in private ownership and not available to public resulting in collapse of structures
	34	Public utility company records	Most public utility companies hold databases of subsurface boreholes and water monitoring. These would be invaluable to any proposed development.
	35	Open databases of rock properties	Subsurface operations need open, easy to find and use rock property data. There is a paucity of these databases for the rock formations of interest to the Energy Transition, throughout the UK.
	36	Access to subsurface data and information	How can we unlock subsurface data and information from various national bodies (BGS, Cranfield University, MRA to mention just a few) and make it accessible in a common format and platform to all actors involved in decision making.
	37	Data beyond the borehole	Understanding / visualising the subsurface beyond boreholes relies on empirical models -- established in oil & gas but limited in other applications. Novel data collection and more forward modelling approaches will improve subsurface exploration.

	38	Establishing the baseline	Establishing the environmental baseline (e.g. groundwater, surface-water quality) before any regional subsurface development with subsequent monitoring will provide understanding of any changes during development and reassurance that impacts are minimised

Raw Group Data: Purple Group



Colour	#	Title	Description
Purple	39	Subsurface excavation: decarbonisation and safety	Excavation of underground space is a carbon intensive process, generally relying on diesel powered machinery. Attempts to decarbonise the sector are ongoing, but the safety issues of switching to H2 or battery powered machinery have not been quantified.
	40	EV charger fires in underground car parks	A significant number of electric vehicle fires occur when charging. EV chargers are becoming common in underground spaces. This will lead to an increase in unattended vehicle fires underground. This needs understood before safety levels can be improved.
	41	Sustainability of the UK aggregates system	Sand, gravel, and crushed rock, aka aggregates, are the most extracted solid materials. Growing demand is damaging ecosystems, triggering social conflicts, and fuelling concerns over sand scarcity. Sustainable pathways needed at system level to meet needs
	42	Impacts of rising groundwater at the coast	The coastal area is a complex zone experiencing multiple processes. Impact of rising groundwater and changes in salinity on coastal sites not well known but can affect: landfill & industrial sites, people & water supply, flora & fauna, infrastructure.
	43	Managing induced seismicity risks	Increased pressures caused by subsurface fluid injection (e.g., CCS) can cause induced earthquakes. Where multiple activities inject into the same rock volume (e.g., a regionally extensive aquifer), managing induced seismicity hazards becomes challenging
	44	Geohazards & multi-hazards	Geohazards and multi-hazards have the potential to significantly impact the sustainable and responsible optimisation of the subsurface. Disaster risk and resilience to geohazards are key cross-cutting considerations for Unlocking the Subsurface.

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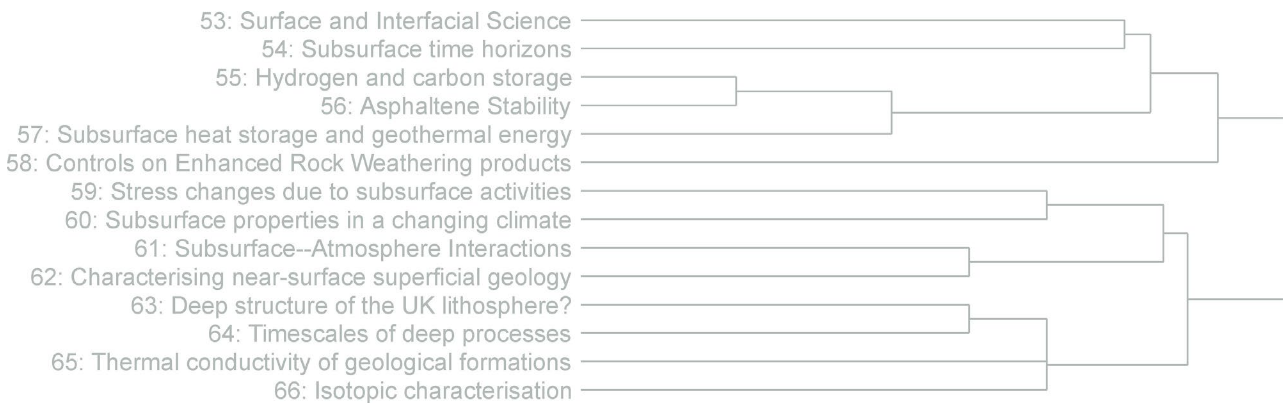
Raw Group Data: Yellow Group

Colour	#	Title	Description
Yellow	45	Combination and competition of uses	In densely populated areas there will be competition for the subsurface. How can we ensure that one installation doesn't negatively influence its neighbour.
	46	Sharing the pore space equitably	For fluid disposal operations (e.g., CCS), the pore space itself is a commodity of value. How can we share this pore space in an equitable way between numerous different industrial users?
	47	Co-located novel subsurface energy technologies	New energy technologies decarbonise numerous sectors that require energy. Optimised use of the subsurface is beneficial but cumulative environmental impacts are poorly understood. These could lead to public hesitancy in adopting these technologies.

Raw Group Data: Pink Group

Colour	#	Title	Description
Pink	48	Link of subsurface to surface infrastructure	While the subsurface holds tremendous potential, the costs/risks are usually high and success depends on surface infrastructure. It is critical to assess the interplay between different subsurface uses (e.g. heat and minerals) with surface infrastructure.
	49	Co-dependence of sub-surface and built structures	When the sub-surface is used for built structures, like metro systems, water distribution pipes, etc. the emergent natural-built sub-surface has properties which are not well known.
	50	Interaction between surface and subsurface	What we do under the ground has an impact on the surface (requires access points, facilities, particular landscape design). We need to better understand the interactions and potential feedbacks between surface and the subsurface to ensure sustainable use.
	51	Circularity of sub-surface	When 'spoil' is removed from the natural sub-surface as part of the construction of a new grey infrastructure, e.g. a new road tunnel, or a sewage network, the process destroys the sub-surface structure and reduces the value of the 'spoil'.
	52	Interaction between natural and engineered systems	Using the subsurface blurs the boundary between the natural and engineered environment. How could natural microbial processes affect engineering materials? Can we cost this? Can we mitigate against it? Can we exploit beneficial microbial processes?

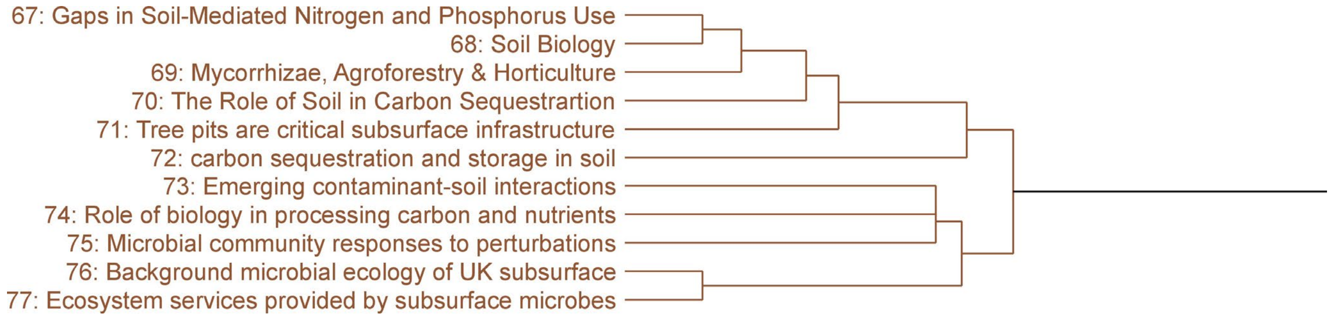
Raw Group Data: Silver Group



Colour	#	Title	Description
Silver	53	Surface and Interfacial Science	Key interfacial science gaps in CO? storage include limited data on wettability, interfacial tension, and film stability under reservoir conditions. These affect trapping and injectivity, requiring advanced tools and models to predict subsurface behaviour.
	54	Subsurface time horizons	Mapping the subsurface over a range of time horizons e.g. 10,100, 1000 years to better understand how the decisions we make today may preclude use of that space going forward. And how do we govern different subsurface uses over different time horizons.
	55	Hydrogen and carbon storage	There is a need to optimise injection, pressure management and extraction (in the case of hydrogen) of CO2 and hydrogen in subsurface aquifers -- hydrogen storage (1-2 months of UK power) is critical for managing intermittency of renewable energy
	56	Asphaltene Stability	CO? injection in depleted oil reservoirs can trigger asphaltene precipitation, causing pore blockage and reduced injectivity. Key gaps include limited understanding of phase behaviour, interfacial interactions, and impacts on storage capacity and flow.
	57	Subsurface heat storage and geothermal energy	Understanding of the potential for heat storage in subsurface aquifers at shallow depths is required for heating and cooling for heat networks across the country -- also the potential for geothermal power and heat generation from deeper in the crust
	58	Controls on Enhanced Rock Weathering products	ERW is promoted as a successful CDR technique, relying on cations entering pore waters, then groundwater before reaching rivers and the ocean. Many external factors influence this success, including the chemistry and biology of subsurface soils and rocks.
	59	Stress changes due to subsurface activities	Many subsurface activities, from near-surface to several kilometres depth, involve transient or permanent changes in the stress state. This interacts

			with and may alter the present strain field and trigger seismicity. Do we know enough about this?
	60	Subsurface properties in a changing climate	Soil, rock and groundwater behaviour will be impacted by climate change, especially drought and intense rainfall. This needs to be better understood for all applications in the subsurface.
	61	Subsurface--Atmosphere Interactions	We lack understanding of how gases and fluids migrate from the subsurface to the atmosphere under different conditions. Research is needed on flux pathways, rates, and risks to support safe storage, emissions accounting, and environmental monitoring.
	62	Characterising near-surface superficial geology	The near surface (first 5-10m) is a key area where the geology interacts with buried infrastructure and rivers & streams. It's highly heterogeneous, generally poorly characterised, difficult to model but highly significant and hence a key knowledge gap.
	63	Deep structure of the UK lithosphere?	It's >40 yr since large-scale geophysical studies of the UK lithosphere. National high resolution seismic, etc., surveys of crustal structure, temperature and permeability would unlock new learning on its history, minerals, geothermal and CCS potential.
	64	Timescales of deep processes	Geological processes in the deep observed crust are "timed" by isotopic and mineral-chemical methods (to - '000s years), or as near-instantaneous seismic events. How can we constrain deep events that occur on intermediate timescales?
	65	Thermal conductivity of geological formations	Accurate thermal analysis is key to the long-term performance of shallow geothermal systems. Ground conductivity--affected by soil moisture and porosity--plays a critical role and changes over time, making detailed hydrothermal characterization essential.
	66	Isotopic characterisation	Use of a comprehensive suite of stable and radiogenic isotopes to characterise in-situ fluids incl gases and any introduced fluids to aid understanding of fluid transport, processes and sources

Raw Group Data: Brown Group



Colour	#	Title	Description
Brown	67	Gaps in Soil-Mediated Nitrogen and Phosphorus Use	Improving nitrogen (N) and phosphorus (P) use efficiency is critical for enhancing global food security while reducing environmental degradation. Soils are central to the cycling, retention, and loss of these essential nutrients, yet major knowledge gaps
	68	Soil Biology	We don't feel information exists about how biological and mycorrhizal communities may respond differently to extreme weather events and how that could impact horticultural crop health.
	69	Mycorrhizae, Agroforestry & Horticulture	We would like to better understand if agroforestry could support mycorrhizal activity which supports the health of horticulture crops through extreme weather events.
	70	The Role of Soil in Carbon Sequestration	Soils represent one of the largest terrestrial carbon reservoirs, yet critical knowledge gaps remain in understanding their full potential for long-term carbon (C) sequestration. Current models often emphasize aboveground biomass, underestimating the comp
	71	Tree pits are critical subsurface infrastructure	Load-bearing tree pits are critical urban infrastructure enabling tree growth, vehicular traffic, utility encasement & stormwater harvesting. How are disciplinary silos broken to unlock the subsurface & realise the multifunctionality of urban tree pits?
	72	carbon sequestration and storage in soil	Many CCS technologies are related to soils (e.g., biochar, enhanced weathering) but it is unclear how soil functions/health will be affected by these technologies. More mechanistic studies and field trials are needed to gather evidence and fill the gaps.
	73	Emerging contaminant-soil interactions	Transport of emerging pollutants in the subsurface is not well understood such as micro/nano-plastics, PFAS and pharmaceuticals. We need to develop tools/methods to study the mechanisms of contaminant-soil interactions and remediation technologies.
	74	Role of biology in processing carbon and nutrients	A lot of life lives subsurface and processes carbon, nutrients and water that enters our groundwater and

			rivers. How climate change will impact subsurface biogeochemical cycles is not well constrained, with implications for CDR techniques.
	75	Microbial community responses to perturbations	Quantifying responses of microbial community to perturbations and impacts on subsurface utilisation cuts across all themes. Optimisation of beneficial processes, control of negatives e.g. biofouling, infrastructure degradation, water quality.
	76	Background microbial ecology of UK subsurface	Fundamental understanding of the background microbial ecology of UK subsurface needs to be better understood, including distribution of functional groups across key rock types, coupling of processes they mediate, energy sources etc.
	77	Ecosystem services provided by subsurface microbes	Microbes provide various ecosystem services in the subsurface, but their contribution is not well understood for many geological settings that will be used in the future. These should be investigated and impact of disturbing them quantified.

6. Annex B – Workshop Attendees

- Mike Kendall, University of Oxford (Chair)
- Michelle Bentham, BGS
- Adrian Butler, Imperial College London
- Jonathan Chambers, BGS
- Anthony Croxford, University of Bristol
- Katriona Edlmann, University of Edinburgh
- Alexandra Gormally-Sutton, Lancaster University
- Chris Jackson, WSP
- Jonathan Lloyd, University of Manchester
- Fleur Loveridge, University of Leeds
- Zoe Shipton, University of Strathclyde
- Mike Simmons, Halliburton
- Dan Smith, University of Leicester
- James Todd, ARUP
- Andrew Valentine, Durham University
- Liz Varga, UCL
- James Verdon, University of Bristol
- Lorraine Whitmarsh, University of Bath

UKRI attendees

- Sarah Newport, NERC, Head of Earth, Energy and Resources
- Charlotte Hawkins, NERC, Senior Programme Manager
- Daniel Knight, NERC, Senior Programme Manager
- Luke Williams, NERC, Programme Manager
- Andrew Telford, ESRC, Senior Programme Manager
- Andy Lawrence, EPSRC, Head of Engineering
- Simon Crook, EPSRC, Senior Portfolio Manager
- Chris Henwood, Innovate UK, Lead on Industrial Decarbonisation