

The UK's geological feasibility for onshore in-situ CO₂ mineralisation

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Climate services for a net zero resilient world



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Data Reporting

This report utilises the British Geological Survey (BGS) Digital Geological Map of Great Britain (formerly known as DiGMapGB) at a range of scales. All data were projected in British National Grid (BNG), EPSG:27700. These data are open access having been made available under the Open Government Licence and can be downloaded at https://www.bgs.ac.uk/datasets/bgs-geology/. Additional information was sourced from literature available in the public domain and has been cited both in the main text and reference list.



About CS N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-NOW aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.







Natural Environment Research Council





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A summary for policy makers

In-situ CO_2 mineralisation in mafic and ultramafic rocks is an alternative solution to the more mature, conventional CO_2 storage in porous geological formations. It removes CO_2 by facilitating the chemical reaction between CO_2 with rocks that are rich in calcium, magnesium or iron to form solid carbonate mineral, thereby permanently trapping the CO_2 .

At the time of writing (March 2024), there is operational one plant. globally, located in Iceland and operated by the company Carbfix. Two further in-situ projects are in development in Oman and the UAE, pioneered by a company called "44.01". In the UK, there are several regions where, the geology might be suitable for in situ CO₂ mineralisation



¹Figure SMP (summary for policy makers). Location map of all potentially suitable geological formations for CO₂ mineralisation across the UK, colour coded based on reactive mafic and ultramafic lithologies (green - highest to red - lowest potential). © BGS/UKRI 2024. All rights reserved. Contains Ordnance Survey data © Crown copyright and database rights 2024. NEXTMap Britain elevation data from Intermap Technologies.

(¹Figure SMP). To date, only the areal extent of these geological formations has been determined. It is not yet known how much CO₂ these formations may be able to sequester. In-situ CO₂ mineralisation is subject to several techno-economic, environmental, and social constraints that currently limit exploitation of this potential technology. This review highlights the existing gaps in data and knowledge surrounding *in-situ* CO₂ mineralisation in the UK, including constraints related to regulations and supply chains. The main findings are

¹This map is purely theoretical and is based on current geological knowledge, available data and inherent limits of analysis at a national scale. The location of existing infrastructure or sites of natural or scientific interests were not considered. Due care should be taken in interpreting this information and data, with consideration to the limitations outlined above. Neither UK Research and Innovation (UKRI) as represented by BGS, nor BGS makes any warranty or representation as to the quality, accuracy, suitability for use for any purpose, or to the completeness of the information or data provided. The use of any information or data provided by the BGS or UKRI is at your own risk. BGS nor UKRI will not be held responsible for any liabilities or consequences arising out of any inaccuracies or omissions, whether intentionally, negligently or otherwise, in the information or data provided; nor use made of it.



summarised below alongside some proposed next steps for improving technology prospects in the UK.

Summary of knowledge gaps and recommendations for the next steps in-situ CO2 mineralisation R&D

	Knowledge gap	Next steps
1	Inconsistent data limiting the identification and 3D delineation of suitable UK formations, including width, length, and thickness of formations at or below the surface; and in subsurface architecture, such as stratigraphy, faults, fractures across the proposed potentially suitable geological formations (PSGF)	Systematic subsurface mapping campaign of all PSGF to improve the understanding of fracture pore networks, identify areas for permanent containment, including depth and temperature at which the UK could support CO ₂ injection, and obtain estimates of storage capacities.
2	Lack of understanding relating to the effectiveness of UK mafic and ultramafic rocks to store CO_2 , including insufficient high-resolution (1-5 m intervals) assessments of the UK mineralogical and geochemical diversity, alterations; physical (porosity and permeability) and geo-mechanical properties at depth of the proposed PSGF	Comprehensive sampling, laboratory characterisation and experimental assessment of CO ₂ fluid – rock interaction of UK igneous lithologies to create a representative dataset of all reactive to non- reactive rocks as well as improve our understanding on the evolution of geochemical
3	Lack of robust understanding of the effect of temperature, pressure, and various CO ₂ -bearing fluids on the potential of UK's mafic and ultramafic lithologies to mineralogically trap CO ₂	and physical properties in given PSGF over time
4	Lack of tested workflows and proven monitoring methods to demonstrate safe and permanent containment of CO ₂ in the target lithologies	A review of current workflows in at-scale injection operations in Iceland and Oman and adaptation of current UK regulations and guidance to facilitate safe application of the technology in the UK
5	Lack of specific regulations for activities related to CO ₂ deep mineralisation onshore or offshore, either via storage license or environmental permit	Development of generic risk assessments for credible case studies to assist regulators in the formulation of appropriate regulations and guidance

Concluding remarks. Some of the UK 's geology has potential to be suitable for in-situ CO_2 mineralisation, but significant knowledge gaps and technological uncertainties remain. These make it difficult to assess the scale of the opportunity for the UK. This report sets out the main geological, regulatory and supply chain requirements for developing the technology in the UK. Some investment in R&D will be required to be able to provide a realistic appraisal of the potential for CO_2 mineralisation technology in the UK, such as scoping studies that integrate the geological and non-geological factors pertaining to the injection of CO_2 at depth. Initially, these could focus on the formations that are most suitable as CO_2 mineralisation targets. There is also an opportunity to create potential synergies with the ex-



situ CO₂ mineralisation and UK mineral and waste industry. The advantages and trade-offs of any significant R&D investment into CO₂ mineralisation in the UK have not been evaluated here.

Executive summary

Carbon Capture and Storage (CCS) is a critical decarbonisation strategy ¹ and currently removes around 40 Million tonnes (Mt) of carbon dioxide (CO₂) per year globally ². The UK government aims to capture and store 20 - 30 Mt of CO₂ per year by 2030 and over 50 Mt CO₂ per year by 2035 in porous reservoir formations deep underground in the UK's offshore. In 2023, the Global CCS Institute reported that there has been a rapid increase in the number of CO₂ capture projects in various stages of development. Projects with a total capacity for storing up to 361 Mt CO₂ per year are now in development, construction, and operation ³.

Carbon Capture and Storage by mineralisation, otherwise referred to as mineral carbonation or CO₂ mineralisation (used in this report) belongs to a portfolio of proposed decarbonisation methodologies ⁴. It is an alternative solution to the more mature, conventional CO₂ storage in porous geological formations. Fundamentally, CO₂ mineralisation is a chemical reaction of CO₂ with low porosity hard rocks that contain significant amounts of calcium (Ca), magnesium (Mg) and/or iron (Fe). The reaction results in the mineral trapping of CO₂ in solid carbonate minerals, such as calcite (CaCO₃), magnesite (MgCO₃), or siderite (FeCO₃), offering a secure and permanent removal of CO₂ from the atmosphere ⁵. There are several strategies to achieve CO₂ mineralisation, including;

- *in-situ CO₂ mineralisation*, where the CO₂ is injected into the subsurface and reacts with the target geological formation at depth,
- ex-situ CO₂ mineralisation, which is an above-ground method that takes place in specifically designated carbonate plants where the captured CO₂ is brought in contact with Ca, Mg and/or Fe bearing feedstock materials,



- surficial mineralisation is the above-ground mineralisation of atmospheric CO₂ through reaction with existing surface feedstock materials located at the surface, such as mine tailings or smelter slags,
- enhanced weathering, where the feedstock is spread over fields and reacts with atmospheric CO₂.

The Department of Energy Security and Net Zero commissioned the British Geological Survey and University College London to undertake a high-level literature review of the *UK's geological feasibility for onshore in-situ* CO₂ *mineralisation,* including supply chains and current regulations around onshore injection of CO₂.

CO2 MINERALISATION STATE-OF-THE-ART GLOBALLY.

The CO₂ mineralisation potential in hard rock geological systems has been estimated at 60 million Gigatonnes (Gt) CO₂ globally, assuming full carbonation ⁶ as well as technoeconomic and environmental viability. This equates to more than 1.5 million years of CO₂ storage at current global CO₂ emissions of around 40 Gt per year. The numbers are quoted to highlight the vast potential of hard rock geological formations to contribute to global decarbonisation. However currently, there are techno-economic, environmental, and social constraints to exploiting this potential resource.

Potentially suitable geological formations (PSGF) for mineralisation in hard rock systems are those that:

- (i) contain abundant magnesium (Mg), calcium (Ca) or iron (Fe) silicate minerals for reaction with the CO₂. These rocks are typically formed by igneous processes and the cooling of magma (molten rock) derived from below the Earth's surface. They can be classified into four groups based on their chemical composition: ultramafic, mafic, intermediate and felsic, of which ultramafic (e.g. peridotite) and mafic (e.g. basalt) rocks have the highest proportions of Mg, Fe and Ca and are thus regarded as most suitable for CO₂ mineralisation processes.
- (ii) exhibit sufficient porosity (surface area for the reactions to take place) and permeability (the ability of fluid to travel through rocks) to provide fluid pathways



that facilitate migration of the injected CO₂ and enable it to come into contact with as much of the storage formation surface area as possible.

At the time of writing, three in-situ CO₂ mineralisation projects are underway globally, including injection of CO₂ into ultramafic rocks in Oman and the UAE (pioneered by a company called "44.01"), into mafic rocks in Iceland (by the company Carbfix), and one completed, the Wallula Basalt Project in Washington State, USA. The projects show that CO₂ mineralisation is a complex endeavour and requires multi-dimensional understanding of the interplay between:

- the geological conditions at the chosen site, including the depth, pressure, temperature, mineralogy and geochemistry of the formation rocks; as well as structural, seismic, and hydrological regimes,
- the injection fluid and CO₂ trapping mechanism at depth. CO₂ dissolved in water (freshwater, seawater) and ²supercritical CO₂ have been used in mineralisation projects globally. While dissolving CO₂ in water offers immediate solubility trapping followed by mineral trapping with time; the injection of less buoyant supercritical CO₂ requires the presence of caprock to prevent it from escaping the target formation before the mineral trapping is complete.
- injection-driven geochemical and physical feedback and, associated evolution of the formation properties over time to appraise and ultimately avoid undesired consequences (contamination or disturbance of subsurface integrity).

CO₂ mineralisation can also be undertaken above ground (ex-situ). This technology is on the rise, with several pilot and small industrial plants in operation globally, including in the UK. Utilisation of mine waste, including tailings and post-metal recovery materials, as a feedstock provides an attractive prospect to integrate processes and technologies for a more efficient transition to Net Zero. The UK critical minerals strategy ⁷ includes a commitment to accelerate the UK's domestic capabilities, and there is an opportunity to create potential synergies with the ex-situ CO₂ mineralisation that could be explored further. For example, some of the expected waste materials from mining and processing of critical minerals ore

² Supercritical CO₂ has a viscosity of a gas and the density of a liquid, attained at >31.1 °C and 73.9 bar



deposits might have compositions that make them suitable for use as feedstock for ex-situ CO₂ mineralisation.

GEOLOGICAL POTENTIAL OF THE UK.

A geological screening for mafic and ultramafic Potentially Suitable Geological Formations (PSGF) was undertaken, which included identifying and ranking all geochemically relevant lithologies and colour coding them (A, green; B, amber; C, red), according to their CO₂ mineralisation potential (A; highest, C; lowest) (Figure ES).





³Figure ES (Executive Summary). Location map of all potentially suitable geological formations (PSGF) for CO₂ mineralisation across the UK, colour coded based on reactive mafic and ultramafic lithologies. © BGS/UKRI 2024. All rights reserved. Contains Ordnance Survey data © Crown copyright and database rights 2024. NEXTMap Britain elevation data from Intermap Technologies.

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Based on available geological bedrock data, the ten most significant PSGF (in terms of their area) have been identified (Figure ES). Each PSGF comprises of more than 85% of highly reactive lithologies and have outcrop surface areas >134 km². There are five in North-West Scotland (Skye Lava Group, Mull Lava Group, Little Minch Sill Complex, Blackstone Band Igneous Complex, Ardnamurchan Central Complex), one in North-East Scotland (Insch Pluton), one in Central Scotland (Clyde Plateau Volcanics), two in Northern Ireland (Antrim Lava Group, Tyrone Volcanic Group) and one in South-West England (the Lizard Complex). An additional PSGF has been identified (Table ES) on Shetland (the Shetland Ophiolite) based on its lithological significance. From this selection, PSGF that are geologically similar to existing, at scale experiments have also been identified.

As no direct measurements were available, relevant analogue data (*e.g.* porosity in igneous rocks) was compiled and used to help calculate Theoretical Pore Space for CO₂ mineralisation for each proposed PSGF.

Table ES (Executive Summary). List of PSGF discussed in the text, with their number relating to descending total outcrop
surface area. Thickness values have been taken as a mean of published estimates and will include surface and subsurface
values. Outcrop surface area values and percentages of geochemically reactive lithologies ranks A to C are from this study.
The Shetland Ophiolite Complex is known to extend offshore but has not been defined using the existing data and are
therefore not shown in Figure ES.

No	Potentially Suitable Geological Formation	Thickness (km)	Offshore Area (km²)	Onshore Area (km²)	Total Area (km²)	Rank A (%)	Rank B (%)	Rank C (%)
1	Antrim Lava Group	0.8	158	3446	3604	98.94	0.02	1.05
2	Skye Lava Group	1.5	843	976	1819	89.62	10.32	0.07
3	Mull Lava Group	1.13	826	744	1570	99.48	0.24	0.29
4	Clyde Plateau Volcanics	0.49	-	1094	1094	85.92	12.49	1.59
5	Little Minch Sill Complex	0.25	509	91	600	100.00	0.00	0.00
6	Insch Pluton	2.5	-	216	216	100.00	0.00	0.00
7	Blackstone Band Igneous Complex	26	184	-	184	100.00	0.00	0.00
8	Tyrone Volcanic Group	4.5	-	143	143	100.00	0.00	0.00
9	Ardnamurchan Central Complex	2.5	76	65	141	89.19	10.74	0.07
10	Lizard Complex	0.95	81	54	135	100.00	0.00	0.00
19	Shetland Ophiolite Complex	1	Undefined	72	72	73.45	26.55	0.00



UK REGULATIONS.

Existing regulations for conventional CO₂ storage in porous formations, and the associated guidance documents, have been reviewed to assess their applicability to CO₂ mineralisation. As CO₂ mineralisation is a less mature storage technology, there is currently no specific regulation for this technology in the UK. In this review, it is assumed that the current regulatory process for CO₂ injection and storage will form the basis for future regulation of in-situ CO₂ mineralisation. Conventional CO₂ storage is principally regulated by the North Sea Transition Authority which awards a storage licence, allowing exploration and appraisal of the geological volume and a storage permit, which allows injection of CO₂ for permanent containment. The regulations apply nationally and are specific to offshore storage. There are no specific regulations for onshore storage. This regulatory process requires a riskbased geological site appraisal. From a geological viewpoint and given the current state of knowledge, the risk-based approach is considered appropriate for application to in-situ CO₂ mineralisation operations provided that the requirement to demonstrate safe and permanent containment will remain. However, these regulations and guidance were developed for CO2 storage in deep porous reservoirs in the UK continental shelf offshore. As the conditions are notably different for deep CO₂ mineralisation (in terms of site location and properties of the target formations), the risks and uncertainties associated with this technology will differ to those associated with conventional CO₂ storage. Therefore, it is anticipated that regulations will require a more detailed review to ensure practical application to specific operational attributes and risk profiles of storage in fractured mafic and ultramafic rocks, particularly onshore.

A fundamental requirement of the regulations for conventional CO_2 storage is the robust demonstration that, following project closure, the CO_2 will be safely and permanently contained. This requires establishing conformance between observed site performance and predictions of future evolution. Deep CO_2 mineralisation is likely to require development, testing and validation of novel monitoring technologies to confirm the secure trapping of CO_2 within the storage reservoir. New developments may also be needed for modelling tools that predict future site evolution as these are likely to be different to those used in conventional CO_2 storage. For example, it is expected that there will be a greater reliance on geochemical



modelling, coupled with simulations fracture-based fluid flow, to test scenarios of future site evolution.

SUPPLY CHAINS.

Given the early stage of technology development, knowledge of the supply chain for storage of CO₂ through in-situ mineralisation is currently limited, with only three projects at demonstration scale. This review explores mineralisation supply chains through interviews with two of the three in-situ mineralisation demonstrators (Carbfix and 44.01) and focused review of existing literature on CO₂ mineralisation. It draws upon UCL expertise on supply chains analysis, in particular on CO₂ removal supply chains understanding, developed through stakeholder engagement for CO₂RE Hub, UK's Greenhouse Gas Removal Hub.

As there is no agreed definition of the boundaries of in-situ CO₂ mineralisation, here we define mineralisation supply chains as encompassing the processes, materials, energy and know how required to (1) identify and prepare the mineralisation site, (2) operate the CO₂ injection, which requires CO₂ capture, CO₂ transport, operation and monitoring of the injection site, and (3) post-injection, covering decommissioning and closure of the site. Based on this definition, this review identified several critical factors which affect the initiation and scale-up of in-situ CO₂ storage through mineralisation: (1) availability of geological data from basin to site level, (2) availability of steady CO₂ supply, (3) permitting specific to in-situ CO₂ mineralisation activities, and (4) public awareness and acceptance of mineralisation supply chains are the mapping of suitable locations, increasing the public awareness on the topic of CO₂ mineralisation and how this differs from oil and gas operations, and demonstrating mineralisation projects in different locations across the UK.

KNOWLEDGE GAPS AND RECOMMENDATIONS

This review identified some significant data and knowledge gaps surrounding the concept of in-situ CO₂ mineralisation in the UK, chiefly pertaining to site characterisation and the regulatory regime. Specifically, the gaps are:

 inconsistent data that limits the identification and 3D geometric constraints of suitable UK formations for CO₂ mineralisation. This includes low-resolution (10's-



100's m) information on the width, length and thickness of formations at or below the surface; and in subsurface architecture, such as stratigraphy, faults, fractures across the proposed PSGF,

- Iack of information of the effectiveness of UK mafic and ultramafic rocks to store CO₂, including no high-resolution (1-5 m intervals⁸) assessment of the UK mineralogical and geochemical diversity, alteration; physical (porosity and permeability) and geomechanical properties at depth of the proposed PSGF,
- The lack of robust laboratory assessment of the effect of temperature, pressure, and various CO₂-bearing fluids on the potential of UK's mafic and ultramafic lithologies to mineralogically trap CO₂ given the lower geothermal gradients experienced by the UK relative to those associated with at scale experiments.
- lack of tested workflows for establishing the permanent containment of CO₂,
- lack of proven monitoring methods to demonstrate safe and permanent storage,
- lack of specific regulations that consider activities related to CO₂ deep mineralisation on shore or offshore, either via storage licence or environmental permit.

To address the data gaps and provide further appraisal of the mineralisation potential in the UK, it is recommended to undertake:

- systematic field and subsurface mapping campaign of all PSGF to de-risk the understanding of fracture pore networks, to establish permanent containment, and provide estimates of storage capacities, as well as the investigation of the depth and temperature at which the UK could support CO₂ injection,
- comprehensive sampling of UK igneous lithologies to create a representative dataset of all reactive to non-reactive rocks underpinned by laboratory characterisation and CO₂ fluid - rock experimental assessment at pressure and temperature approximating the conditions at depth. This would improve our understanding on the evolution of geochemical and physical properties in given PSGF with time and, provide insight into the sequestration efficiency factor needed for calculation of the potential storage volume,



- a review of how current regulations could be adapted, and guidance developed, to facilitate safe and permanent deep mineralisation,
- development of generic risk assessments for credible case studies to assist regulators and policymakers in the formulation of appropriate regulations and guidance.

This report has also touched upon the ex-situ mineralisation and highlighted that utilisation of ultramafic and mafic mine waste for CO₂ mineralisation provides a unique opportunity to integrate processes and technologies for a more efficient transition to Net Zero. The UK critical minerals strategy ⁹ includes a commitment to accelerate domestic capability in critical minerals production, and this can create potential synergies with the CO₂ mineralisation agenda.



1. CO₂ mineralisation: global state-of-the-art

Lacinska, A.M., Watkins, I.

Key points:

- In-situ CO₂ mineralisation involves an injection of CO₂-bearing fluid at depth into geological formations where *via* a chemical reaction, the CO₂ is trapped in a solid carbonate mineral.
- CO₂ can be injected as CO₂ dissolved in water or in a supercritical state. The depth of injection depends primarily on the depth of the target formation, the pressure and temperature at depth dictated by regional geothermal gradient, as well as the intended type of fluid.
- Mafic and ultramafic rocks meet compositional suitability criteria for Potentially Suitable Geological Formations (PSGF) as they contain abundant magnesium (Mg), calcium (Ca) or iron (Fe) silicate minerals for reaction with the CO₂.
- Three in-situ CO₂ mineralisation projects are underway globally and show that a multidimensional understanding of the interplay between the geological conditions at the chosen site, the injection fluid and CO₂ trapping mechanism at depth and, the injectiondriven geochemical and physical feedback is required. Several challenges remain and have been described.
- CO₂ mineralisation can also be undertaken above ground (ex-situ) utilising waste materials as a feedstock and as such, providing an attractive prospect to integrate processes and technologies for a more efficient transition to Net Zero.

1.1 Introduction

At the time of writing, the atmospheric concentration of CO₂ reached 422.80 ppm (January 2024). An increase of over a third from 1958, when the first measurement of 317.51 ppm was recorded at the Mauna Loa Observatory¹⁰. The average global temperature on Earth has increased by at least 1.1°C since 1880 ¹¹, soon after the start of the Industrial Revolution. Anthropogenically-driven global warming is evident.



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Projections indicate that opportunities for adaptation to many climate risks will become constrained and have reduced effectiveness if a threshold of 1.5°C global warming is exceeded ¹². The Intergovernmental Panel on Climate Change (2022) states that if this threshold is passed, many key risks (including, water security, food security, human health or, peace and human mobility) will intensify rapidly worldwide, causing damage to assets and infrastructure and losses to economic sectors that will entail high recovery and adaptation costs.

Carbon Capture, Utilisation and Storage (CCUS) is a critical decarbonisation strategy ¹ and currently removes around 40 million (Mt) of CO₂ a year from the atmosphere ². The UK's Government recognises the importance of CCUS technologies, and has increased investment in research, development, and demonstration programmes, aiming to capture 30 Mt/year by 2030 and over 50 Mt/year by 2035 ¹³. In 2023, the Global CCS Institute reported a rapid increase in the number of CO₂ capture projects in various stages of development, with up to 361 Mtpa in development, construction, and operation ³.

CCUS involves storing CO₂ underground in geological formations onshore or offshore, or above ground using CO₂ as an input for reuse or feedstock to create products, *e.g.* carbonate minerals. CCS by mineralisation, otherwise referred to as mineral carbonation or <u>CO₂ mineralisation</u> (used here) belongs to a portfolio of CCUS technologies. It is an alternative solution to the more mature conventional CO₂ storage in porous geological formations, in sedimentary basins. CO₂ mineralisation achieves storage of CO₂ by reacting it with rocks containing a significant amount of calcium (Ca), magnesium (Mg) and/or iron (MgFe), resulting in mineral trapping of CO₂ in a solid carbonate mineral, such as calcite (CaCO₃), magnesite (MgCO₃), or siderite (FeCO₃), following a simplified reaction:

Metal oxide + $CO_2 \rightarrow$ Metal carbonate

This method potentially offers a secure and permanent removal of CO₂ from the atmosphere. Since the inception of the CO₂ mineralisation concept in the 1990s ¹⁴, the subject has been studied extensively by academia and industry worldwide. CO₂ mineralisation is spontaneous in nature, occurring in association with weathering processes. Atmospheric CO₂ dissolved in rainwater interacts with geochemically suitable rock over time to producing carbonate and several other minerals, including silicate and hydroxide minerals. Natural analogues are abundant and include exhumed high-temperature (100-200°C) systems, with carbonates forming in the Earth's crust ^{15,16} and low temperature weathering-driven systems ^{17,18}. These



natural analogues provide insight into the reaction pathways, reactivity of different types of rocks, and long-term stability of the carbonated system, ultimately serving as a basis for concept development and process design for engineered CO₂ mineralisation technologies.

There are several strategies to achieve CO₂ mineralisation, including;

- *in-situ CO₂ mineralisation*, where the CO₂ is injected into the subsurface and reacts with target geological formation at depth,
- ex-situ CO₂ mineralisation, which is an above-ground method that takes place in specifically designated carbonate plants where the captured CO₂ is brought in contact with Ca, Mg and/or Fe bearing feedstock materials,
- surficial mineralisation is the above-ground mineralisation of atmospheric CO₂ through reaction with existing surface feedstock materials located at the surface, such as mine tailings or smelter slags ¹⁹,
- enhanced weathering, where the feedstock is spread over fields and reacts with atmospheric CO₂ ^{20,21}.

One of the most substantial natural analogues for CO₂ mineralisation is associated with the uptake of carbon by oceanic crust in submarine geothermal systems. Here, the CO₂ originates from the degassing of magma ²². Studies on the mineralisation of oceanic crust suggest that deep-sea basalt offers vast capacities and permanent geochemical trapping potential ²³⁻²⁵. Significant uncertainties remain due to lack of data and experience within the field, and site-specific geological research and pilot studies are required to assess the feasibility fully ²⁶.

The CO₂ mineralisation potential in hard rock geological systems has been estimated at around 60 million gigatonnes (Gt) CO₂ globally, assuming full carbonation and techno-economic and environmental viability ⁶. This equates to > 1.5 million years of current global annual CO₂ emissions of around 40 Gt.

The numbers are quoted to highlight the vast potential of hard rock geological formations to significantly contribute to global decarbonisation. However, there are techno-economic, environmental, and social constraints (Chapter 3) to exploiting the estimated resource.



1.2 In-situ CO₂ mineralisation

In-situ mineralisation involves the injection of CO₂ at depth into suitable geological formations. To date, the injection fluids used for in-situ mineralisation included CO₂ dissolved in water (e.g. fresh or seawater) prior to, or during injection (Carbfix or 44.01 method, 1.4.1. and 1.4.2); or CO₂ in a supercritical state⁴ (Columbia River Basalt method, 1.4.3.). Following injection, supercritical CO₂ remains highly mobile and buoyantly flows upward while, CO₂ dissolved in water is dense and sinks in the storage formation ²⁷. These properties determine the dominant CO₂ trapping mechanisms at depth beneath the Earth's surface. Although, some of these mechanisms operate in the conventional CO₂ storage systems in porous formations, this section focusses on processes relevant to the CO₂ mineralisation processes. Accordingly, depending on the type of CO₂ fluid (supercritical CO₂ or CO₂ dissolved in water), the trapping mechanisms include:

- structural, stratigraphic and residual trapping, which utilise the natural porosity and structures of the host geological formation to store supercritical CO₂,
- solubility trapping requiring the dissolution of CO₂ in water,
- mineral trapping, *i.e.* formation of a solid carbonate mineral into which CO₂ is incorporated crystallographically.

The progress from structural trapping through to solubility trapping to mineral trapping decreases CO₂ mobility and thus, increases storage security ²². Mineral trapping is not instantaneous, and depending on the type of CO₂ fluid injected, mineral trapping is always preceded by either structural or stratigraphic trapping when supercritical CO₂ is injected, or solubility trapping, when water-charged fluids are used. The absolute timing and subsurface location of the mineral trapping is difficult to constrain, but (i) it is generally faster when using CO₂ dissolved in water as opposed to supercritical CO₂, and (ii) based on the use of geochemical tracers and geochemical analysis of fluids extracted from monitoring wells, 60 - 95% of the injected CO₂ can be mineralised within 2 years ^{28,29}. The main advantage of storing CO₂ in the supercritical state is that the required storage volume is substantially lower than if the CO₂ was dissolved in water. However, a cap rock is needed to stop the gas from escaping the target storage formation. Conversely, CO₂ charged water offers immediate solubility trapping and removes the need for a caprock as the gas is no longer buoyant ³⁰, but

⁴ Supercritical CO₂ has a viscosity of a gas and the density of a liquid attained at >31.1 $^{\circ}$ C and 73.9 bar.



the process is water intensive. For example, the Carbfix methodology requires 27 to 32 tons of fresh water for each ton of CO₂ at 25°C and 25 bar ^{8,22,31}. To put this in context, the water footprint of other CCS technologies ranges from 0.74 to 575 m³ H₂O/tonne CO₂ ³², that at standard pressure and temperature gives 0.74 to 575 tonnes H₂O/tonne CO₂. More recently, the utilisation of seawater has been considered and early testing suggests that at temperatures \leq 170°C, the efficiency of mineralisation in seawater is similar to that of freshwater, albeit mineralisation is likely to progress at a slower rate driven by different CO₂-fluid reaction pathways in the two water systems ³³.

The depth of injection depends primarily on the depth of the target formation, the pressure and temperature at depth dictated by regional geothermal gradient (the rate of change in temperature with respect to increasing depth), as well as the intended type of fluid (supercritical CO₂ or CO₂ dissolved in water), and other technological and infrastructure/economics constraints. Injection of supercritical CO_2 necessitates a target depth > 800 m, where the pressure and temperature conditions will maintain the supercritical state, allowing for initial structural trapping ahead of mineralisation. The CO₂ dissolved in water can be injected at shallower depths, with the choice of target depth dictated by the compositional and structural properties (porosity/permeability) of the target formation and the regional geothermal gradient, again besides other technological, including slower reaction kinetics at lower temperature affecting the dissolution of rock formations and, thus the amount of cations available for the reaction with the CO₂. The average geothermal gradient of the upper 1 km of the continental crust in the UK is 28°C/km, giving an average temperature around 38°C at 1 km depth ³⁴. These temperatures might be suitable for the precipitation of carbonate minerals as long as there are cations in the fluids ready for the reaction with CO₂. Raising temperature by 10°C doubles the rate of a reaction and, the faster the dissolution of the target formation rocks, the more cations available for the formation of carbonates and other minerals. A recent study on calcite extracted from Carbfix (Iceland) submersible pump shows mineralisation temperature of 45 - 51°C at 400 m³⁵. Iceland exhibits geothermal gradient of 50 - 150°C per km ³⁶. This is higher than most other parts of Europe, related to subsurface magmatic activity, and allows for enhanced reactivity of target formation at shallower depths of injection. Kelemen et al (2019)⁶ also noted that from an economic standpoint, the cost of injecting fluid into peridotite per ton of CO₂ becomes very high if temperatures at depth are < 50°C, where the reaction kinetics of dissolution and precipitation are relatively slow ⁶.



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The ease of injection of the CO₂ into the storage site, known as injectivity, is an important factor ³⁷. The injectivity depends on the porosity and thickness of the target formation ³⁷ and, will vary between different types of target formation. As the system evolves in response to the fluid-rock interactions at depth, original minerals dissolve and new minerals precipitate. The precipitation of minerals has the potential to open new pathways through reaction-driven cracking ³⁸ or to block the intrinsic porosity and the pathways for the CO₂ rich fluid to be injected. The latter will affect the original injectivity of the system and might result in a pressure build up, leading to technical difficulties and reducing the volume of CO₂ that can be injected over time. To avoid injectivity issues, the target injection rates must be optimised on a case-by-case basis, considering the evolution of the intrinsic porosity with time driven by complex fluid-rock reactions.

To date, in-situ CO₂ mineralisation was implemented on a pilot scale in Iceland (Carbfix, ongoing and progressing to large scale injection); Washington State, USA (Wallula Basalt Project, injection completed in 2013) and Oman and the United Arab Emirates (44.01, ongoing). A range of parameters were considered prior to starting these projects, including the reactivity of rocks and minerals at different pressure and temperature conditions, geomechanical characterisation of target formations, fluid flow within the host rock, and modelling of reaction pathways ³⁸⁻⁴⁶. This report is a high-level review and mainly focusses on the (i) compositional pre-requisites of geological formations as an introduction to Chapter 2 followed by the (ii) description of four insitu injection projects, 44.01 Oman and the UAE, Carbfix and Columbia River Basalts.

1.3 Prerequisites for in-situ target rock formations

The prerequisites for any geological unit to be suitable for mineralisation target formation are ⁴⁷:

■ composition - containing divalent (Ca²⁺, Mg²⁺ or Fe²⁺) cations available for the CO₂ mineralisation process,

permeability (the ability of fluid to travel through rocks) - this should be high enough to provide fluid pathways to facilitate migration of the injected CO₂ in order for it to come into contact with as much of the storage formation surface area as possible.

porosity – containing sufficient surface area for the reactions to take place.

These prerequisites can be assessed by:



 geological characterisation of outcrops equivalent to the formations at depth using existing and new data,

pilot boreholes and geochemical sampling, wireline geophysical surveys, hydrological testing,

 laboratory-based approaches and experimental studies in which the cation availability of the storage formation is demonstrated ⁴⁷.

The choice of a method to assess a formation depends on the data available and knowledge gaps per specific site. To obtain a comprehensive understanding of formation potential, multiscale and multi-technique evidence is needed and that requires a combination of the abovementioned methods.

In this section, we describe the rock-types that are most likely to be suitable on the basis of their composition, and then discuss the likely permeability and porosity of these formations (0).

Rocks with the composition suitable for CO_2 mineralisation are typically formed by igneous processes, by the cooling of magma (molten rock) derived from below the Earth's surface. Igneous rocks can be classified into four groups based on their chemical composition: ultramafic, mafic, intermediate and felsic (Figure 1). These groups have a compositional spectrum, with ultramafic rocks having the highest proportions of magnesium (Mg) and iron (Fe) and lowest proportions of silica (SiO₂) and the alkali elements (Na₂O + K₂O), and felsic rocks having the highest SiO₂ and alkali element content. The most efficient carbonation is achieved through the reaction of CO_2 with rocks and other materials containing Mg, Ca or Fe - bearing silicate and hydroxide minerals. During fluid-rock reaction, these minerals, also called metal donors, release elements that bind the CO_2 and form carbonates such as magnesite (MgCO₃), calcite (CaCO₃), or siderite (FeCO₃).

The igneous rock compositions have been ranked using a colour-based key to reflect their reactivity with CO_2 bearing fluids. Green regions indicate compositional suitability, amber indicate possible suitability but further research in is required. Formation rocks in the red region are classified unsuitable, based on high silica and alkali element content which will not react with CO_2 in either the short or long term, compromising the mineralisation capacity (Figure 1). Rocks in the grey areas are non-reactive and not considered in this report.



It should be noted that the ranking is based on the primary igneous composition of a rock and does not reflect structural properties (0 & A.2.) or alteration and their impact on the rock's reactivity. These aspects must be considered on a case-by-case basis.



Figure 1 Chemical classification of volcanic rocks (black) and plutonic (white) based on the total alkali-silica content, modified from ⁴⁸.

Ultramafic and mafic rocks meet prerequisite criteria based on their composition and are described below in more detail. These rocks form by cooling and solidification of hot (1000 - 1400°C) magma kilometres below the Earth's surface, in the continental and oceanic crust or the mantle (intrusive, plutonic rocks), or on the surface during volcanic eruption (extrusive, volcanic rocks). In some geological settings, portions of Earth's mantle and oceanic crust can be uplifted and emplaced onto continental crust forming complexes known as ophiolites. These complexes serve as natural analogues to study the geological suitability of formations for CO₂ mineralisation, for example the ophiolite of the United Arab Emirates (UAE) and Oman that has mafic and ultramafic rocks exposed over a strip of land around 500 km in length.



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If subjected to change of pressure and temperature beneath the Earth's surface, mafic and ultramafic rocks can be modified by metamorphism and, the growth of new minerals. Metamorphism does not usually change the bulk chemical composition; the process is complex and often involve water. Mafic and ultramafic rocks are not stable in the presence of water and undergo hydration readily at various pressure and temperature regimes. Water ingress causes changes to mineral structure and can initiate migration of metals, resulting in compositional modification which can variably affect the favourability for CO₂ mineralisation (see below).

ULTRAMAFIC ROCKS contain more than 90% of dark - coloured mafic minerals such as olivine (Mg,Fe)₂SiO₄, orthopyroxene (Mg,Fe)SiO₃ and clinopyroxene (Mg,Ca,Fe)₂SiO₆. Intrusive rocks dominated by olivine are referred to as peridotites (including dunite – dominated by olivine, and harzburgite - an olivine and pyroxene rock), whereas those dominated by pyroxene are pyroxenites. In many geological settings, ultramafic rocks have been metamorphosed to assemblages including metamorphic olivine, pyroxenes, amphiboles, serpentine, talc, carbonate, brucite, hydroxy-carbonate, chlorite, quartz ⁴⁹. Some metamorphosed ultramafic rocks are suitable for the reaction with CO₂ based on their composition, but abundant metamorphic hydrated minerals such as amphibole e.g. Mg₅Ca₂Si₈O₂₂(OH)₂ or chlorite e.g. (Mg,Fe,AI)₆(Si,AI)₄O₁₀(OH)₈ have shown low reactivity during laboratory-based leaching ⁵⁰. These minerals might prove reactive during longer time scales, but further research is required. Conversely, the hydration of olivine and some pyroxene in ultramafic rocks leads to the formation of serpentine minerals Mg₃Si₂O₅(OH)₄ and iron oxides, and some serpentinites are notably more reactive with CO₂. The process of serpentinisation is common, and most ultramafic rocks are affected by it to some degree, e.g. harzburgites and dunites from Oman are 65 - 100% hydrated ⁵¹. Rocks where the hydration is pervasive are called serpentinites. Serpentine minerals consist of an interlocking mosaic of three main polymorphs, (minerals of the same composition Mg₃Si₂O₅(OH)₄ but different crystal structure), including lizardite, chrysotile and antigorite. The different structure determines their reactivity in the presence of CO₂-bearing fluids, from the most reactive chrysotile through to poorly crystalline serpentine and lizardite to the least reactive antigorite ⁵². Serpentinisation also leads to the formation of brucite Mg(OH)₂, a hydroxide mineral that has proven to be highly reactive in the presence of CO₂ in both laboratory scenario experiments, and natural analogue studies ^{53,54}.

The idealised reactions of (i) olivine, (ii) serpentine and (iii) brucite with CO₂ are as follows:



- (i) $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
- (ii) $Mg_3Si_2O_5(OH)_3 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
- (iii) $Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$

The serpentinisation is associated with a solid volume increase of 45% as the minerals transform from unhydrous olivine or pyroxene to hydrated minerals ⁵⁵. The change in volume leads to stress build-up in rocks and can trigger fracturing ^{46,56}. The fracture network will provide permeability pathways for injected CO₂. However, the fractures can become infilled over time by the growth of new minerals, forming veins. These veins may include carbonate minerals, forming through a natural process of CO₂ mineralisation. Near-surface ultramafic rocks have low fracture-dominated porosity, on the order of ~1 vol% ⁵⁷. The presence of a fracture network permeability is key to in-situ mineralisation in ultramafic formations, and the viability of mineralisation technology depends greatly upon the thorough understanding of fracture distribution and interconnectivity at depth. At the time of writing, the injection of CO₂ into ultramafic rocks is underway in Oman and the UAE (1.4.1).

MAFIC ROCKS contain < 53 wt% of silica and > 25 wt% of Ca, Mg and Fe oxides. The group comprises a wide range of rocks distinguished based on the proportion of mafic minerals: olivine, orthopyroxene and clinopyroxene, and on grain size. Intrusive, coarse-grained mafic rocks are gabbro and related rocks, containing pyroxene and plagioclase (*e.g.* CaAl₂Si₂O₈) along with subordinate amphibole, olivine and accessory minerals (including Fe-Ti oxides).

Basalt is the most common mafic volcanic rock fine grained rock. Basalt formations originate from volcanic eruptions and typically consist of layered lava flows, representing a series of cyclic eruptive events. It is finely crystalline, with SiO₂ content of 45 - 52 wt% (Figure 1) and typically composed of plagioclase, pyroxene and olivine, and subordinate Fe-Ti oxides. Rapid cooling leads to the formation of volcanic glass in basalts. As the cooling progresses, heterogeneous textures form as a result of degassing, thermal contractions, and interaction with water ⁵⁸. During degassing, gas bubbles trapped in the magma can migrate to the top of a lava flow and form round, ovoid or elongate irregular cavities called vesicles, which are the main constituent of porosity in basalts. The amount, size and interconnectivity of these vesicles are important to CO₂ mineralisation processes, as they provide the fluid flow pathways and space for the new carbonate minerals to form. The vesicles can be interconnected, but the prime property of the



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lava flow that enhances the interconnectivity is the presence of fractures ⁵⁹. The vesicular and fracture porosity and permeability are key properties determining capacity and injectivity of CO₂ into basaltic flows, and thus the geological feasibility of the mineralisation technology.

The reactivity of mafic rocks in the presence of fresh water, sea water or a CO₂-bearing fluid at different pressure and temperature conditions has been widely studied ⁶⁰⁻⁶⁴. Basalts containing a high proportion of volcanic glass are highly reactive, the rate of dissolution and precipitation in the mafic system is generally slower than in ultramafic rocks. This is largely related to the rate of metal release from plagioclase as compared to olivine at conditions relevant for CO₂ injection, but the controlling factors are complex 65-67. The initial fast dissolution of volcanic glass and other reactive phases can also lead to an increase in porosity and permeability, which in turn weakens the rigidity of the rock volume significantly ⁶⁸. Further work is needed to understand how the system evolution affects the formation integrity with time, and the consequences associated with upscaling injections at an industrial level. The reaction of basalt with carbonated water can result in the formation of carbonate minerals, but also a range of other products such as silica, Fe oxide/oxyhydroxide, clay minerals and zeolites. The volume of these secondary phases is substantially greater than that of the basaltic glass that was dissolved to make them. This can lead to reaction-driven cracking ³⁸ and opening of new pathways and/or potential clogging of the available pore spaces and, in some cases, result in a decrease of the host rock permeability.

Two projects (Carbfix, Iceland and the Wallula Basalt injection in the US) have carried out CO₂ injection into basalts and so, provide further detail on the CO₂ fluid type, injection depth, challenges, and potential mitigation strategies to overcome negative geochemical feedback in the subsurface (1.4.2 and 1.4.3). It is important to note that all these aspects must be considered on a case-by-case scenario, and a thorough investigation of all formation properties and their evolution in time must be undertaken for each new injection site.



1.4 In-situ CO₂ mineralisation projects

Four CO₂ injection projects have been initiated in the last two decades. These include demonstrations in ultramafic rocks (Oman and the UAE) and initiatives in basaltic formations: a completed operation in the US, the Columbia River Basalt Project, and a scaling up project in Iceland, Carbfix.

1.4.1 44.01 Company. CO₂ mineralisation in ultramafic rocks.

Based on literature available in the public domain and personal communication with Prof. Juerg Matter, the Head of Subsurface for 44.01 (January 2024).

44.01 (the *name originates from the molecular weight of* CO_2), also known as Protostar Group Limited, is a company pioneering in-situ injection of CO_2 into ultramafic formations. 44.01 started in 2020, and in 2021-22 a small-scale injection was undertaken in Oman. This was a ⁵push-pull test in shallow formations from 100 – 400 m with few hundred kg of CO_2 , resulting in the injection of around 1 tonne of CO_2 into partially serpentinised peridotite. The CO_2 was dissolved in fresh water before injection. The resultant acidic solution of pH 3 reacted with the host formation, leading to the release of cations available for subsequent mineralisation. Early tests show that 88% of the few hundred kg of CO_2 injected was mineralised within 45 days.

Following initial results from the injection in Oman, the Abu Dhabi National Oil Company (ADNOC) has formed a partnership with 44.01 to commence injections at a site in Fujairah in the United Arab Emirates. The Fujairah project envisages injection of 10 000 tonnes of CO_2 dissolved in sea water into partially serpentinised peridotites at depths of > 600 m below the surface. The Fujairah injection site includes a Direct Air Capture (DAC) plant, and both the injection system and the DAC operations are powered by solar energy.

Key learnings:

FORMATION CHARACTERISATION. Characterisation is a vital component of the technological viability assessment. For 44.01, it was attained through a multiyear Oman Deep Drilling Project Multi-Borehole Observatory, an international initiative to build understanding of ultramafic mantle rocks exposed at the Earth's surface ⁵¹. The target formation is a partially serpentinised peridotite with a pervasive fracture network, and the target depth of injection

⁵ single well CO₂ fluid injection followed by few days' of fluid incubation period before extraction to quantitatively determine a wide range of aquifer physical, chemical and biological processes⁵



is 800 – 1500 m. Upscaling will need geoengineered reactivation of a fracture network at depth.

- WATER CONSUMPTION. The amount of water (CO₂ carrier) required varies from approximately 20 to 35 tonnes per tonne of CO₂ injected, depending on the injection depth, and local hydrostatic pressure. For such high volumes of water, the water must be readily available, and the formation must be of significant capacity; both aspects driving 44.01 R&D initiatives to reduce the water penalty.
- CO₂ FATE. The partial pressure of the CO₂ dissolved in water (sea water, fresh water) must be lower than the hydrostatic head in the formation to allow for immediate solubility trapping of the CO₂. This mitigates the risk of CO₂ de-gassing and escaping to the shallower depths of the formation or to the surface. Geochemical tracers are used to assess the fate of the CO₂ injected and quantify it based on mass balance calculations ⁶⁹. Recycling of original carbonate in veins leading to potential release of CO₂ is not an issue in the target formation, because the abundance of carbonate veins declines steeply from a few volume percent in the upper tens of meters to near zero in cores from more than 100 m below the surface ⁵¹

1.4.2 Carbfix. CO₂ mineralisation in basalts

Based on literature available in the public domain and personal communication with Dr S. Ó. Snæbjörnsdóttir and Dr C. Marieni (January 2024).

Carbfix is currently the world's only operating in-situ CO₂ mineralisation project in basaltic rocks. Begun in 2006, and since undergone scientific, technology and operational evolution through several test injections and pilot projects, supported by Reykjavik Energy, University of Iceland, CNRS Toulouse and Columbia University via several EU Framework Programmes. The overall cost of the pilot phases was approximately 12 million EUR ⁶⁹. The funding covered laboratory studies, pre-injection field hydrology studies, numerical modelling, studies of natural analogues, design and construction of injection and tracer equipment, operation of pilot injections, monitoring, and coring. Cost of the pilot gas capture plant and pre-existing well infrastructure, both provided by Reykjavík Energy to the project, are excluded ⁷⁰. At current rate, Carbfix captures and stores one third of the CO₂ emissions and nearly all the H₂S emissions from the Hellisheiði geothermal power plant, representing ~12,000 tonnes annually along with 6000 tonnes of H₂S ⁴⁷. Preparation work is underway to increase capture and injection to 95% of the CO₂ from the power station by 2025 ⁴³.



Carbfix 1 delivered two injection tests into basaltic lavas and hyaloclastites near the Hellisheidi Geothermal Power Plant, with access to a concentrated source of CO₂ ^{8,40,69,71}. Test I resulted in 175 tonnes of pure CO₂ injected between January - March 2012, while test II involved injection of 73 tonnes of CO₂-H₂S gas mixture between June - August 2012, of which 55 tonnes was CO₂ ⁶⁹. The basaltic formation at the site comprises olivine-rich basalts ^{8,31}, with porosity of 8.5% ⁷². Gases were dissolved in fresh water during injection to mitigate CO₂ gas leakage through fractures, and to avoid degassing, the CO₂ concentration was kept below its solubility saturation at formation conditions ⁶⁹. The dissolved CO₂ solutions were injected into the target formation at a depth between 400 - 540 m and a formation temperature of 20 to 50°C. Isotopic tracers were used to monitor CO₂ plume migration and reactivity ^{8,40,69}, and results indicate that 95% of the injected CO₂ was mineralised within two years as calcite, and approximately all of the H₂S was mineralised within four months as pyrite (FeS₂) ⁷³.

Carbfix 2 – An EU-funded upscaled injection into geothermally altered basalts at temperatures of 260°C beginning in June 2014. By the end of 2017, 23,200 metric tonnes of CO₂ and 11,800 metric tons of H₂S had been injected to a depth of 750 m. After 3.5 years of injecting a CO₂-H₂S charged fluids for mineralisation into subsurface basaltic rock, there was no reduction in permeability of the target formation. This is likely because (i) fluid pathways near the injection wells were opened as a result of the injection of acidic and undersaturated with respect to the minerals present in the target formation; (ii) the volume of carbonate, sulphide, and other secondary minerals precipitating in the target aquifer was no more than a total of 0.025 vol.% of the target formation; (iii) the potential formation of new fractures as a result of pressure and temperature gradients close to the injection well induced by the injection of cooler gas-charged fluids ⁷³. As part of the Carbfix 2 project, a direct air capture (DAC) plant, designed and installed by the Swiss company Climeworks, was in operation at Hellisheiði from October 2017 until 2021 ⁴⁷. After the development of the pilot Project Arctic Fox between 2017 and 2020, the DAC technology was upscaled and Project Orca that has been operational since 2021 within ON Power's Geothermal Park ⁷⁴. The capture capacity of Project Orca is stated at 4000 tons of CO₂ per year 74.

Project CO₂ Seastone is an investigation of sea water as a carrier for CO₂ to unlock the potential for CO₂ mineralisation in regions with limited water resources and expand the Carbfix method application to coastal and offshore locations ⁷⁴. Following laboratory and modelling work to



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determine the feasibility of CO₂ mineralisation in sea water, pilot injection of CO₂ dissolved in sea water commenced in November 2023 at Helgyvík in Reykjanesbær.

In late 2019, Carbfix was established as a subsidiary of Reykjavik Energy and subsequently commenced operations as a separate entity in January 2020 ⁷⁴. The company aims to rapidly and permanently store 1Gt of CO₂, supported by ongoing Project Silverstone and Coda Terminal as well as future commercial projects around the world. Project Silverstone obtained EU-funding to develop an operational CO₂ capture and injection facility at the Hellisheidi ON geothermal power plant with anticipated injection planned for January 2025, and is expected to reduce emissions by 150,000 tonnes of CO₂ over the project lifetime. The Carbfix Coda Terminal aims to provide full life cycle to CO₂ mineralisation, aiming to capture and transport CO₂ from mainland Europe to Iceland with temporary storage at the Coda Terminal, and subsequent transport to nearby injection wells for CO₂ sequestration. Carbfix aims to commence injection of CO₂ from the Coda Terminal in 2025 ⁷⁴.

Key learnings:

- FORMATION CHARACTERISATION was obtained by mineralogical and geochemical analysis of drill cuttings, well logs, well data, outcrop analyses and geological maps.
- WATER CONSUMPTION. The Carbfix method requires a significant quantity of water during the injection of dissolved CO₂. For each ton of CO₂ at a temperature of 25°C and a pressure of 25 bar, 27 to 32 tons of water are required ^{8,31}. For context on water consumption in other CCS technologies, please see paragraph 1.2.
- CO₂ FATE. Carbfix methodology includes two stages: (i) solubility trapping and (ii) mineral trapping. It is now widely accepted that the solubility trapping, offering immediate trapping, plays a major role in the CO₂ mineralisation technology, and that the mineral trapping is predicted to happen in time but its spatial and lateral distribution in the formation is difficult to constrain and this would require resource-intensive drilling. The evidence for CO₂ mineralisation is mainly derived from the analysis of fluids extracted from monitoring wells, sporadically supported by characterisation of materials extracted from the well ³⁵. Equally, although pore clogging can be mitigated initially by adjusting pH of the injection fluids ⁷⁵, in the far-field, away from the injection well, such adjustments are not possible, and the risk of clogging and thus, reduced permeability remains.
- FORMATION INTEGRITY AND INDUCED SEISMICITY. The risk of induced seismicity can be associated with the injection of fluids, in this case containing the dissolved CO₂, owing to the



Climate services for a net-zero resilient world

large volume of fluid that would need to be injected into the subsurface, as well as the compositional evolution of the subsurface formation, affecting system rigidity. For context, supercritical CO₂ is more compressible and less dense than water at pressures and temperatures typical for CCS formations and would be expected to produce lower risk of induced seismicity ⁷⁶. However, despite those differences in properties, it has been suggested that induced seismicity magnitudes produced by both fluids are comparable 77. Following the injection of geothermal wastewater at Hellisheidi geothermal power plant in September 2011, at a flow rate of around 500 kg/s, up to 2 cm of surface displacement was observed in 2011-2012, indicating expansion of the crust. Micro-seismicity increased immediately in the area north of the injection sites, with the largest seismic events in the sequence being two M4 earthquakes on the 15th of October, 2011 ⁷⁸. This risk has now been mitigated by adjusting the flow rate of the effluent water associated with geothermal production and keeping the injection parameters as constant as possible⁷⁹. It is critical that prior to injection, a site-specific study of the regional seismicity must be performed to determine the seismic risk and should include a thorough characterization of depths, times, locations and magnitudes of seismic events ²².

1.4.3 Columbia River Basalts. CO2 mineralisation in basalts

 CO_2 injection into flood basalts of the Columbia River Basalt Group (CRBG) near Wallula, Washington is the only in-situ CO_2 mineralisation field test accomplished in the US, and the world's first supercritical CO_2 injection. The CRBG covers over 200,000 km² and has a total estimated volume of > 224,000 km^{3 58,80}. The CRBG consists of > 300 individual lava flows with a maximum composite thickness of >5 km in the central portion of the Columbia Basin. The thickness of the vesicular portion of a flow may range from a few centimetres to almost the entire flow thickness, but most vesicular flow tops comprise 15 - 30% of the flow's thickness ⁵⁸.

Key learnings:

FORMATION CHARACTERISATION. A seismic survey was undertaken in 2007 and provided the framework for fault detection and first order characterisation of subsurface stratigraphy and structure at the site ⁸¹. The prospective site for the injection was drilled to a depth of 1253 m for geological characterisation. The data from the drilling helped identify three brecciated interflow zones between 828 and 887 m below ground surface. These were hydrologically characterized, and subsequently isolated for subsequent CO₂ injection. The target CO₂


injection intervals were two permeable basalt interflow formation zones with a combined thickness of ~20 m that occur within a layered basalt sequence in the Grande Rhonde formation, at a depth of 830 - 890 m below ground surface. The field testing was completed in May 2009, the CO_2 injection permit was then granted by the State of Washington in March 2011, and injection of 977 MT of CO_2 was completed in August 2013.

 CO₂ FATE. 977 MT of supercritical CO₂ was injected into the isolated basalt formation. Foodgrade CO₂ was used for the injection, supplied from refineries located in either Washington State or California. Cold CO₂ was heated and pressurised on site before entering the injection well as a supercritical fluid ⁸².

The injection was completed in August 2013 and surface soil gas monitoring and water samples collected from nearby monitoring wells have shown no evidence of CO₂ leakage. Fluid samples collected from formation depth showed elevated concentrations of Ca, Mg, Fe and Mn suggesting a rapid reaction of the injected CO₂ with basalt. Fluid sampling and analysis continued to 2015 ⁸². Laboratory analysis of discrete carbonate nodules removed from post-injection side-wall cores identified them as ankerite ((Ca,Fe)(CO₃)₂), which contained isotopic signatures closely aligned with the isotopic composition of the injected CO₂ ⁸³. The isotopic signature coupled with groundwater chemistry data and geophysical wellbore surveys show CO₂ mineralisation in the basalt formation within 24 months of injection.

Other sites. Albeit no other injection site is under construction, in-situ CO₂ mineralisation is being considered globally, and several potential formation characterisation programmes are ⁶underway. For example, studies of the formation properties and reactivity of the Faroe Islands Basalt Group suggest a high potential of offshore sequences as a target for in-situ injection and recommend further work on the effect of faulting and fracturing, layer dimension and morphologies on CO₂ migration in volcanic sequences ⁸⁴. In India, the basalts of the Deccan Volcanic Province have been identified for potential CO₂ mineralisation and are the subject of an extensive field-laboratory research programme ^{85,86}. Some studies however indicate that due to complex structural geology with many dykes, potentially acting as vertical barriers to flow, the large-scale injection of CO₂ in the Deccan Traps is likely to be limited ⁸⁷. Basaltic rocks on

⁶ Carbfix x Deep Sky, Carbfix & Great Carbon Valley



Northern Ireland, UK have been recently reviewed, and proposed as a viable location for a series of small-volume storage sites suitable for capture at industrial point-sources or purposebuilt CO₂ 'harvesting' facilities ⁸⁸.

1.5 Opportunities and Challenges

The vast global resources of mafic and ultramafic systems ⁶ make the technology potentially applicable in regions where conventional sequestration in sedimentary basins is not possible. Additionally, CO₂ mineralisation can create opportunities for smaller scale injectionmineralisation systems servicing local industries. Several challenges remain and the viability of in-situ CO₂ mineralisation technology is based on several assumptions, one being that subsurface ultramafic and mafic formations host sufficient porosity and fracture density to allow for efficient solubility trapping and subsequent carbonation. These physical properties will vary from site to site, but mafic formations generally have a greater intrinsic porosity than ultramafic formation. For ultramafic formations, geoengineering technologies may have to be considered to enhance the reactive surface area. Any geoengineering endeavour to enhance permeability faces risks and challenges, including formation integrity, and associated potential for induced seismicity or public perception, and requires an appropriate technology assessment phase. It is likely that the injection of CO₂ dissolved in a large volume of water at depth will disturb the insitu physical and geochemical stability of the formation. This may lead to the dissolution and precipitation of a mineral assemblage re-equilibrated to the new conditions, including the desired carbonates but also a range of silicate minerals, most commonly clay minerals, zeolites, silica, oxide-hydroxides. There are three aspects that might be considered challenging here (i) competition for cations between carbonates and silicates (ii) porosity clogging by the newly formed minerals; (iii) formation integrity and induced seismicity. The Carbfix sequestration methodology shows that it is possible to manage the technology to reduce concerns of this kind. For example, adapting the injection rates to the formation properties or controlling the pH of the fluids can provide measures to minimise induced-seismic events or the precipitation of undesired, porosity clogging minerals; respectively. One major challenge that remains, is the water penalty. Snæbjörnsdóttir et al 2020²², in their discussion over CO₂ buoyancy versus water penalty, outline the advantages and disadvantages of the injection of water charged with CO2 and liquid or supercritical CO₂, and suggest that, despite the large water volumes required, the method is simple and can be cost-effective and importantly reduces the risk of CO₂ leakage.



There might be cases where injection of supercritical CO₂ is more favourable, for example necessitating operations with fewer wells in sub-ocean systems ²².

There is a lack of relevant geological data to underpin the assessment of target formations in many parts of the world. For example, the size, injectivity, permeability, geomechanics, and microstructure of peridotite formations are relatively unknown. Understanding nano-scale rock behaviour is essential to understanding the macro-evolution of the formation, and more research is needed in this field ⁶. Despite the potential of analogue sites to provide indication of properties at depth, every site considered for CO₂ mineralisation will have to undergo a thorough geological, geochemical and hydrological field and laboratory scoping programme, besides all other requirements necessary to obtain planning permissions and move towards pilot injections, such as policy research, public outreach, and investigation of political and social factors in nearby communities and regions ⁵⁷. The initial site assessment is time- (several years) and resource- intensive; the latter usually requires funding sources and academic-industry-community collaboration. The cost of Carbfix project was \$1-3 M per year in the early stages, increasing to \$10 to \$20 M per year for 100,000 to 1 M ton/year scale I ⁵⁷. At this point and time, we don't know how representative these costs are for the UK.

Finally, the locations of potentially suitable geological formations and the sites of outstanding natural beauty, or sites of Special Scientific Interest often coincide, necessitating careful assessment of the benefits and risks associated with the development of in-situ injection facility.

1.6 Ex-situ CO₂ mineralisation

Ex-situ CO₂ mineralisation involves processes that lead to the formation of carbonate minerals above the ground, in a specifically designated carbonation plant. The source of Mg, Ca or Fe cations is called feedstock material. The origin of feedstock is diverse, and rocks, industrial waste (slags, fuel ash or paper sludge) and mine tailings have been considered and studied ^{19,89-91}. The aim of the reaction of feedstock with CO₂ in either water-based solutions, or as a gaseous or supercritical phase, is to produce a solid, harmless material that can be disposed of, or used in industry. For example, in the cement industry, CO₂ mineralisation not only offers permanent storage of CO₂ but could potentially avoid emissions from producing cement by partially substituting conventional cement with the obtained carbonation products ⁹². A comprehensive assessment of inorganic waste materials suggests that the UK has the theoretical potential to capture 14 Mt/year CO₂, if all waste products were used for CO₂



mineralisation ⁹³. However, by 2012 recycled concrete aggregate, steel slag and blast furnace slag did not present any tonnage available for mineralisation, because no waste was available, being either reused or recycled. Pulverised fuel ash, air pollution control residue, incinerator bottom ash, biomass ash, paper sludge ash and cement kiln dust had the potential to become a feedstock in the UK with a potential CO₂ capture capacity of about 1 Mt/year or 0.2% of the total UK CO₂ emissions ⁹³. Apart from industrial waste streams, ex-situ mineralisation can utilise rocks and geological waste, such as mine tailings. A comprehensive study of the geological feasibility of UK for ex-situ mineralisation that focused on the distribution of ultramafic rocks suggests that there is sufficient rock source material in the UK for CO₂ mineralisation to be a viable proposition ⁹⁴. Mafic rocks, mafic quarry fines and dust are also potentially suitable for ex-situ or enhanced weathering technologies ^{21,95}. A spatial inventory of mafic rock resources in the UK along with current production capacity and permitted reserves, suggest that scaling up of enhanced weathering technology in the UK, would require expansion in rock extraction, and face potential environmental and social limitations ⁹⁵.

Worldwide, there is significant work developing and optimising ex-situ mineralisation utilising geological and/or industrial waste; exemplified by

• ⁷Carbon8, a UK company capturing CO_2 directly from the source to treat industrial residues, thereby manufacturing products that can be reused, as aggregate or fertiliser,

⁸Cambridge Carbon Capture, a UK company using Mg silica feedstock, and developing processes that can extract other metals from the feedstock, including nickel, cobalt or chromium, and silicon oxide (silica) for their use in other technologies. The company also invests efforts into a hybrid Direct Air Capture and Enhanced Weathering Project which uses mineral feedstock in the Direct Air Capture to remove carbon dioxide, extract residual metals from the feedstock and produce carbon neutral magnesium oxide which is then exported to satellite Enhanced Weathering Sites to remove even more carbon dioxide over time,

⁹MCi Carbon, an Australian-led commercial decarbonisation technology using industrial waste, mine tailings or raw quarried minerals for transforming CO₂ into building products and materials for the circular carbon economy

⁷ https://www.carbon8.co.uk/solution

⁸ https://www.CO2loc.com/

⁹ https://www.mineralcarbonation.com/



Ultramafic mine tailings and ore processing waste materials are widely considered for CO₂ removal, having the potential to contribute to carbon neutral mining operations ^{19,91,96}. Global production of minerals such as nickel and platinum group metals generates ~419 Mt of ultramafic and mafic mine tailings annually; and assuming complete carbonation, this provides the potential to sequester ~175 Mt CO₂/year ⁹⁷. Decarbonising the world economy relies on a secure and sustainable supply of critical metals and minerals that underpin low-carbon technologies. The development of wind, hydro- and geothermal energy technologies, as well as energy storage systems and low-carbon transport solutions, requires critical minerals and will continue to rely on primary mining for the foreseeable future. Utilisation of mine waste, including tailings and post-metal recovery materials, for CO₂ mineralisation provides a unique opportunity to integrate processes and technologies for a more efficient transition to a greener future. The UK critical minerals strategy includes a commitment to accelerate domestic capability in critical minerals production, and this can create potential synergies with the CO₂ mineralisation agenda. Indeed, some of the expected waste materials, mainly those from mafic and ultramafic systems, present an interesting opportunity, and creating industry synergies should be explored further.

Ex-situ mineralisation has several benefits, offering an immediate and easily auditable evidence of the permanence of carbon stored in the mineralized product(s), the products are of economic value and the technology meets the need for a circular economy ⁹⁸. Further, ex-situ CO₂ mineralisation also has the potential to reduce the toxicity of some mine waste ⁹⁹⁻¹⁰¹ and/or to stabilise tailings through cementation by carbonate minerals ¹⁹. The drawbacks are mainly related to energy penalty and economics, the cost of operations or the competitiveness of the carbonate or silica market ⁹⁸.



2. Geological potential of the UK

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Key Points

- The UK has experienced several phases of mafic and ultramafic igneous activity throughout geological time that has created rocks that are likely suitable for CO₂ mineralisation.
- Geological screening of these rocks based on their relevant geochemically reactive lithologies and outcrop surface area has helped identify 11 Potentially Suitable Geological Formations (PSGF) that are of interest and are suggested for further investigation.
- Several important elements that affect mineralisation and fluid flow in igneous rocks are discussed. A Theoretical Pore Space (TPS) for CO₂ mineralisation has been calculated for each PSGF based on data published for each formation or suitable analogue data for a similar lithology.

2.1 Summary of UK igneous geology

The United Kingdom has been subject to several phases of igneous activity throughout its geological history, related to episodes of continental rifting, subduction, and continental collision. These different tectonic events each produce different compositions of igneous rocks, and thus, a full understanding of the geological context is required to identify areas of mafic and ultramafic compositions. Three geological periods in particular saw large volumes of volcanic lavas extruded: the Devonian, Carboniferous, and Paleogene (Figure 2). This section describes the various igneous systems by age, and their potential relevance to CO₂ mineralisation.





Figure 2 Geological timescale with periods of greatest volumes of extruded lava indicated. Modified from ¹⁰².

2.1.1 Archean to Neoproterozoic.

The oldest igneous rocks in the UK occur in the Archean age Lewisian Gneiss Complex in Northwest Scotland and have been metamorphosed at high temperatures and pressures. They are largely composed of felsic rocks, but also include several kilometre-scale mafic-ultramafic igneous bodies ¹⁰³. Cross-cutting the Lewisian Gneiss Complex are the Palaeoproterozoic Scourie Dykes, which are steeply dipping mafic bodies of gabbro, peridotite and amphibolite. While laterally extensive, they are rarely more than 20 m in width, and therefore unlikely to be suitable for CO₂ mineralisation. Other more extensive mafic igneous bodies of Palaeoproterozoic age occur largely in the South Harris Igneous Complex, the Loch Maree Group, and in the Glenelg Inlier. These are mostly amphibolite in composition, up to a few km across and likely extend to significant depths ¹⁰⁴. However, the mixed lithologies and limited extent make them relatively unimportant for CO₂ mineralisation.



Other Precambrian rocks are represented by the southwest Scotland Neoproterozoic Tayvallich Volcanic Formation within the Dalradian Supergroup, which is related to volcanism associated with continental rifting and opening of the Iapetus Ocean. These are metamorphosed basaltic lavas, sills and some tuffs all interbedded with metasedimentary strata ¹⁰⁵. Other outcrops of basaltic material within the Dalradian are likely to be too volumetrically small for CO₂ mineralisation.

2.1.2 Cambrian to Ordovician

Through the Upper Cambrian to Early Ordovician, the lapetus Ocean began to close with southward-directed subduction resulting in thrusting of mafic oceanic crust onto the continental margin, producing the Tyrone Igneous Complex in Northern Ireland and the Shetland and Ballantrae ophiolites in Scotland. The Tyrone Igneous Complex comprises a metamorphosed suite of mafic to intermediate volcanics and mafic intrusive lithologies ^{106,107}. The Shetland ophiolite is dominated by variably serpentinised ultramafic rocks ¹⁰⁸ and is the closest analogue to the 44.01 sites in Oman and the UAE. The Ballantrae ophiolite comprises tectonically juxtaposed slices of serpentinite and lava ¹⁰⁹ and may be less suitable for CO₂ mineralisation.

Additional volcanic activity during the Ordovician produced the Northeast Grampian Basic Suite in Northeast Scotland, comprises several mafic and ultramafic plutons that may extend to significant depth from the surface ¹¹⁰. These plutons are quarried for roadstone and may be appropriate sources for ex-situ CO₂ mineralisation.

2.1.3 Devonian

Following closure of the lapetus Ocean, supra-subduction volcanism associated with slab break-off produced extensive granitoid emplacement and associated volcanism in the northern part of the UK during the Devonian. Volcanism was dominated by more silica-rich compositions (including the Midland Valley Arbuthnott-Garvock Group volcanics and Lorne Plateau Volcanic Formation, ¹¹¹) and is relatively unsuitable for CO₂ mineralisation. Also of Devonian age is the Lizard Ophiolite in southwest England, which is associated with the Variscan Orogeny. It contains peridotites ¹¹² and is of potential interest for CO₂ mineralisation.

2.1.4 Carboniferous

During the Carboniferous and Permian, intracontinental rifting led to mafic magmatism, mainly basaltic in composition, across Central Scotland and Northern England. Major laterally



extensive microgabbro sill complexes such as the Whin Sill and Midland Valley Sill were emplaced at this time. These sills are typically a few tens of metres thick, but if continuous in the subsurface, they potentially extend over 100s of km². Current understanding is that their subsurface extent is likely too limited for them to be valuable for in-situ CO₂ mineralisation. However, they are quarried for roadstone, and may be sources of material for ex-situ mineralisation. In contrast, Carboniferous volcanic rocks are extensive, with the most significant extent in the Clyde Plateau Volcanic Formation of Central Scotland, which is up to 1000 m in thickness ¹¹³.

2.1.5 Paleogene

The most widespread mafic-ultramafic magmatism in the UK is the Palaeogene North Atlantic Igneous Province, which includes outcrops across Western Scotland, Northern Ireland, the Faroes, Iceland and East Greenland ¹¹⁴. These include mafic-ultramafic central complexes, notably those of Rum, Ardnamurchan, Mull, Skye and Slieve Gullion; and plateau basaltic lavas, notably in Northern Ireland (Antrim Lava Group) and on Mull and Skye, as well as offshore. The plateau lavas may be up to several km in thickness ¹¹⁵. Major gabbroic sill complexes are associated with the plateau lavas. The central complexes typically comprise interlayered gabbro and peridotite with abundant basaltic sheeted intrusions. Extensive basaltic dyke swarms found in the central complexes of Mull and Skye. Individual dykes have thicknesses of less than 20 m¹¹⁶ and are not considered suitable for CO₂ mineralisation.

2.2 Geological screening

To categorise the potential for CO₂ mineralisation across the UK, we used existing geological map data to identify suitably reactive igneous lithologies and define outcrop surface areas with interpolation of rock volumes based on field observations and physical properties. Similar geological map-based assessments have been undertaken at a range of scales, in Northern Ireland ⁸⁸, southwest Portugal ¹¹⁷, the USA ¹¹⁸, and the onshore and coastal areas of Iceland ^{26,119}. Due to the low risk of leakage associated with CO₂ mineralisation, the requirement for a low permeability caprock is removed and has not been a consideration in the screening process ²⁴.



2.2.1 Available Data

The baseline onshore and offshore data were provided by the current British Geological Survey (BGS) Digital Geological Map of Great Britain (formerly known as DiGMapGB) at 1:50,000 scale and 1:250,000 scale, respectively. Northern Ireland onshore data is provided by the Geological Survey of Northern Ireland (GSNI) 250K Digital Bedrock Geology map (formerly DiGMapNI-250) at 1:250,000 scale. These data are available as a series of geographically referenced geological maps with each area attributed with information including lithostratigraphical, chronostratigraphical or lithodemic nomenclature and composition (¹⁰rock type or lithology).

Full analysis of the offshore data was outside the scope of study and therefore only the offshore extent of mapped onshore bodies and bodies located in the near inshore were considered. The data were filtered based on the selection criteria below, with additional information such as subsurface borehole locations incorporated to provide thickness and direct measurements of physical properties where possible.

2.2.2 Lithological Filtering

Our primary selection criteria were the modal mineralogical compositions suitable for CO₂ mineralisation ^{22,37}. The first stage of screening filtered the geological data by first order lithological classifications to select all igneous and metamorphic lithologies. The second stage of screening filtered this igneous-metamorphic dataset for relevant geochemically reactive lithologies (*e.g.* basalt; Table 1, Appendix A1). This removed acidic lithologies (*e.g.* granite) from the dataset as they are unsuitable for CO₂ mineralisation. The third stage of screening removed vertical to sub-vertical intrusive systems (*e.g.* dykes). Although they may extend kilometres down into the subsurface, they are relatively thin (<20 m thick) and the bulk rock volume at or close to the surface will not be large enough for mineralisation. The igneous bodies remaining after this final stage were laterally extensive lava flows, mafic to ultramafic intrusive plutons, horizonal to sub-horizontal sheet intrusion systems (*e.g.* sills), and ophiolite complexes.

The geological results were then ranked from A to C and colour coded (A, green; B, amber; C, red), from most potential to least potential for CO₂ mineralisation, following the lithological classification in Chapter 1 (Figure 1, Table 1). A complete list of filtered lithologies, BGS lexicon codes and their assigned rankings can be found in Appendix A1. The results of the lithological

¹⁰ The BGS Lexicon of Named Rock Units https://webapps.bgs.ac.uk/lexicon/



filtering can be seen in Figure 3, where the bulk lithology, rank and associated colour for each igneous body are presented. Users of the map should be aware that extent is the outcrop surface area and that our screening has removed fine scale lithological heterogeneities to display the geological data at the scale of the UK.

Table 1 Geological screening criteria based on lithological classifications suitable for CO₂ mineralisation, see Figure 1, Chapter 1 for relative chemical composition.

Classification	Example Lithologies	Reactivity	Rank	Colour
Ultramafic	Peridotite, Picrite, Picrobasalt, Dunite, Harzburgite	High	A	Green
Meta-Ultramafic	Serpentinite	High	А	Green
Mafic	Basalt, Microgabbro, Gabbro, Norite	High	А	Green
Meta-mafic	Metabasalt, Metagabbro, Metamicrogabbro	Moderate	В	Amber
Alkali-rich and Mafic-Intermediate	Basanite, Basaltic-andesite, Hawaiite, Tephrite	Moderate	В	Amber
Intermediate	Andesite, Trachyandesite, Diorite, Microdiorite	Low	С	Red
Acidic	Granite, Rhyolite, Dacite, Trachyte, Trachydactite	Very Low	N/A	N/A

2.2.3 Thickness, Area and Volume

There are no published minimum recommendations for thickness, area and volume of rock units that can be used to undertake CO₂ mineralisation. Therefore, understanding published geological screening approaches or geometric estimates from real world experiments is vital (Table 2). Andrews, 2023 calculated a usable thickness (240-780 m) below a depth cutoff for specific Northern Irish basalt formations, then derived a range of low, mid and high cases for volume (1.45–5.08 km³) by using different estimates of effective porosity (Φ) calculated from petrophysical data, before settling on a weighted average. While no thicknesses were specified, Pedro et al., 2020 ¹¹⁷ selected outcropping areas in Southwest Portugal with a minimum of 10 km² and expected volumes >10 km³ calculated using geological principles and subsurface data where applicable.

The best data available is from at scale CO_2 mineralisation experiments, such as the Wallula Basalt Project in the Columbia River Basalt Group. This is a major continental flood basalt province containing >200,000 km³ of basalt and proven in wells to be >1 km thick¹²⁰. This pilot project injected CO_2 into a permeable zone 60 m thick at 830 m depth below surface of the



basalt lava pile ¹²¹. The injection zone of 50 m around the pilot borehole was defined based on post-injection results of CO₂ lateral flow and mineralisation ^{83,121}. In Iceland, the total onshore area of basalt flows is extensive at approximately 100,000 km² ¹¹⁹. Carbfix 1 targeted a fraction of this by injecting CO₂ into a zone of basalt lava flows and hyaloclastites ~400 m thick at a depth between 400-800 m, with a surface area of 4.5 km² and subsurface volume of 1.8 km³ ^{31,69,72}. Carbfix 2 has targeted a minimum thickness of ~1500 m composed of basalt lava flows, hyaloclastites and microgabbroic intrusions, with an area of 42 km² and volume of 63 km³ ^{43,45}.

For the UK study, where required, the mapped onshore and offshore data were merged to accurately assess total area and based on the results of lithological filtering of the formations. Geological criteria, including age of emplacement, associated igneous stratigraphy and surface extent were considered in the lateral extend of the individual formations. This has resulted in each body being referred to by the most appropriate formation or group level name. Outcrop surface areas ranged from 0.001 km² to 3604 km², demonstrating the variety and complexity in UK igneous geology and surface extent. Rather than define minimum recommendations, we have selected the mafic to ultramafic bodies with the largest areas as these will in turn have a higher probability of greater thickness and volume.

2.2.4 Depth Requirements

Depths >800 m ¹²² with overlying caprock is required for injection of supercritical CO₂. For injection of CO₂ dissolved in water there are no minimum requirements, and depth is governed by the existence of suitable lithologies and dictated by the formation pressure and temperature conditions ¹²³. This can be seen in the depth ranges published by theoretical and experimental studies (Table 2). Andrews ⁸⁸ had a theoretical depth cutoff of ~500 m for Northern Ireland basalt formations. At Carbfix 1, CO₂ was injected at ~400 m ⁶⁹, with injection at Carbfix 2 occurring deeper at ~750 m ^{45,75}, while it was deepest at Wallula at ~830 m depth ⁸³.

Our screening approach uses direct evidence of rocks at or close to surface, with extrapolations of the relevant formations that extend into the subsurface where possible. Given the temperatures needed for CO_2 mineralisation and that the average UK geothermal gradient is 28°C per km, locally increasing to >30°C per km³⁴. It is likely that to support CO_2 mineralisation in the UK a minimum depth of 1 km will be required. Thus, it is important that we have evidence of mafic-ultramafic rocks extending to that depth.



	5	I	5		1	
	Thickness of injection formation (m)	Area (km²)	Subsurface Volume (km³)	Depth (km)	Туре	Reference
	60	-	-	0.83	Experiment	Wallula ^{83,121}
_	240-780	-	1.45-5.08	0.5	Screening	Northern Ireland 88
_	400	4.5	1.8	0.4	Experiment	Carbfix 1 31,69,72
_	-	≥10	>10	-	Screening	Southwest Portugal ¹¹⁷
_	1500	42	63	0.75	Pilot	Carbfix 2 43,124

Table 2 Screening criteria from published studies and geometric estimates of at scale experiments for CO₂ mineralisation.

2.3 Geological Considerations for Sequestration

While access to sufficiently reactive lithologies is fundamental, CO₂ mineralisation is also dependent on the range of physical properties of the rock being injected. These include how the igneous material reacts to fluid injection and pressure fluid changes, tectonic loading and the potential for failure (faulting). This will be controlled by crystal size, geometry and distribution, pore size, geometry and distribution of pores, as well as orientation ^{125,126}. Injection may also be affected by the presence of planar surfaces, such as faults, fractures or foliations (a parallel alignment of minerals common in meta-igneous rocks) and how they react to local stress. For a more detailed synopsis of these factors, please see Appendix A2.

2.3.1 Porosity and Permeability

Fluid flow through any formation is dependent on the related properties of porosity and permeability. Igneous rocks are typically made up of interlocking crystals of their constituent minerals, and primary porosity can be either intracrystalline (*e.g.* diktytaxitic texture where cavities occur between crystals ¹²⁷ or vesicular (*i.e.* preserved gas bubbles ¹²⁸). Secondary porosity can develop where additional pore space is created by subsequent processes such as dissolution or fracturing along foliated surfaces (*i.e.* peridotite) ⁶⁸. The total porosity (total pore volume of rock) can be significantly higher than the effective porosity (connected pore volume of a rock ¹²⁹) and is dependent on lithology. In unaltered basaltic lava flow tops, total porosity (Φ_t) can vary from 0-85% ¹³⁰ but effective porosity (Φ_e) can be 1-35% ¹³¹. A porosity reduction of 1-10% can occur due to the precipitation of secondary mineral phases such as zeolites, silica, chlorite, epidote, and prehnite (as seen in Carbfix 2 ^{73,132}).



Permeability (the ability of fluids to travel through the rock) depends on the existing porosity, including the size, shape, volume and connectivity of the pores ¹²⁸. Variable pore fabrics or alignment of microfractures can create permeability anisotropy, giving different vertical (K_V) and horizontal (K_H) permeability values that may vary across an igneous body ¹³³. Permeability can vary over orders of magnitude, from ~10⁻²⁰ to ~10⁻¹¹ m² in igneous rocks ¹³¹. Most estimates of permeability do not adequately account for faults or fractures within the host rock, independent of lithology. Caution is therefore advised on relying purely on laboratory experiments due to the sampling bias created by use of small (cm-scale) cylindrical samples with no or few edge defects that do not necessarily reflect real world systems. Such laboratory measurements should be considered as indication of the minimum permeability within the targeted rock system.

Permeability is not a fixed value and can be altered by mechanical changes, such as thermal expansion and contraction by the injection of cold fluid into hot rock (as seen in Carbfix 2 ⁴⁵). This is unlikely to be an issue in the UK, due to the lack of recent volcanic and tectonic activity and relatively cool geothermal temperatures are experienced across the UK ³⁴.

2.3.2 Use of Direct and Analogue Data

While many of the igneous rocks across the UK have been widely identified and mapped in detail, direct measurements of the physical properties are not available or have not been collected. To better understand their likely suitability for CO₂ mineralisation or to calculate their volumes, a range of physical properties based on analogue lithologies were used (Table 3). This analogue data is not exhaustive or always representative, and application of these data should be taken with caution. Only measurements taken directly from the igneous rocks of interest will provide accurate assessments of physical properties for volumes, fluid flow, and potential mineralisation.



Table 3 Physical property analogues categorised by lithology.

Climate services for a net-zero resilient world

Lithology	Control	Porosity (%)	Permeability (m²)	Reference
Basalt (lava flow tops)	Unaltered	22.4–30.8	-	Hawaii: ¹²⁵
	Hydrothermally altered	15–30	7.40 x 10 ⁻¹⁴ – 1.48 x 10 ⁻¹³	Wallula: ⁸³
Basalt (lava flow core)	Unaltered	12.18–13.26	-	Hawaii: Bubeck, et al. ¹²⁵
	Hydrothermally altered	0–3	-	Wallula: McGrail, et al. ⁸³
Basalt (lava flow base)	Unaltered	12.4–19.6	-	Hawaii: Bubeck, et al. ¹²⁵
Basalt (lava flows)	Unaltered	1–35	-	Iceland: Scott, et al. ¹³¹
	Geothermally altered	8.5	1.7 x 10 ⁻¹³ – 3 x 10 ⁻¹³	Carbfix 1: Matter, et al. ^{31,} Matter, et al. ^{69,} Aradóttir, et al. ⁷²
	Geothermally altered, fracture dominated	0.2–3.5	1 x 10 ⁻¹²	Carbfix 2: Snæbjörnsdóttir, et al. ⁴⁵
Basalt (hyaloclastites)	Unaltered	20–50	-	Iceland: Scott, et al. ¹³¹
	Hydrothermally altered	20–30	1 x 10 ⁻¹⁴	Iceland: Scott, et al. ¹³¹
	Geothermally altered	20	1 x 10 ⁻¹⁶	Iceland: Scott, et al. ¹³¹
Basalt (intrusions)	Unaltered	1–15	-	Iceland: Scott, et al. ¹³¹
	Geothermally altered	2–10	1 x 10 ⁻¹⁷	Iceland: Scott, et al. ¹³¹
Dolerite / Microgabbro	Unaltered, fracture dominated	6–14	-	New Jersey: Goldberg and Burgdorff ¹³⁴
Gabbro	Geothermally altered, fracture dominated	11–15	7.2 x 10 ⁻¹⁶ – 1 x 10 ⁻¹⁴	Iceland: ¹³⁵
Peridotite / Serpentinite	Hydrothermally altered, fracture dominated	0.12–3.4	1.57 x 10 ⁻²¹ – 2 x 10 ⁻¹⁷	Oman: Katayama, et al. ¹³⁶



2.3.3 Storage Volume and Capacity

The conventional storage capacity of sedimentary rocks is determined by calculating the volume, porosity and water saturation, together with the volume of injected and produced water during storage ¹³⁷. While igneous rocks have been identified as volumetrically significant for CO_2 mineralisation, there is no established methodology for calculating storage capacity, with considerable uncertainty surrounding published estimates. Some authors have calculated potential storage capacity using rock volume, porosity and density of CO_2 ^{23,138} while others have modified the subsurface volume calculations, using additional qualifiers to correct for unreactive volume or yields of stored CO_2 in basalts ⁸⁸.

To calculate potential storage capacity, an understanding of a wide range of other interacting factors is required, but hard to quantify. These include mineral reactivity to determine how effectively the rocks will chemically react with CO₂ to form stable carbonate compounds. Minerals with higher reactivity possess a greater ability to dissolve and release a cation for sequestration of CO₂ through carbonation ³⁷. It is also important to understand that once mineralisation starts, the bulk volume of the rock will be altered with estimates of a ~20% increase in basalt ¹³⁹ and ~44% increase in peridotites ¹⁴⁰. Therefore, storage capacity is not a static number, but will need to be recalculated at regular intervals for up-to-date estimates.

There are currently no established CO₂ sequestration rates, as the process is a complex interplay between the injection rate, temperature and depth, together with the fluid type and additive gases. CO₂ dissolved in water produces different mineral phases to that of supercritical CO₂ 6,37,64,141 . Xiong et al. (2018) ¹⁴² estimated a rate of 1.24 ± 0.52 kg of CO₂/m³ for Miocene age basalts, with most work has been done on younger volcanic rocks, which differ from older and more altered rocks present across the UK. Published CO₂ conversion rates (the amount of injected CO₂ considered to have undergone mineral trapping) vary from 60% (<2 years at the Wallula pilot ^{29,121}) to 95% (<2 years at Carbfix1 ^{28,69}). Understanding the sequestration potential and conversion rates of UK rock formations would require investigation into both the reactive mineralogy and rate at which carbonation might occur.

Considering these factors, we propose the following simple geometric calculation (Equation 1) to estimate a Theoretical Pore Space (TPS) measured in km³, for the most suitable areas identified during geological screening. This is based on calculating Gross Rock Volume (GRV) in km³ using Thickness (m) x Area (km²). This is multiplied by the percentage of highly reactive



(rank A) lithologies, known as Reactive Formation (RF) which removes less reactive / unreactive rocks from the GRV, thereby defining the volume of rock most suitable for CO₂ mineralisation (after ¹⁴³). By using a percentage estimate of Effective Porosity (Φ_e), we use the connected pore volume of the rock as input for the reactive surface areas for CO₂ mineralisation.

Equation 1 Simple geometric calculation to estimate the Theoretical Pore Space (TPS) of a formation in km³.

$$TPS = GRV * RF * \Phi_e$$

TPS = Theoretical Pore Space (km^3) GRV = Gross Rock Volume (km^3) RF = Reactive Formation (%) Φ_e = Effective Porosity (%)

2.4 Potentially Suitable Geological Formations

A Potentially Suitable Geological Formation (PSGF) has been defined as an igneous body of rock that is likely to be suitable for CO₂ mineralisation on the basis of existing data. Each igneous body is addressed by the most appropriate geological formation or group level name, defined based on lithology, age, and surface expression including onshore to offshore extension where mapped. Current offshore mapping is less detailed than onshore mapping, which has increased the uncertainty of exact offshore extents of offshore formations. The results of the geological screening of mapped outcrop surface areas of mafic and ultramafic rocks based on currently available data, together with ranking of relevant geochemically reactive lithologies, are presented in Figure 3.

In total 11 PSGF have been identified from this study, with a breakdown of their onshore, offshore and total area, lithological rank percentages and a mean estimate of thickness from published studies presented in Table 4. Thickness includes data measured at surface and into the subsurface and should be taken with some caution. Estimates of Gross Rock Volume (GRV) and Theoretical Pore Space (TPS) for CO₂ mineralisation are given in Table 5, and are a likely an overestimation based on the high-level mapping undertaken. They have been calculated with analogue porosity values based on lithology and likely alteration due to the lack of subsurface data. We are unable to define what is below the 1 km threshold and refinement would be advised to better understand the volume of igneous rock available for CO₂ mineralisation. The lack of subsurface data also hinders evaluation of depth, as this study has only been able to categorise



the formations at or close to surface. Until additional data is presented or acquired, these PSGF remain of interest as they are expected to extend to depth. However, the selection of PSFS is subject to change as a result of any future geological investigation.

2.4.1 Significant Outcropping PSGF

We have selected the ten most significant PSGF based on descending surface outcrop area that have highly reactive (rank A) lithologies. They include five in North-West Scotland, one in North-East Scotland, one in Central Scotland, two in Northern Ireland, and one in South-West England (Figure 3). An additional PSGF has been identified on Shetland but is lithologically significant, rather than areal significant (it is 19th in outcrop surface area for rank A lithologies) and is discussed in section 2.4.2. During the screening process, several other significant bodies of igneous rock with large outcrop surface areas were identified, but due to their composition of moderate to lower reactive (rank B and C) lithologies, they are less suitable for CO₂ mineralisation. A full list of recognised PSGF, their lithological percentages and related areas can be found in Appendix A3.

Each PSGF exceed 85% of highly reactive (rank A) lithologies and have outcrop surface areas >134 km². Six of the PSGF have combined onshore and offshore extents, with two PSGF found onshore and the remaining PSGF located entirely offshore (Table 4). There is a significantly larger outcrop surface area for the top four PSGF, from 600 km² to >1000 km² as they are composed of basaltic lava flows which are typically laterally extensive due to composition and emplacement mechanisms. Thickness has been taken as a proxy for depth, as limited information exists, with all but two PSGF thicker than the minimum of 1 km suggested for CO_2 mineralisation.

2.4.2 Analogue PSGF to Experiments

In addition to recognising the more extensive PSGF, we have identified those that are the most geologically similar to the at scale experiments of CO₂ mineralisation. The three Palaeogeneage flood basalt lavas of the Antrim Lava Group, Skye Lava Group and Mull Lava Group (Figure 3) are expected to be close analogues to both, the Wallula Basalt Project in the Columbia River Basalt Group and the Carbfix projects in Iceland. The dominant lithology is basalt and its variations, with stacked and laterally continuous lava flows with massive, low vesicular cores with columnar joints, and highly vesicular and brecciated flow tops. Each group has accumulated



significant thicknesses and are geologically young enough to have limited alteration that may reduce porosity for the injection of CO₂.

The Ordovician-age Shetland Ophiolite Complex and the Devonian-age Lizard Ophiolite (Figure 3) are likely analogues to the rocks investigated by 44.01 in Oman. The dominant lithologies are peridotite, serpentinite, and gabbro that have been extensively hydrothermally altered and are fracture dominated, therefore they may react similarly to the injection of CO₂. Detailed geological descriptions for each PSGF discussed in the text can be found in Appendix A4.





¹¹Figure 3 Location map of all potentially suitable geological formations (PSGF) for CO₂ mineralisation across the UK, colour coded based on reactive mafic and ultramafic lithologies. © BGS/UKRI 2024. All rights reserved. Contains Ordnance Survey data © Crown copyright and database rights 2024. NEXTMap Britain elevation data from Intermap Technologies.

¹¹ This map is purely theoretical and is based on current geological knowledge, available data and inherent limits of analysis at a national scale. The location of existing infrastructure or sites of natural or scientific interests were not considered. Due care should be taken in interpreting this information and data, with consideration to the limitations outlined above. Neither UK Research and Innovation (UKRI) as represented by BGS, nor BGS makes any warranty or representation as to the quality, accuracy, suitability for use for any purpose, or to the completeness of the information or data provided. The use of any information or data provided by the BGS or UKRI is at your own risk. BGS nor UKRI will not be held responsible for any liabilities or consequences arising out of any inaccuracies or omissions, whether intentionally, negligently or otherwise, in the information or data provided; nor use made of it.



Table 4 Summary of PSGF discussed in the text, with their number relating to descending total outcrop surface area. Thickness values have been taken as a mean of published estimates and will include surface and subsurface values. Outcrop surface area values and percentages of geochemically reactive lithologies ranks A to C are from this study. The Shetland Ophiolite Complex is known to extend offshore but has not been defined using the existing data and are therefore not shown in Figure 3.

No	Potentially Suitable Geological Formation	Thickness	Offshore	Onshore	Total	Rank A (%)	Rank B (%)	Rank C (%)
	(PSGF)	(km)	Area (km ³)	Area (km³)	Area (km²)			
1	Antrim Lava Group	0.8	158	3446	3604	98.94	0.02	1.05
2	Skye Lava Group	1.5	843	976	1819	89.62	10.32	0.07
3	Mull Lava Group	1.13	826	744	1570	99.48	0.24	0.29
4	Clyde Plateau Volcanics	0.49	-	1094	1094	85.92	12.49	1.59
5	Little Minch Sill Complex	0.25	509	91	600	100.00	0.00	0.00
6	Insch Pluton	2.5	-	216	216	100.00	0.00	0.00
7	Blackstone Band Igneous Complex	26	184	-	184	100.00	0.00	0.00
8	Tyrone Volcanic Group	4.5	-	143	143	100.00	0.00	0.00
9	Ardnamurchan Central Complex	2.5	76	65	141	89.19	10.74	0.07
10	Lizard Complex	0.95	81	54	135	100.00	0.00	0.00
19	Shetland Ophiolite Complex	1	Undefined	72	72	73.45	26.55	0.00



Table 5 Indication of likely analogues and calculation of Theoretical Pore Space (TPS) available for CO₂ mineralisation for the PSGF discussed in the text. All porosity measurements are from analogue data and have been selected based on lithology and likely alteration, with an estimated mean value taken from the porosity range where required. *GRV and TPS should be treated as indicative only as further work is needed to constrain the 3D geometric ranges of the UK's PSGF; currently the uncertainty ranges of these measurements are from tens to several hundreds of metres.

No	Potentially Suitable Geological Formation (PSGF)	Analogue To	Age	Dominant Lithology	GRV* (km³)	RF (%)	Φ _e (%)	TPS* (km³)
1	Antrim Lava Group	Wallula, Carbfix	Paleogene	Basalt	2883	99	18	513
2	Skye Lava Group	Wallula, Carbfix	Paleogene	Basalt	2728	90	18	440
3	Mull Lava Group	Wallula, Carbfix	Paleogene	Basalt	1774	99	18	318
4	Clyde Plateau Volcanics	N/A	Lower Carboniferous	Basalt	536	86	8.5	39
5	Little Minch Sill Complex	N/A	Paleogene	Microgabbro	150	100	10	15
6	Insch Pluton	N/A	Devonian	Gabbro	540	100	13	70
7	Blackstone Band Igneous Complex	N/A	Ordovician	Gabbro	4773	100	13	620
8	Tyrone Volcanic Group	N/A	Ordovician	Basalt	645	100	8.5	55
9	Ardnamurchan Central Complex	N/A	Paleogene	Gabbro	353	89	13	41
10	Lizard Complex	Oman	Devonian	Peridotite and Serpentinite	128	100	1.76	2
19	Shetland Ophiolite	Oman	Ordovician	Peridotite and Serpentinite	72	73	1.76	1

GRV - Gross Rock Volume, RF – Reactive Formation, Φ_e – Effective Porosity, TPS - Theoretical Pore Space.



3. Non-geological factors pertaining to regulations of CO₂ injection at depth in the UK.

3.1 UK regulations

Pearce, J.

Key Points:

- Existing regulations for conventional CO₂ storage in porous formations, and the associated guidance documents, have been reviewed to assess their applicability to CO₂ mineralisation. As CO₂ mineralisation is a less mature storage technology, there is currently no specific regulation for this technology in the UK.
- The CO₂ storage regulations are applied nationally, since the concern storage in the UK's waters. The principal regulator for assessing the geological aspects of CO₂ storage in the North Sea Transition Authority.
- Conventional CO₂ storage is principally regulated by the North Sea Transition Authority which awards a storage licence, allowing exploration and appraisal of the geological volume and a storage permit, which allows injection of CO₂ for permanent containment. This regulatory process requires a risk-based geological site appraisal.
- From a geological viewpoint and given the current state of knowledge, the risk-based approach is considered appropriate for application to in-situ CO₂ mineralisation operations provided that the requirement to demonstrate safe and permanent containment will remain.
- As the conditions are notably different for deep CO₂ mineralisation (in terms of site location and properties of the target formations), the risks and uncertainties associated with this technology will differ to those associated with conventional CO₂ storage. Therefore, it is anticipated that regulations will require a more detailed review to ensure practical application to specific operational attributes and risk profiles of storage in fractured mafic and ultramafic rocks, particularly onshore.

3.1.1 Introduction

The storage of CO₂ via deep mineralisation is a novel activity that is not yet part of an existing permitting or licencing regime. This review summarises the existing and most relevant



regulations for other subsurface activities that are akin to CO₂ storage via deep mineralisation. Specifically, it reviews the UK's current regulations for CO₂ storage in porous rocks. We have focussed on the geological aspects of these regulations and associated guidance. Aspects such as the requirements to demonstrate appropriate commercial competency and financial security or planning requirements are not covered by the review, as these are not specific to CO₂ storage projects it is assumed these will be common requirements for all CO₂ storage projects.

Key assumptions for this review are that:

- Storage of CO₂ via deep mineralisation will be regulated in a similar way to other forms of deep geological storage of CO₂.
- The current regulations, which pertain to the offshore geological storage of CO₂, will form the basis for storage via deep mineralisation, either offshore or onshore.
- Those bodies currently regulating CO₂ storage operations will also be required to regulate CO₂ storage via deep mineralisation.
- Planning permission will be required for onshore projects. These regulations are not reviewed here.

The review is intended to provide an overview of the current regulatory situation in the UK. It does not constitute legal advice for future policy development in this area. The review draws on BGS's technical and practical regulatory experience of the UK's storage licensing regime. It assesses existing regulation, including the Energy Act 2008 and related DESNZ policy documents, to consider the extent to which these regulations might be relevant and applicable to CO₂ mineralisation. We identify some regulatory aspects that would require particular attention in the development of any future regulations by qualified policy experts with appropriate legal and regulatory support.

It is worth noting that the CO₂ storage regulations, reviewed here, are currently being actively implemented. At the beginning of 2024, 27 CO₂ storage licences have been granted, with most storage licence holders currently developing their applications for storage permits.

3.1.2 UK Regulations for CO₂ Storage (offshore)

The UK licensing regime for the Storage of Carbon Dioxide is defined in the Energy Act 2008 ¹⁴⁴. This Act effectively transposes the EU Storage Directive 2009/31/EC ¹⁴⁵. The Energy Act requires a developer of a CO₂ storage project to hold a storage licence that allows the



permanent disposal of CO_2 in a controlled place. The legislative regulatory regime was originally introduced to allow a CO_2 capture and storage demonstration project to be operational by 2014, which was to be commissioned by UK Government. Although the demonstration project was subsequently cancelled, this framework now provides the basis for CO_2 storage in the UK.

A storage licence is required for the following activities ¹⁴⁴:

- storage of carbon dioxide with a view to its permanent disposal,
- conversion of a natural feature (for example, a saline aquifer) for such storage,
- exploration for a carbon dioxide storage site, and
- establishment or maintenance of an installation for any of those purposes.

The framework is limited to the offshore area, specifically to controlled places which are defined as places in, under or over the territorial sea and the wider area of the UK's Gas Import and Storage Zone. A fundamental principle of the regulations is that the activities should lead to the permanent disposal of CO₂. Demonstration that the injected CO₂ will be permanently and safely stored is a fundamental test that all licence holders must meet to be granted a storage permit. Additional aspects of the EU Storage Directive (EU 2009) were subsequently transposed into UK law:

- The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2010/2221) ¹⁴⁶
- The Storage of Carbon Dioxide (Termination of Licences) Regulations 2011 (2011/1483) ^{147,148},
- The Storage of Carbon Dioxide (Access to Infrastructure) Regulations 2011 (2011/2305)¹⁴⁹, and
- The Storage of Carbon Dioxide (Inspections etc.) Regulations 2012 (2012/461) ¹⁴⁸.

Following the UK's exit from the European Union, The Storage of Carbon Dioxide (Amendment and Power to Modify) (EU Exit) Regulations 2019¹⁵⁰ were implemented. This instrument amended secondary legislation to enable the UK to implement and change the primary regulations.

In addition to a storage licence, an offshore CO₂ storage project developer must also lease the seabed and spaces under the seabed from The Crown Estate (TCE) or the Crown Estate for Scotland (CES), depending on the jurisdiction. A Lease is required for rights to develop offshore



pipeline transportation, seabed and subsurface storage sites. The Lease provides the holder with access rights to explore, appraise and develop the seabed and pore spaces below the seabed. TCE and CES operate as commercial landowners under the provisions of the Crown Estate Act 1961 ¹⁵¹.

BEIS OPRED is the environmental regulator for the offshore storage of carbon dioxide in the UK's territorial sea (except Scottish Territorial Sea). The Offshore Oil and Gas Exploration, Production, Unloading and Storage (Environmental Impact Assessment) Regulations 2020¹⁵² apply to certain carbon storage activities and set out the requirements for an Environment Impact Assessment ('EIA').

The EC Storage Directive ¹⁴⁵ has four supporting guidance documents, published in 2011 which establish important principles for the regulation of CO₂ storage:

- EC CO₂ Storage Directive Guidance document 1: CO₂ Storage Life Cycle Risk Management Framework ¹⁵³
- EC CO₂ Storage Directive Guidance document 2: Characterisation of the Storage Complex, CO₂ Stream Composition, Monitoring and Corrective Measures ¹⁵⁴
- EC CO₂ Storage Directive Guidance document 3: Criteria for Transfer of Responsibility to the Competent Authority ¹⁵⁵
- EC CO₂ Storage Directive Guidance document 4: Financial Security (Art. 19) and Financial Mechanism (Art. 20) ¹⁵⁶

These guidance documents are currently (2024) being updated by the EC following extensive consultation in 2023.

3.1.3. Licencing process

The storage licence enables a storage developer to explore and appraise a volume of rock in the UK Continental Shelf (UKCS) for the purpose of submitting an application for a storage permit. The storage permit provides the developer with permission to inject carbon dioxide. The storage licence process is regulated by the North Sea Transition Authority (NSTA). Initially, storage licences were granted on an *ad hoc* basis, in response to storage developers wishing to build storage projects under past Government initiatives to support the nascent CCS industry. In 2022, NSTA initiated the first UK storage licensing round, and invited potential applicants to bid for licences in prescribed areas of the UKCS. These areas were largely identified by storage



developers (mainly oil and gas companies) and reflected their areas of interest identified during *ad hoc* discussions with NSTA. In this first round, 21 licences were awarded to 14 companies. Future licensing rounds are expected and applications for new storage licences will only be accepted as part of future licensing rounds.

Injection of CO₂ into the deep subsurface of the UKCS can only take place once the NSTA has granted a storage permit. The licence and permitting process, from licence award to site closure and post-transfer involves a series of steps (Figure 4):

1. NSTA invite applications from prospective storage developers in pre-defined areas,

2. The applicant prepares documentation as required by NSTA outlining their planned project, their current understanding of the geology of the area to be licensed and propose the boundaries of the area they wish to licence. Multiple applications for the same area are possible,

3. NSTA review licence applications, discuss applications and licence conditions with applicants and grant licences. All licence holders are publicly announced in a Public Register,

4. Applicants explore and appraise the volume of rock to develop the evidence base required to demonstrate safe and permanent disposal,

5. Applicants apply for a storage permit, which, if granted, permits the injection of CO₂. It is possible that an applicant may choose not to apply for a permit and their Licence would be revoked. It is possible that NSTA may not grant a Permit,

6. Once the injection project has completed, the Operator will apply for permission to close the site,

7. Following site closure, the Operator will be required to continue to monitor the site performance for an agreed period (nominally 20 years) to demonstrate permanent and safe storage,

8. At the end of the post-closure period, responsibility and liability for the site returns to the State,

Steps 1-3, *i.e.* getting to the point of being granted a licence, can take up to 18 months. Potential applicants may have previously undertaken some desk-based pre-feasibility studies in preparation for a future Licence application, which may take additional months to years in duration. A condition of a licence will be that the holder must apply for a storage permit by an



agreed date or relinquish their licence. Site appraisal and development of a storage permit application (Step 4 above) may require 4-6 years. Therefore, the lead time to the start of CO₂ injection may be 6 years or more. The length of the project injection phase is dependent on storage capacities and commercial considerations but are expected to last for several decades.

In support of the regulatory process, NSTA have issued the following guidance documents:

1. Guidance on the application for a Carbon Dioxide Appraisal and storage licence ¹⁵⁷,

2. Guidance on Applications for a Carbon storage permit Operations Guidance on Applications for a Carbon storage permit ¹⁵⁸,

3. Guidance on the content of an offshore permit application Operations Guidance on the content of an offshore permit ¹⁵⁹,

3.1.3.1. Storage Licence

Storage licence applications are made in response to a formal invitation by NSTA. The first and only (as of January 2024) storage licensing round was initiated by NSTA in May 2022.

A Licence is required for the whole duration of a carbon dioxide storage project (Figure 4) which comprises:

• An Initial or Appraisal Term – the period for exploration, appraisal, and project 'assess' and 'define' phases. This term ends with either a grant for a storage permit or the expiration of the licence. Where a Work programme is in place, this term will be the Appraisal term and when no such work programme is in place it will be the Initial Term. This term will be as the duration of the work programme,

• The Operational term – the period beginning with date of the storage permit, until the closure of the storage site,

• The post-closure period - the period beginning immediately after the closure of the storage site and continuing until the licence is terminated pursuant to The Storage of Carbon Dioxide (Termination of Licences) Regulations 2011 ¹⁴⁷.



Carbon Storage Agreement for Lease	Carbon S E			
C The Storage	Termination of a Carbon Storage License The Storage of Carbon Dioxide (Termination of Licenses) Regulations 2011			
Appraisal Term	Post-Transfer			
(or Initial Term)	Operational Term Post-		Post-Closure Period	Period
Appraise Assess Define Phase Phase Phase	Execute (Phase	Operate Phase	Post-Closure Monitoring Phase	Post-Transfer Monitoring Phase

Figure 4. The periods of a CO₂ storage project that are covered by a Storage Lease, storage licence and storage permit ¹⁵⁷. Contains information provided by the North Sea Transition Authority and/or other third parties.

On receipt of a licence application, the NSTA assesses the applicant's ability to undertake the necessary appraisal and planning, and to submit a credible permit application. Where more than one application is received for the same area, the NSTA may select one application and reject the other or suggest to competing applicants to become one licensee ("a marriage"). The licence application must include a technical and commercial evaluation, as well as project plans for the storage site. For each site, the following data and maps must be provided:

- An estimate of the storage resource, and the calculation inputs provided,
- A summary of the subsurface risks and details about legacy wells (pre-existing wells, whether plugged and abandoned, suspended or to be used for subsequent use during the storage operation) located within the licencing area,
- A map of the reservoir, including the delineation of the outer boundaries of the licence area,
- A representative seismic section and a separate geological cross-section,
- A technical description, including a summary of all data used to achieve the evaluation.

A Storage licence cannot be granted until the NSTA has received agreement to issue the licence from the Secretary of State under the Habitats regulations ¹⁶⁰.



3.1.3.2. Storage Appraisal

The work programme described in Appendix B.3. will enable the developer to reduce uncertainties and design the project during the appraisal term. At the end of the appraisal term, the developer should be in a position to apply for a storage permit.

The NSTA have divided the Appraisal Term into four distinct stages ¹⁵⁷:

Exploration and Appraisal:

- Early Risk Assessment (Identification of the critical risks, project and engagement plan)
- Site Characterisation (Definition of the proposed Storage Site and Complex, Geophysical surveys, exploration & appraisal wells)
- Assess and Define:
- Assess (Initial Field development planning, including Development drilling, Construction & Commissioning, where applicable)
- Define (Storage Permit Application submission)

3.1.3.3. Storage Permit

Before granting a storage permit, the NSTA must be satisfied that ¹⁵⁸:

- The storage complex and surrounding area have been sufficiently characterised and assessed in accordance with the criteria set out in Annex I to the EC Storage Directive ¹⁴⁵
- No part of the storage complex extends beyond the territory of the United Kingdom
- Under the proposed conditions of use of the storage site, there is no significant risk of leakage or of harm to the environment or human health.
- The proposed operator is technically competent (including in the operation of environmental management systems), financially sound, and can be relied upon to carry out the functions of an operator; and
- The proposed operator has in place an appropriate programme of professional and technical development and training.



Onshore Environmental regulations (onshore)

The onshore environment is regulated by the Environment Agency (EA). Depending on how site operations interact with different components of the environment (e.g. groundwater), different permits or licences may be needed for CO₂ storage activities via deep mineralisation, including waste treatment and disposal permits and a groundwater activity permits/ licences.

3.1.4.1 Environmental regulations relating to waste.

Carbon dioxide is currently not classified as a waste in environmental regulations in England ¹⁶¹ or equivalent legislation in Wales ¹⁶² or Scotland ¹⁶³. It is therefore uncertain what type of environmental permit(s) will be needed.

Permit requirements can be met by using one of the following:

- A regulatory position statement where the EA does not require a permit considered unlikely given the potential scale, uniqueness, and level of maturity of onshore CO₂ deep mineralisation activities.
- An exemption considered unlikely given the potential scale, uniqueness, and level of maturity of onshore CO₂ deep mineralisation activities.
- a 'standard rules permit' a set of fixed rules for common activities. As CO₂ deep mineralisation is immature and uncommon, this is considered an unlikely permitting route. However certain activities associated with onshore CO₂ deep mineralisation may be subject to some standard permits see below.
- a 'bespoke permit' Potential scale, uniqueness, and level of maturity of the activities related to onshore CO₂ deep mineralisation, make it likely that a bespoke environmental permit will be needed. ¹⁶¹⁻¹⁶³ prior to application, the applicant will be required to satisfy competency and legality checks, develop an appropriate management system, complete a risk assessment, design the facility to avoid and control emissions. The EA consults on bespoke permit applications.

Although currently only applicable to prospecting for oil and gas, Standard Rules SR2015 No1 ¹⁶⁴ may apply for the management of wastes generated from drilling, coring, pump tests, stimulations and decommissioning, undertaken during site investigations, operation and site closure.



Groundwater activities

A hydrogeological risk assessment may be required HMG ¹⁶⁵. This assessment must consider the potential risks, sensitivity of the surrounding environment and the hazards posed, and the likelihood of the risks happening. The structure of the hydrogeological risk assessment comprises, inter alia, the proposed assessment scenarios, the priority substances identified, a review of the technical precautions, including monitoring and a detailed risk assessment.

Where abstraction of water is planned, for example to dissolve CO₂ during injection to increase rates of mineralisation and reduce CO₂ leakage, a water abstraction licence will be required ¹⁶⁶. Similarly, reinjection of water may require a discharge permit. An abstraction licence may not be required where the water is effectively recirculated back into the formation from which it is extracted. A discharge permit is likely to be needed where chemistry of abstracted water has changed prior to reinjection (i.e. due to the dissolution of CO₂).

A consent to investigate a groundwater source will be required (prior to obtaining an abstraction licence) for activities such as ¹⁶⁷:

- drilling or excavating a borehole or well.
- excavating a catchpit or a seepage-fed lagoon
- completing pumping tests.

In 2010, the Environment Agency published Environmental Permitting Guidance Groundwater Activities ¹⁶⁸, which summarises the activities that may require a permit. This guidance accompanies the Environmental Permitting (England and Wales) Regulations 2010 ¹⁶⁹.

We have not consulted with the regulators (such as the Environment Agency) on their views on regulatory requirements for activities relating to deep CO₂ mineralisation. While they are not explicitly included in these regulations, the regulators may still consider (aspects of) them as part of their environmental permitting regime which is based on a risk-based approach to regulation.

3.1.1 Application to CO₂ mineralisation

A key assumption for this review is that activities related to the CO₂ mineralisation will be regulated in a similar manner to activities related to CO₂ storage in porous rocks, *i.e.* that the regulations for the latter will be applied in some way to this new activity. The regulations pertaining to CO₂ storage in porous rocks and associated guidance (summarised above) have



been developed specifically for the activities related to that technology (i.e. injection and storage of gaseous CO₂ in suitable geological formations offshore). While they do not specifically define the type of storage project, nor the type of rock into which CO₂ is to be injected, the identified risks (that the regulation aims to mitigate) relate specifically to this technology. As there are some important differences between storage in porous *versus* CO₂ mineralisation, we provide some preliminary considerations on the extent to which current regulatory requirements might be relevant and can address the risk expected from CO₂ deep mineralisation activities (Table 6).

Current regulatory requirement ¹	Relevance to CO ₂ deep mineralisation	Comment
Storage in offshore UK continental shelf.	Partially relevant. Current regulations are not considered to support storage onshore	This is the biggest gap in the current regulatory process. Consideration needs to be given to how activities onshore might be regulated and whether additional legislation (such as the Energy Act) will be needed.
Storage Licence and Permit	Expected to be required, with the licence enabling site exploration and appraisal, in preparation for a permit application.	
Storage Licence	Data is likely to be significantly more limited to enable this mainly 'desk- based' study, as previous exploration activities to image the subsurface in detail are unlikely to be available.	
Storage complex	Partially relevant. Whilst a storage complex may be defined, identifying secondary storage formations may not be appropriate.	Consider the extent to which injection scenarios may be relevant for both basalt and any sandstone storage.
	The Storage Complex boundaries must be defined, requiring confidence that the full extent of migration can be determined during site appraisal. This may be particularly difficult to achieve in the absence of data on fracture	

Table 6 Summary of the relevance of the regulatory requirements identified in this review to CO₂ deep mineralisation.



	network geometries and connectivity, to establish extent and pathways of migration.	
	Permanent containment is the key objective and demonstrating this is a fundamental test of the regulatory framework.	Consideration must be given to methods that establish permanent containment, including monitoring and assessment of future site evolution and the potential for dissolution and CO ₂ release.
CO ₂ Plume	The concept of a monitorable CO ₂ plume will be significantly less relevant for storage via deep mineralisation, by definition.	Some monitoring may be required to demonstrate that permanent containment has been achieved.
Storage capacity	Storage capacities must be estimated and the uncertainty in these calculations may be significantly higher than for traditional CO ₂ storage.	
Storage efficiency	Relevant and will need testing during site appraisal	
Injectivity	Relevant and will need testing during license application and subsequent site appraisal.	
Technical Work Programme	Currently assumes that seismic data acquisition is the primary tool for assessing subsurface structure. However, this is unlikely to be applicable in the detail required.	Seismic imaging may not be suitable for mafic and ultramafic rocks. Regulators and applicants will need to consider appropriate methods that robustly enable definition of permit boundaries and subsequent containment.
Definitions of reservoir, seal, and primary and secondary storage sites.	The concept of a seal may not be applicable and the extent to which mineralisation as the ultimate trapping mechanism can be relied upon to achieve permanent containment must be carefully evaluated in future research projects. It is not clear the extent to which secondary storage, for example in adjacent strata, will be required either by the operator or regulator.	



Early Risk Assessment	Relevant but likely to focus on a different range of risks.	Conceptual and generic early risk assessments would be beneficial to test technologies and concepts with regulators, operators, policy makers and local communities.
Geological interpretation and storage complex characterisation	Current NSTA guidance is based on storage within a sedimentary sequence and requires identification of key parameters that may be less relevant, such as capillary entry pressures and reservoir quality.	Current guidance outlines a workflow for appraisal of storage in sedimentary porous rocks. New workflows and associated guidance, aligned to robust assessments of demonstrable permanent containment, will be required. Most aspects of the characterisation outlined in current guidance are relevant at a high level though specific analytical; and simulation tools will be different.
Faults, fractures and leakage paths	As storage is predicated on fracture permeability to access minerals for reaction, this is essential.	In contrast to storage in porous rocks, fractures are desirable, but the network of hydraulically connected rock volume will need to be characterised in great detail. Potential leakage points will also need to be identified, again requiring very careful and robust mapping of hydraulically connects flow paths, and modelling of potential flow paths, hydrogeology and potential flux rates (coupled geochemistry and flow).
Containment Risk assessment	Essential and workflow valid.	
MMV Plan	A key concept is that, through observation, the permanent containment of CO ₂ can be demonstrated. This requires monitoring technologies capable of establishing this.	Traditional and well-established seismic monitoring, as currently required in NSTA's guidelines, is unlikely to be applicable to storage in mafic and ultramafic rocks. The monitorability of CO ₂ deep mineralisation must be established as a priority.
Corrective Measures Plan	Required	
Closure and post-closure plan	Required	The methods and technologies that could be applied following closure must be identified and validated. Noting that remote monitoring is unlikely to be sufficient and borehole access will not be possible.



Onshore	Likely and expected to be required.	Although it is expected that environmental permits,
environmental		possibly, including some form of groundwater
permits		investigation permit, will be needed, the current
		regulations do not explicitly pertain to CO_2 (to the
		extent we have been able to confirm this), primarily
		because CO_2 is not currently listed as a waste or
		contaminant. This appears to be a significant current
		gap in onshore regulation which will need to be
		addressed by the responsible regulators, i.e. EA,
		SEPA, NRW and other bodies.

3.2 Supply chain.

Butnar, I. (UCL)

Key Points:

- Supply chains encompass all the actors providing the space, goods and services to support the delivery of CO₂ storage by mineralisation, including, but not exhaustively, activities around planning, design, purchasing, manufacturing, distribution, sales, legal, professional and financing services to ensure that the right skills, leadership and process systems are in place, as well as the materials and energy required.
- This report focusses on three key blocks of the supply chain: pre-injection activities, operation of CO₂ injection and closure and decommissioning of the injection site.
- Several potential bottlenecks associated with the in-situ mineralisation supply chains in the UK were identified based on at-scale operations in Iceland, USA, Oman and other examples from the literature.

The storage of CO₂ through in-situ mineralisation is currently limited, with only three projects at demonstration scale, i.e. Carbfix in Iceland, Wallulla in the USA, and 44.01 in Oman and the UAE. Given the incipient stage of mineralisation supply chains, this review draws upon UCL expertise on supply chains analysis, in particular on CO₂ removal supply chains understanding developed through stakeholder engagement for CO₂RE Hub, UK's Greenhouse Gas Removal Hub. This review explores mineralisation supply chains though interviews with two of the three in-situ mineralisation demonstrators (Carbfix and 44.01) and focused review of existing literature on CO₂ mineralisation.


As there is no agreed definition of the boundaries of in-situ CO₂ mineralisation, here we define mineralisation supply chains as encompassing the processes, materials, energy and know how required to (1) identify and prepare the mineralisation site, (2) operate the CO₂ injection, which requires CO₂ capture, CO₂ transport, operation and monitoring of the injection site, and (3) post-injection, covering decommissioning and closure of the site. Based on this definition, this review identified several critical factors which affect the initiation and scale-up of in situ CO₂ storage through mineralisation: (1) availability of geological data from basin to site level, (2) availability of steady CO₂ supply, (3) permitting specific to in situ CO₂ mineralisation activities, and (4) public awareness and acceptance of mineralisation activities. In the UK context, key bottlenecks for the deployment of mineralisation supply chains in the UK are the mapping of suitable locations, increasing the public awareness on the topic of CO₂ mineralisation and how this differs from oil and gas operations, and demonstrating mineralisation projects in different locations across the UK.

3.2.1 CO₂ mineralisation supply chain.

There is no agreed definition on what constitutes a CO₂ mineralisation supply chain. Here, we define it as encompassing all the actors providing the space, goods and services to support the delivery of CO₂ storage by mineralisation, including, but not exhaustively, activities around planning, design, purchasing, manufacturing, distribution, sales, legal, professional and financing services ¹⁷⁰ to ensure that the right skills, leadership and process systems are in place, as well as the materials and energy required. This report focusses on three key blocks of the supply chain (Figure 5):

(i) Pre-injection activities:

- Screening for suitable mineralisation sites. This requires geological and hydrological assessment at regional, to national level,
- Identification of potential storage sites. This can be done by combining geological information with socio-economic and environmental conditions, mapping of current and future CO₂ capture points and CO₂ networks, and water sources (if CO₂ is injected dissolved in water),
- Preliminary exploration to allow detailed site characterisation. This requires drilling machinery, geophysical and geological investigation, and monitoring equipment.



(ii) Operation of CO₂ injection:

- CO₂ capture from a Direct Air Capture plant, or carbon capture installed on a power plant, a manufacturing plant, or other type of industrial point emitter,
- CO₂ transport using pipelines, or modular transport, *e.g.* ships, cargo trucks, freight; and
- CO₂ geological storage, covering the geological storage site, conditioning installation and/or intermediary storage tanks for CO₂ and water (if used), injection and monitoring wells, monitoring equipment.

(iii) Closure and decommissioning of the injection site.

Two-three years of site monitoring is critical to evidence the permanence of the storage of CO₂.





CO₂ for in-situ mineralisation can be captured either directly from the atmosphere (DAC), or from a point source, *e.g.* power generation, hydrocarbon processing (including hydrogen production), production of iron, steel, fertilizers, and chemicals. Carbon capture can be an energy intensive process, requiring between 0.4 and 3.8 GJ/tCO₂ if the CO₂ is captured from a



point source, and between 3.5 and 12.5 GJ/tCO₂ if, the CO₂ is captured through DAC (Table 7). DAC can also consume high volumes of water, between 1.6 and 8.2 t water /tCO₂.

The choice of the CO₂ transport method depends on the distance from the CO₂ source to the storage site, the CO₂ volume to be transported and pressure requirements ¹⁷¹. The most proven and cheapest form of CO₂ transport is by pipeline, which is currently deployed at commercial stage ¹⁷². Shipping of CO₂ is currently at pre-commercial stage and could be utilised mainly for long distances. Rail and road CO₂ transport would only be considered for short distances ¹⁷². The liquefication and conditioning of CO₂ for transport requires an order of magnitude less energy as compared to carbon capture (Table 7).

The injection fluid used for mineralisation includes freshwater, *e.g.* Carbfix methodology, processed water, *e.g.* 44.01 in Oman, or sea water which is currently being investigated, *e.g.* Carbfix pilot in SW Iceland. Injection of CO₂ dissolved in water can require large volumes of water, *e.g.* Carbfix uses between 25 and 27 tonnes water per tonne CO₂ injected ²², but the amount of water required can vary between 3 and 35 tonnes water per tonne CO₂ depending on the CO₂ partial pressure. The energy consumption required for injecting dissolved CO₂ is relatively low as compared to the other stages of the mineralisation supply chains, ranging between 0.03 and 0.07 GJ per tonne CO₂ for compressing dissolved CO₂ vs 0.18 GJ per tonne CO₂ for pressuring pure CO₂.

Resource requirements\ Supply chain stage	CO ₂ capture	CO₂ transport	CO₂ geological storage
Water use	8.2 t water/tCO ₂ in liquid DAC vs 1.6 t water /tCO ₂ in solid DAC systems ¹⁷³	N/A	3-35* t water/t CO ₂ injected ^{22,37,123}
Energy use	 0.4 - 3.8 GJ/tCO₂ depending on the capture technology ¹⁷⁴ 6.6 - 12.5** GJ/tCO₂ in liquid vs 3.5-6.6 GJ/tCO₂ in solid DAC systems ^{173,175} 	0.3-0.7 GJ/tCO ₂ required for conditioning CO ₂ for pipeline transport 174 0.05 – 0.5 GJ/tCO ₂ required for CO ₂ liquefaction for shipping 171	0.03 - 0.07*** GJ/tCO ₂ for compressing dissolved CO ₂ vs 0.18 GJ/tCO ₂ for pressuring pure CO ₂ ^{22,173}

Table 7. Resource requirements (energy, water, land) for in-situ CO₂ mineralisation supply chains



Land use	0.2 m ² /tCO ₂ for DAC powered	N/A	No available data
	by own solar PV ¹⁷⁵		

* Original values: 25-27* t water/t CO₂ injected ^{22,37,123}; 3-35 t water/tCO₂ injected (44.01 interview).

** Original values: 8.4 - 12.5 GJ/tCO₂ in liquid vs 3.9-5.9 GJ/tCO₂ in solid DAC systems ¹⁷³ and respectively 6.6 – 9.9 GJ/tCO₂ in liquid vs 3.5-6.6 GJ/tCO₂ in solid DAC systems ¹⁷⁵.

*** Original values: Energy required to pressurise CO₂ dissolved in water at 25C and 25 bar: 20 kWh/tCO₂ for pressurising dissolved CO₂ vs 50 kWh/tCO₂ for pressuring pure CO₂ 22 ; 0.03 GJ/tCO₂ for compressing pure CO₂ from 10.7 to 16 MPa 173 .

3.2.2 Monitoring requirements to evidence CO₂ storage through mineralisation

At the injection site, there are several points where potential CO_2 loss should be monitored and reported. These include (i) CO_2 pipeline coming to the intermediary CO_2 storage tank, or transfer of CO_2 from ship vessels to the intermediary storage tank, (ii) CO_2 pipeline from the intermediary tank to the injection well, (iii) the injection wells, (iv) leakage from wellbores or non-sealed fractures in the caprock, the latter being more relevant to the projects injecting supercritical CO_2 ^{6,29,43}.

If CO₂ is injected with other gases, then collective loses should be monitored. For instance, at the Hellisheiði site, Carbfix injects a CO₂ stream co-captured with other acidic gases, such as H₂S and SO₂. Whilst this does not affect mineralisation of CO₂ 22,119,176 , these gases are contributing to aerosol formation which can either warm (through absorption of solar radiation on dark particles) or cool (from forming cloud droplets and reflecting radiation) the atmosphere.

Commercial and pilot injections to date have shown that in-situ mineralisation is feasible and safe ⁶. Monitoring results published by Carbfix show that the dissolution of CO₂ in water results in an immediate solubility trapping and that mineralisation happens in < 3 years after injection 22,119,176 . Since, the CO₂ charged water is denser than the formation waters, the risk of leakage is small, contributing to high public acceptance of previous CO₂ mineral storage projects 123 .

3.2.3 From demonstration to large scale carbon capture and in-situ storage

As highlighted in the Global Status of CCS report, the number of carbon capture and storage projects has increased exponentially in the last 5 years ¹⁷⁷. Historically, the carbon capture, transport and storage supply chain would be operated through vertically integrated industry consortia. These projects however faced high risks and costs due to co-dependency between the different parts of the supply chain, *e.g.* each part of the chain facing different challenges.



With the rise of different types of carbon capture from a variety of industrial emitters, energy plants and DAC systems, there has been a clear transition to a model of carbon capture and storage networks, in which several CO₂ sources share CO₂ transport infrastructure and geological storage. For instance, the Carbfix Coda Terminal plans to ship CO₂ from across Europe, including the UK, to store it through in-situ CO₂ mineralisation. In the UK, several new networks have been announced, whilst the development of existing networks continues, *e.g.* the Medway CCS Project ships CO₂ by canal and rail from multiple power stations east of London to offshore storage in the Camelot depleted gas fields in the North Sea ¹⁷⁷. In parallel, some technology providers are utilising capture-as-a-service model, in which they offer bespoke carbon capture to an individual emitter, also potentially designing the full supply chain up to geological storage, *e.g.* Aker Carbon Capture operating in several locations across the US, Europe and Scotland.

The Coda Terminal represents the first scale-up of the Carbfix technology, starting commercial injection of 0.5 million tonnes CO₂ per year in 2026, scaling up to 3 million tonnes per year from 2030¹²³. The scale-up is designed in steps, starting with a lower injection capacity to keep upfront costs and risks low, with the potential to upscale gradually in line with the availability of CO₂. The Coda Terminal project and other examples in the literature suggest that there are potential bottlenecks associated with the mineralisation supply chains, that are transferable to UK scenarios:

- Availability of geological and geophysical data. Access to data is fundamental for the characterisation of potential CO₂ storage. From a project developer perspective, acquisition of new data on site characterisation through field operation or purchase is cost intensive. *Potential bottleneck mitigation* cost reduction by screening of sites with suitable geological characterisation by public and/or sharing proprietary data by private institutions, *e.g.* oil and gas companies ¹²³. This project has described the national scale theoretical estimates of potential, but further investigation would be required to progress to basin and -specific scale in the most suitable locations. Specific sites selection requires the introduction of further selection criteria such as proximity to CO₂, water and renewable energy sources, in locations which meet environmental constraints, and are economically and socially feasible.
- Proximity to water and CO₂ supply. A consistent CO₂ supply and access to water, if CO₂ is injected dissolved, are both key for the feasibility of mineralisation in a specific location ^{37,123}. Access to continuous CO₂ supply is currently a bottleneck to CO₂ mineralisation in the UK.



As current water supply in the UK is already affected by the changing climate and increased urbanisation, access to consistent water supply may be a bottleneck in the future if freshwater is used, see e.g. ¹⁷⁸. A *mitigation* to this potential bottleneck is to refine the mapping of suitable geological formations to prioritise the further exploration of the sites within 30 km from water sources and less than 300 km away from CO₂ sources e ³⁷. In the UK, industries are clustering together to combine CO₂ emissions to enable collective CO₂ reduction. New CO₂ networks have been announced in parallel with the further development of existing networks. Prioritising sites which are near these networks and industrial clusters could improve the economics of injection.

- Availability of exploration equipment and skilled workforce. Once a prospective site is identified through crossing geological suitability with CO₂ and water availability, further site investigation and characterisation is needed. This will involve the drilling of test wells and undertaking monitored test injection. ¹²³. Given the inexistence of in situ CO₂ mineralisation in the UK, both specific equipment and skills could be a bottleneck for the start and scaling up of the industry. As a mitigation, transferable skills in the oil and gas and mining sector in the UK could be leveraged to facilitate the development of the industry,
- Proximity to renewable or thermal energy sources. This preliminary review suggests mineralisation has a relatively low energy consumption at existing test injection sites, operational scale up will increase the energy penalty. To ensure energy independence from the grid, and to reduce the impact on the local communities, it would be favourable to install renewable energy sources to power injection and monitoring equipment. This would provide energy security and clean energy but would require an initial up-front investment.
- Public engagement and public acceptance. The 2023 Global Status of CCS report highlights lack of public support as key bottleneck in demonstration and development of CCS projects ¹⁷⁷. Social science research based on extensive interviews with the public showed their negative perception caused by oil and gas activities, e.g. fracking ¹⁷⁹. Both, Carbfix and 44.01 agreed that early engagement of the public is key for the success of any mineralisation project (pers.comm with Snæbjörnsdóttir, Marieni and Matter; January 2024). They suggest that public engagement is initiated as early as a site is confirmed, to ensure that adequate awareness and support is built before the injection starts. It was also suggested that public engagement should be a priority in locations with a history of oil and gas extraction and CCS, as it would need to build confidence that the new injection is



fundamentally different from oil and gas operations. Whilst the UK public is becoming familiarised with CO₂ storage via other technologies, e.g. biochar, enhanced rock weathering, public understanding of in-situ mineralisation is critical to their awareness and acceptance of development of new projects in the UK. However, more dissemination and social research specific to CO₂ mineralisation activities is needed.

Environmental considerations. This project has delivered a first pass mapping of potential UK locations suitable for CO₂ storage though in-situ mineralisation. The theoretical potential is high, there are a number of considerations to be addressed before in-situ mineralisation can be developed further in the UK. These bottlenecks identified further work to be done before trade-offs between decarbonisation goals enabled by CO₂ mineralisation and other land and coastal uses can be fully assessed. Notably, some suitable locations fall in areas of designated biodiversity protection, *e.g.* in the northwest of Scotland, Northern Ireland or are key tourism destinations, Shetland Islands or the Lizard Peninsula.

4. Knowledge gaps and recommendations

Key Points:

- In undertaking this study, several data and knowledge gaps pertaining to site characterisation, regulatory regime and supply chains fundamental to the application of CO₂ mineralisation in UK hard rocks have been identified. While specific to the UK in regard to characterisation of suitable formations, CO₂ storage regulations and supply chains, there are wider implications as this technology advances and is scaled up.
- Knowledge gaps pertaining to site characterisation, regulations and supply chains were identified and recommendation provided, where appropriate.
- The recommendations provide an integrated and multi-resolution data gathering programme. Nothing of this scale has been attempted or if it has, been published, although smaller scale or less focused studies exist. One example is the The Big Sky Carbon Sequestration Partnership (BSCSP), created by the U.S. Department of Energy to support the Wallula pilot project and expand regional knowledge. It investigated the mafic formations of the Columbia River Basalt group that covered Montana, Wyoming, Idaho, South Dakota, eastern Washington and Oregon. Another is the online Mineral



Storage Atlas produced by CarbFix that identifies globally favourable mafic geology that might support CO₂ mineralisation.

4.1 Site characterisation

4.1.1 Knowledge gaps:

- inconsistent data that limits the identification and 3D geometric constraints of suitable UK formations for CO₂ mineralisation. This includes low-resolution (10's-100's m) information on the width, length and thickness of formations at or below the surface; and in subsurface architecture, such as stratigraphy, faults, fractures across the proposed PSGF,
- lack of information of the effectiveness of UK mafic and ultramafic rocks to store CO₂, including no high-resolution (1-5 m intervals⁸) assessment of the UK mineralogical and geochemical diversity, alteration; physical (porosity and permeability) and geomechanical properties at depth of the proposed PSGF,
- The lack of robust laboratory assessment of the effect of temperature, pressure, and various CO₂-bearing fluids on the potential of UK's mafic and ultramafic lithologies to mineralogically trap CO₂

4.1.2 Recommendations

To provide a framework for site characterisation, including the ten Potentially Suitable Geological Formations, it is recommended to:

(i) Undertake field and subsurface mapping

The lack of geometric constraints from primary data led to the use of mean thickness estimates taken from analogues or published literature to calculate the volume and potential storage capacity of the relevant PSGF. The uncertainty ranges of these measurements are from tens to several hundreds of metres. This study was desk based and use of subsurface data such as geophysical, gravity and magnetic surveys was out of scope due to time constraints. However, it is recommended that a systematic field and subsurface mapping campaign is undertaken for all proposed PSGF before being expanded to other areas of interest.

This should include the collection and interpretation of a range of subsurface data as mentioned above, complimented with boreholes and petrophysical log data. It is important to note that



seismic imaging of igneous rocks can prove difficult due to their layered and crystalline nature, which causes the scattering of seismic (acoustic) energy and production of a poor image ¹⁸⁰. To calibrate subsurface data and provide insight into finer scale heterogeneities and internal structure (*e.g.*, lithological variations, and any fault and fracture networks), integration with extensive field-based data and detailed geological mapping is vital.

These data would provide crucial information on stratigraphic thicknesses and extents of high and low geochemically reactive lithologies; geological properties; zones of high and low porosity, permeability and alteration; the location and density of faults and fractures; the current fluid flow regime through the igneous rocks, which is likely groundwater ¹⁸¹. There are also opportunities to utilise legacy hydrological and hydrocarbon subsurface data collected over several decades. Much of these data are open access and include seismic, borehole and associated lithological studies, that could be reprocessed and reinterpreted with a new perspective and updated geological knowledge to support the search for PSGF.

(ii) Undertake a comprehensive sampling of UK igneous lithologies

Our assessment through the filtering and ranking of relevant geochemically reactive lithologies suitable for CO₂ mineralisation, while valid, is an oversimplification of a diverse mineralogical systems. It is recommended that a comprehensive sampling of all UK igneous rocks is undertaken, as even those PSGF proposed as 100% potentially suitable, will likely be composed of a variety of lithologies. These will include rocks that might be less or non-reactive, therefore understanding how these may interact with any injected CO₂ is essential; for example, rocks may act as a barrier/baffle to flow or impede mineralisation; equally, some rocks may prove more reactive or permeable than expected.

Collection of a fully representative dataset could be achieved through an integrated field-based approach, with a borehole drilling campaign to take core samples. A range of thin section, laboratory and core logging would provide direct measurements of geochemical and stratigraphic variety, porosity, permeability, existing alteration, poroelasticity and geomechanical properties. At present the lack of direct measurements has resulted in a high-level theoretical approach using estimated formation properties from analogue studies, introducing a high degree of uncertainty to the theoretical capacity estimates. While lithologically comparable, the analogue data was compiled from non-UK samples which have undergone different geological histories to the rocks of the UK (such as burial, exhumation). Therefore, the volume



and potential storage capacity should be treated with caution as they use non-UK porosity values as input, and a better assessment can only be achieved with data that directly represents each PSGF.

(iii) Investigate Depth and Temperature Controls

This study categorised each PSGF at surface using current bedrock geological map data, with the expectation that each formation will continue at depth. Based on the geothermal gradient of the UK, we have suggested a minimum depth of 1 km or greater for CO₂ mineralisation. Documented injection depths at scale experiments are shallower, such as at Carbfix in Iceland, where the geothermal gradient varies from 50 - 150°C per km along the volcanic rift zone ³⁶. Without a volcanic rift zone to provide excess geothermal heat, it is likely that the optimum depth for injection in the UK with be significantly deeper. To constrain this, it is recommended detailed laboratory studies are undertaken to understand the effect of CO₂ injection at different temperatures and depths on various PSGF lithologies and computer models constructed to simulate a range of fluid flow and mineralisation pathways.

iv) Data Collection Strategies

Several of the PSGF are situated in a relative proximity, being located on the Western coast of Scotland or the Eastern coast of Northern Ireland. This is related to the outcropping of the Palaeogene mafic-ultramafic rocks of the North Atlantic Igneous Province (see Summary of UK igneous geology 2.1). Data collection could therefore focus on the geographically concentrated PSGF. However, in order to create a smoothly integrated and cost-effective programme, it would be recommended to choose one location to trial all stages of data collection and laboratory analysis, before a full roll out to all PSGF.

4.2 UK regulations

Current regulations focus on activities related to the conventional geological storage of CO₂ They are based on offshore storage in sedimentary rocks with a porous and permeable reservoir. The key terms, definitions and workflows outlined in the regulations and accompanying guidance are designed to licence and permit activities related to this concept. The regulation is currently being applied for the first time; hence practical knowledge of its efficacy is still limited.



4.2.1 Knowledge gaps

The main regulatory gap is the lack of specific regulation that considers activities related to CO_2 deep mineralisation, or to CO_2 storage offshore, either via storage licence or environmental permit, for CO_2 deep mineralisation.

As the UK is expected to develop offshore storage in conventional porous and permeable reservoirs in sedimentary sequences, it is reasonable to assume that these would take preference over mineralisation for any storage deemed necessary to be offshore. Storage operators wishing to develop storage projects offshore are likely to prefer to develop these conventional storage types over untested CO₂ mineralisation. This is because the likely amount of characterisation needed, as the pre-existing data available will be extremely limited, might make CO₂ mineralisation options subeconomic relative to conventional CO₂ storage. Furthermore, the current regulatory uncertainty and lack of maturity in the technology at scale will also lead to additional risk being borne by the operators relative to conventional storage development.

However, onshore CO_2 mineralisation may be needed for isolated emitters, where it may prove more economic to develop a bespoke CO_2 mineralisation project locally thus avoiding high transport costs, rather than transport the CO_2 to an existing node on a transport network. Onshore geological storage, including deep mineralisation, may require specific guidelines and regulation (which may require new legislation). Interactions between onshore environmental permitting and CO_2 storage licensing should be assessed and evaluated.

4.2.2 Recommendations

In our review, we have assumed that the current CO₂ storage regulatory and licensing framework, as reviewed here, will form the basis for regulating activities related to CO₂ deep mineralisation. This review indicates that many of the principles of risk-based site appraisal and development of robust 'safety cases' prior to the award of a storage permit, are a good basis for the regulation of deep mineralisation. However, some concepts are not fit-for-purpose and recommendations on what might be required to address this include:

 New workflows and associated guidance, aligned to robust assessments of demonstrable permanent containment. At a high level, most aspects of the characterisation outlined in



current guidance are relevant. However, specific appraisal, analytical and simulation technologies will be different.

• Conceptual, and generic risk assessments, based on credible exemplar case studies.

This is to provide greater understanding of the appraisal activities that would be needed in CO_2 deep mineralisation projects. The current regulatory process is founded on site appraisal that seeks to reduce risks and uncertainties in future site performance and subsequent evolution post-closure. A site- and project-specific Early Risk Assessment, completed by the project developer, is evaluated by the regulator within the first few months of being awarded a storage licence. The risks and uncertainties determine the specific site appraisal and technical studies that will be undertaken by the project developer during the development of their application for a permit. Whilst a typical set of risks for storage in sedimentary and porous reservoirs are emerging, the risk profiles in CO_2 deep mineralisation will be quite different. Therefore, conceptual, and generic risk assessments, based on credible exemplar case studies, should be performed to provide greater understanding of the appraisal activities that would be needed in CO_2 deep mineralisation projects. These trial early risk assessments would be very beneficial to test technologies and concepts with regulators and policy makers, enabling them to develop prototype regulations, where needed, and supporting guidance.

- Regulatory guidance on methodologies and workflows for site appraisal that establish the evidence for safe and permanent containment.
- Testing and validating of specific methodologies for the assessment of future site evolution in CO₂ deep mineralisation projects (*e.g.* through R&D and pilot-scale tests). These methodologies will need to reflect the technology- and site-specific risk profiles that will be most relevant for CO₂ deep mineralisation and might be expected to require a different suite of technologies (*i.e.* different modelling tools) to those deployed in conventional CO₂ storage projects. For example, approaches developed over many decades in the radioactive waste industry, with a focus on fracture-based fluid flow and geochemical reactivity, should be reviewed as a basis for robust methodologies to establishing long-term safety cases.
- Regulators and project developers will need to consider appropriate methods that robustly enable definition of permit boundaries (*i.e.* storage site and storage complex, monitoring areas) and subsequent containment.



- Establish the monitorability of CO₂ deep mineralisation. Well-established and mature seismic monitoring technologies, as currently required in NSTA's guidelines for CO₂ storage in porous sedimentary reservoirs, are unlikely to be applicable to storage in mafic and ultramafic rocks. This is because the resolution and sensitivity of the technique may be insufficient to detect the CO₂ at the volumes injected into the fracture networks (and especially if injected as dissolved in the produced water).
- Identification and validation of methods and technologies for monitoring conformance between site behaviour and predictions of future behaviour, that could be applied following closure. Remote monitoring (such as seismic techniques) is unlikely to be sufficient and borehole access will not be possible.
- Development of environmental permits for onshore regulations, possibly including some form of groundwater investigation permit.

4.3 Supply chains.

CO₂ storage via deep mineralisation is currently being demonstrated in four locations globally *i.e.* Iceland, Oman, UEA and USA. As mineralisation supply chains are being formed, practical knowledge on which configurations could work and in particular, what would work in the UK context is very limited or non-existent. This lack of knowledge applies both to the current small demonstrative scale, and larger, industrial scale, of million tonnes CO₂ mineralised per year.

Knowledge gaps and recommendations

Whilst CO₂ injection for mineralisation is demonstrated in other locations around the world, demonstration in the UK geological, socio-economic and environmental context is key for understanding its practical potential in the UK. This would test:

- Feasibility of currently employed injection techniques in the UK geological context,
- CO₂ injection rates which are compatible with UK geophysical conditions,
- Environmental and social constraints to scaling up mineralisation in the UK, which should be considered in the specific regulation being developed for in-situ mineralisation,
- Business models specific to the UK context, which could help these projects scale-up.





Appendix A Geological Formations

A.1. UK Geological Formations

Appendix Table A1. BGS rock classification scheme and lithological rank used in the geological screening methodology.

RCS_X	BGS Rock Classification Scheme Description (RCS_D)	Rank
AGBA	AGGLOMERATE, BASALTIC	А
GBAN	ANALCIME-GABBRO	А
GBAN + PCT	ANALCIME-GABBRO AND PICRITE	А
GBANH	ANALCIME-GABBRO, HORNBLENDE	А
MCGBAO	ANALCIME-MICROGABBRO, OLIVINE	А
BA	BASALT	А
BA + BCLAVA	BASALT AND BASALTIC LAVA	А
BA + HAW	BASALT AND HAWAIITE	А
BA + MCGB	BASALT AND MICROGABBRO	А
FPBA	BASALT, FELDSPAR-PHYRIC	А
BA + HAW + MUG	BASALT, HAWAIITE AND MUGEARITE	А
BALAVA	BASALT, LAVA	А
BALVPW	BASALT, LAVA-PILLOWED	А
BAMAP	BASALT, MACROPHYRIC	А
BAMCP	BASALT, MICROPORPHYRITIC	А
BAOCM	BASALT, OLIVINE-CLINOPYROXENE-MICROPHYRIC	А
BAOM	BASALT, OLIVINE-MACROPHYRIC	А
BAPOCM	BASALT, PLAGIOCLASE-OLIVINE-CLINOPYROXENE-MACROPHYRIC	А
PXPBA	BASALT, PYROXENE-PHYRIC	А
BATUF + BCLAVA	BASALTIC LAVA AND BASALTIC TUFF	А
BCLAVA + SDST	BASALTIC LAVA AND SANDSTONE	А
BCLAVA + VCBR	BASALTIC LAVA AND VOLCANICLASTIC-BRECCIA	А
BCLAVA + CONGAP + OLBA	BASALTIC LAVA, OLIVINE-BASALT AND ANGULAR PEBBLE-GRADE CONGLOMERATE	A
MBACLV + MTUFB	BASALTIC METALAVA AND BASALTIC METATUFF	А
BAR + HAW	BASALTIC ROCK AND HAWAIITE	А
BATUF + BCLAVA	BASALTIC TUFF AND BASALTIC LAVA	А
BA + BATUF + HY	BASALTIC TUFF, HYALOCLASTITE AND BASALT	А
BAR	BASALTIC-ROCK	А
BAROCM	BASALTIC-ROCK, OLIVINE-CLINOPYROXENE-MACROPHYRIC	А
BARPMA	BASALTIC-ROCK, PLAGIOCLASE-MACROPHYRIC	А
BARPM	BASALTIC-ROCK, PLAGIOCLASE-MICROPHYRIC	А
BRPOCM	BASALTIC-ROCK, PLAGIOCLASE-OLIVINE-CLINOPYROXENE- MACROPHYRIC	A
BARPOM	BASALTIC-ROCK, PLAGIOCLASE-OLIVINE-MICROPHYRIC	А
DOLR	DOLERITE (SYNONYMOUS WITH MICROGABBRO)	А



DUN	DUNITE	A
GB	GABBRO	А
GB + MCGB	GABBRO AND MICROGABBRO	А
GB + NO	GABBRO AND NORITE	А
GB + UMR	GABBRO AND ULTRAMAFIC ROCK	А
GBBY	GABBRO, BYTOWNITE	А
GBFLX	GABBRO, FLUXIONED	А
GBHB	GABBRO, HYPERSTHENE-BEARING	А
DI + GB + MCGB	GABBRO, MICROGABBRO AND DIORITE	А
OLGLGB	GABBRO, OLIVINE-GLOMEROCRYSTIC	А
PEGGB	GABBRO, PEGMATITIC	А
GBXEN	GABBRO, XENOLITHIC	А
GBR	GABBROIC-ROCK	А
GBR + MSDR	GABBROIC-ROCK AND METASEDIMENTARY ROCK	А
GBR + MCGBR	GABBROIC-ROCK AND MICROGABBROIC-ROCK	А
GBRA	GABBROIC-ROCK, APPINITIC	А
GBRCNT	GABBROIC-ROCK, CONTAMINATED	А
GBRMG	GABBROIC-ROCK, MAGNETIC	А
HZBT	HARZBURGITE	А
HY	HYALOCLASTITE	А
MGBHB + MMGBHB	HYPERSTHENE-BEARING METAGABBRO AND HYPERSTHENE- BEARINGMETAMICROGABBRO	A
MFIR	IGNEOUS-ROCK, MAFIC	А
LAVA	LAVA	А
BALAVA	LAVA, BASALT	А
BCLAVA	LAVA, BASALTIC	А
MFLAVA	LAVA, MAFIC	А
MAFI	MAFITE	А
MLGB	MELAGABBRO	А
DUN + MLTROC + PDT	MELATROCTOLITE, PERIDOTITE AND DUNITE	А
MCGB	MICROGABBRO	А
BA + MCGB	MICROGABBRO AND BASALT	А
GB + MCGB	MICROGABBRO AND GABBRO	А
BA + BAANDT + MCGB	MICROGABBRO, BASALT AND BASALTIC ANDESITE	А
ANDGL + BA + MCGB	MICROGABBRO, BASALT AND GLASSY ANDESITE	А
MGBOCM	MICROGABBRO, OLIVINE-CLINOPYROXENE-MACROPHYRIC	А
MGBOMA	MICROGABBRO, OLIVINE-MACROPHYRIC	А
MGBPMC	MICROGABBRO, PLAGIOCLASE-MICROPHYRIC	А
MGPOCM	MICROGABBRO, PLAGIOCLASE-OLIVINE-CLINOPYROXENE- MACROPHYRIC	A
MGBPOM	MICROGABBRO, PLAGIOCLASE-OLIVINE-MICROPHYRIC	А
MCGBPP	MICROGABBRO, PLAGIOCLASE-PHYRIC	А
MCGBP	MICROGABBRO, PORPHYRITIC	А



MCGBTH	MICROGABBRO, THOLEIITIC	A
MCGBV	MICROGABBRO, VARIOLITIC	А
MCGBR	MICROGABBROIC-ROCK	А
NO	NORITE	А
GB + NO	NORITE AND GABBRO	А
GBNO + NO	NORITE AND GABBRONORITE	А
NOQB	NORITE, QUARTZ-BIOTITE	А
OLBA	OLIVINE-BASALT	А
OLGB	OLIVINE-GABBRO	А
NO + OLGB	OLIVINE-GABBRO AND NORITE	А
OLGB + OLGBNO	OLIVINE-GABBRO AND OLIVINE-GABBRONORITE	А
OLGB + OPXGB	OLIVINE-GABBRO AND ORTHOPYROXENE-GABBRO	А
OLGB + TROCT	OLIVINE-GABBRO AND TROCTOLITE	А
OLGBFE	OLIVINE-GABBRO, FE-RICH	А
OLGBP	OLIVINE-GABBRO, PORPHYRITIC	А
MCOLGB	OLIVINE-MICROGABBRO	А
OPXGB	ORTHOPYROXENE-GABBRO	А
CPXNO + OPXGB	ORTHOPYROXENE-GABBRO AND CLINOPYROXENE-NORITE	А
OPXT	ORTHOPYROXENITE	А
PDT	PERIDOTITE	А
MLTROC + PDT	PERIDOTITE AND MELATROCTOLITE	А
IBREC + MLTROC + PDT	PERIDOTITE AND MELATROCTOLITE (INTRUSION BRECCIA)	A
PDT + PXT	PERIDOTITE AND PYROXENITE	А
PDT + SEPITE	PERIDOTITE AND SERPENTINITE	А
PDT + TROCT	PERIDOTITE AND TROCTOLITE	А
PDTFC	PERIDOTITE, FELDSPATHIC	А
PCBA	PICROBASALT	А
PYBRB	PYROCLASTIC-BRECCIA, BASALTIC	А
PYBA	PYROCLASTIC-ROCK, BASALTIC	А
SEPITE	SERPENTINITE	А
SCHT + SEPITE	SERPENTINITE AND TREMOLITE SCHIST	А
CONG + LMST + SEPITE	SERPENTINITE, CONGLOMERATE AND LIMESTONE	A
BATHL + MCGBTH	THOLEIITIC MICROGABBRO AND THOLEIITIC BASALT	А
UMR	ULTRAMAFIC-ROCK	А
GBR + UMR	ULTRAMAFIC-ROCK AND GABBROIC-ROCK	А
BAVBR	VOLCANICLASTIC-BRECCIA, BASALTIC	А
AND + BA	BASALT AND ANDESITE	В
BA + BAANDT	BASALT AND BASALTIC ANDESITE	В
BA + FELS	BASALT AND FELSITE [COMPOSITE INTRUSION]	В
HFBA	BASALT, HORNFELSED	В
BALAVA + ANDLAV	BASALT, LAVA and ANDESITE, LAVA	В
BALAVA + SDST	BASALT, LAVA and SANDSTONE (UNDIFFERENTIATED)	В



ANDCLA + BCLAVA	BASALTIC LAVA AND ANDESITIC LAVA						
BCLAVA + MUG	BASALTIC LAVA AND MUGEARITE						
BAANDT	BASALTIC-ANDESITE (TAS)	В					
BAAPH	BASALTIC-ANDESITE, PORPHYRITIC	В					
BSN	BASANITE	В					
BSNAN	BASANITE, ANALCIME	В					
BSNBT	BASANITE, BIOTITE	В					
NBSN	BASANITE, NEPHELINE	В					
BA + BSN + CAMPTN +MONCHQ	CAMPTONITE, MONCHIQUITE, BASALT AND BASANITE	В					
DI + GB	DIORITE AND GABBRO	В					
GB + MCGN	GABBRO AND MICROGRANITE						
ANDGL + BAGL	GLASSY BASALT AND GLASSY ANDESITE	В					
ANDGL + BAGL + MCGBGL	GLASSY MICROGABBRO, GLASSY BASALT AND GLASSY ANDESITE						
HAW	HAWAIITE	В					
HAW + MUG	HAWAIITE AND MUGEARITE						
HAWAPH	HAWAIITE, APHYRIC						
FPHAW	HAWAIITE, FELDSPAR-PHYRIC						
OPHW	HAWAIITE, OLIVINE-PHYRIC	В					
HBGB	HORNBLENDE-GABBRO						
HBGB + [GNR]	HORNBLENDE-GABBRO, WITH GRANITIC VEINS						
MGBRH + MMGBRH	HORNFELSED METAGABBROIC-ROCK AND HORNFELSED METAMICROGABBROIC-ROCK	В					
LAVA	LAVA (UNDIFFERENTIATED)	В					
LAVA + TUF	LAVA AND TUFF	В					
BTLAVA	LAVA, BASALTIC-TRACHYANDESITE	В					
GBL	LEUCOGABBRO	В					
HY + MFLAVA	MAFIC LAVA AND HYALOCLASTITE	В					
MFLAVA + MFTUF	MAFIC LAVA AND MAFIC TUFF	В					
HY + MFTUF	MAFIC TUFF AND HYALOCLASTITE	В					
MFTUF + TUFTM	MAFIC TUFF AND MAFIC TUFFITE	В					
MBA	METABASALT	В					
MBAPH	METABASALT, PHYLLITIC	В					
MBA + PEL + PSAMM	METABASALT, PSAMMITE AND PELITE	В					
MBAR	METABASALTIC-ROCK	В					
MDUN	METADUNITE	А					
MGB	METAGABBRO	В					
HBSCH + MGB	METAGABBRO AND HORNBLENDE SCHIST						
MGB + MMCGB	METAGABBRO AND METAMICROGABBRO	В					
MGBSH	METAGABBRO, SHEARED	В					
MGBR	METAGABBROIC-ROCK	В					
MGBR + UMR	METAGABBROIC-ROCK AND ULTRAMAFIC-ROCK	В					
MGBMG METAGABBROIC-ROCK, MAGNETIC							



MHZBT	METAHARZBURGITE	A
MLAVA + MTUF	METALAVA AND METATUFF	В
MMR	METAMAFIC-ROCK	В
MMCGB	METAMICROGABBRO	В
AMPHB + MMCGB	METAMICROGABBRO AND AMPHIBOLITE	В
MMGFP	METAMICROGABBRO, FELDSPAR-PHYRIC	В
MLAVA + MTUF	METAMORPHOSED LAVA AND TUFF, METAMORPHOSED	В
MOPXT	METAORTHOPYROXENITE	В
MPDT	METAPERIDOTITE	А
MPXT	METAPYROXENITE	В
MTUF	METATUFF	В
MULMR	METAULTRAMAFIC-ROCK	В
MUFT	META-ULTRAMAFITITE	В
MVCIR	METAVOLCANICLASTIC-IGNEOUS-ROCK	В
MUG	MUGEARITE	В
NMZGB	NEPHELINE-MONZOGABBRO	В
OGNSM	ORTHOGNEISS, MAFIC	В
PYRR	PYROCLASTIC-ROCK	В
QGB	QUARTZ-GABBRO	В
MCQGB	QUARTZ-MICROGABBRO	В
LAVA + SLTE + TUF	SLATE, LAVA AND TUFF	В
TRBA	TRACHYBASALT	В
BA + TRBA	TRACHYBASALT AND BASALT	В
LAVA + TUF	TUFF AND LAVA	В
BATUF	TUFF, BASALTIC	В
MFTUF	TUFF, MAFIC	В
BCLAVA + TUF + VCIR	TUFF, VOLCANICLASTIC-IGNEOUS-ROCK AND BASALTIC LAVA	В
TUFTM	TUFFITE, MAFIC	В
AMPHB	AMPHIBOLITE	С
AMPHB + HBSCH	AMPHIBOLITE AND HORNBLENDE SCHIST	С
AMPHB + OGNSM	AMPHIBOLITE AND MAFIC ORTHOGNEISS	С
AMPHB + HBSCH + MGB	AMPHIBOLITE, HORNBLENDE-SCHIST AND METAGABBRO	С
AMPHB + PEL + PSAMM +SEMPEL	AMPHIBOLITE, SEMIPELITE, PELITE AND PSAMMITE	С
AND	ANDESITE	С
AND + BA	ANDESITE AND BASALT	С
AND + BAANDT	ANDESITE AND BASALTIC ANDESITE	С
ANDA	ANDESITE, AUGITE	С
ANDGB	ANDESITE, GARNET-BEARING	С
ANDH	ANDESITE, HYPERSTHENE	С
PAND	ANDESITE, PORPHYRITIC	С
ANDPX	ANDESITE, PYROXENE	С



PXPAND	ANDESITE, PYROXENE-PLAGIOCLASE-PHYRIC					
ANDTH	ANDESITE, THOLEIITIC	С				
AGG + ANDTFF + MFTUF	ANDESITIC TUFF, MAFIC TUFF AND AGGLOMERATE	С				
ANDR	ANDESITIC-ROCK	С				
BAANDT + RY	BASALTIC ANDESITE AND RHYOLITE	С				
BUXCLY	BAUXITE-CLAY	С				
BENMOR	BENMOREITE	С				
AMPHB + GNSS	GNEISS AND AMPHIBOLITE	С				
AMPHB + PSMGN	GNEISSOSE PSAMMITE AND AMPHIBOLITE	С				
ANDLVH	HORNBLENDE-ANDESITE, LAVA	С				
AMPHB + HBSCH	HORNBLENDE-SCHIST AND AMPHIBOLITE	С				
ANLTUF	LAPILLI-TUFF, ANDESITIC	С				
ANDCLA	LAVA, ANDESITIC	С				
AANDLV	LAVA, AUGITE-ANDESITE	С				
MBARST	METABARITE-STONE	С				
AND + MCDI	MICRODIORITE AND ANDESITE	С				
AND + MCDI + MCGD	MICROGRANODIORITE, MICRODIORITE AND ANDESITE	С				
BENMOR + MUG	MUGEARITE AND BENMOREITE	С				
OAMPHB	ORTHO-AMPHIBOLITE	С				
PAMPHB	PARA-AMPHIBOLITE	С				
AMPHB + PSAMM	PSAMMITE AND AMPHIBOLITE	С				
SDST + CONG + LAVA	SANDSTONE (UNDIFFERENTIATED) AND CONGLOMERATE AND LAVA (UNDIFFERENTIATED)	С				
LAVA + SR	SEDIMENTARY ROCK AND LAVA	С				
TRAND	TRACHYANDESITE	С				
TAFMP	TRACHYANDESITE, FELDSPAR-MACROPORPHYRITIC	С				
TRBAND	TRACHYBASALT TO TRACHYANDESITE	С				
ANDTFF	TUFF, ANDESITIC	С				
TRATUF	TUFF, TRACHYANDESITE	С				

A.2. Additional Geological Considerations for CO₂ Mineralisation

Impact of Internal Structures

Both porosity and permeability are created by the internal structures that develop as igneous rocks cool ¹³⁰. In basalt lava flow tops, primary porosity can vary greatly from 0-40% due to the presence of vesicles or brecciated material ¹⁸². Where there is significant lateral continuity, porosity can be relatively high with great enough permeability to provide measurable fluid flow ^{83,130}. Within basalt lava flow interiors or intrusions, or at flow boundaries, relatively high permeabilities can exist due to horizontal (sheet joints) to vertical or sub-vertical fractures and



faults (columnar joints). While primary porosity is often low to none, secondary porosity can be generated, with fluid flow along, not across, the fracture planes ^{83,134,183}. Volcaniclastic rocks have highly variable porosities and permeabilities, with the high volume of glass content often creating "microporosity" ¹⁸². Primary porosity is often reduced due to hydrothermal alternation, with precipitation of secondary minerals, while a decrease in permeability relates to compaction, early calcite cements or devitrification of volcanic glass ^{184,185}.

The internal structure of igneous rocks can also affect how physical properties change, and therefore how fluid could flow within the rock volume. This is most commonly seen in stacked basaltic lava fields, where there are often a variety of lava flow facies types (e.g., compound / braided / tabular / and transitional flow types; ¹⁸⁶ interbedded with volcaniclastic, sedimentary and palaeosol units. At the millimetre to decimetre scale, properties are controlled by the percentage of vesicles, vesicle geometry and mineral alignment ^{125,126}. At the metre scale, it is determined by the structure of the individual flow units (vesicular flow top vs avesicular flow core ^{125,187}). Finally at the tens to hundreds of metre scale this is due to the heterogeneity, anisotropy, and varying joint patterns associated with the range of lava flow facies, together with the higher permeabilities in the non-igneous facies ^{188,189}. A single lava field as described may comprise multiple stacked facies (such as the Skye lava field; ¹⁸⁶), such that horizontal and vertical permeabilities and fluid transmissivity may vary at different points within the structure.

Faults and Alteration

Faults and fractures are common in igneous rocks, from large faults to small scale fractures, and help create additional reactive surface areas for CO₂ mineralisation. Fault zone architecture can vary from simple to complex zones of deformation that typically comprise a fault core with a principal slip zone (where faulting occurs), which is flanked by a damage zone (an area of higher fracture density). Material in the damage zone displays a significant reduction in grainsize from the surrounding intact rock (*e.g.* breccias, cataclasite and/or ultracataclasite). Fracture density decreases away from the fault core, and in the undeformed igneous host rock may be related to preexisting internal structure, such as columnar joints ¹⁹⁰.

Faults zones can be affected by circulating hydrothermal fluids, groundwater, and/or meteoric water, which can cause the precipitation of calcite, cements and veins along the fault core ^{189,191}. Zeolite veins may be porous and permeable, such that where interconnectivity of zeolite veins occurs the fault zone may be more permeable ¹⁸⁹. Authigenic clays commonly deposit within fractures within the fault core and damage zone, enveloping lenses of more porous material ¹⁹¹.



This creates cross-fault permeability anisotropy, where the fault core is relatively permeable with along fault flow, the damage zone acts as a relatively impermeable baffle that inhibits fluid migration into the fault core.

Faults experience multiple cycles of movement, especially with the migration of fluid into and along the fault zone, which can lead to complex fault zone architecture and fluid transmissivity networks ¹⁹¹. Altered basalt is typically found to be less reactive to CO₂ than fresh basalt ¹⁹², so where faults and fractures have altered basaltic material, there may be additional baffles to fluid migration as well as processes that are causing CO₂ mineralisation. The faulting patterns within igneous rock should therefore be considered during site selection to minimise formation compartmentalisation.

Poroelasticity and Effective Stress

How a porous rock volume reacts to an applied stress is known as poroelasticity and is controlled by the density of pores and the mechanical properties of the rock ^{193,194}. Poroelasticity is important for understanding and predicting the stability of the rock mass, including pre-existing fault and fracture systems, during fluid pressure fluctuations and during chemo-mechanical changes. Pore spaces in rock are traditionally modelled as spherical voids or randomly oriented cracks, meaning that any change in fluid pressure causes an equal effect on the system in all directions. Where an increase in fluid pressure occurs, it will bring the rock volume closer to failure (more likely to form new fractures), and closer to reactivation of preferentially oriented structures ^{195,196}. However, the pore space in igneous rocks is typically non-spherical, comprising a combination of vesicles and microfractures. This non-spherical void space affects how the system responds to changes in fluid pressure and the stability of pre-existing structures.

The injection of CO₂ will likely result in dynamic changes to the fluid pressure and to the inherent geomechanical properties of the chosen igneous rock. The filling of pore space with new carbonate minerals may reduce porosity and network connectivity ¹²⁹, and alteration of the rock mass during cation leaching may lead to changes in material mechanical properties. Understanding the potential impact of these changes and the associated implications for poroelastic responses will aid in understanding and estimating rock mass stability during continued injection.

Present-Day UK Stress Regime

Understanding the present-day in-situ stress conditions is vital for characterising the stability of existing structures (*e.g.* faults) and predicting the orientation of any new natural or induced



fractures (*e.g.* hydrofractures). Mapped faults and their orientations vary greatly across the UK by region and age of strata. However, analysis of data including the World Stress Map database ¹⁹⁷, UK earthquake focal mechanism data ¹⁹⁸, borehole breakout and drilling-induced fractures ¹⁹⁹, together with other in-situ stress test data ²⁰⁰ indicate that the present-day stress regime across the UK is generally strike-slip (*i.e.* rock mass move parallel past each other).

The maximum horizontal stress is the maximum principal stress (SH = σ 1) and generally oriented NW-SE, with the minimum horizontal stress is the minimum principal stress (SH = σ 3) and oriented NE-SW, and the vertical stress is the intermediate principal stress ($\sigma v = \sigma$ 2), such that: SH > σv > SH. This means that new fractures would likely develop orientation NW-SE. However, local variations to this pattern occur and should therefore analysis of the stress regime should be on a case-by-case basis. The local fault pattern at potential sites should therefore be characterised in detail and in combination with the local in-situ stress state and susceptibility modelling (*e.g.* Healy and Hicks ²⁰¹). This will provide a better understanding of fault stability and provide a mechanism of risk assessment.

	Mapped A	vrea (km²)			Lithology			
Name of Intrusive Complex / Formation	Α	В	С	Total	% A	% B	% C	Rank
ANTRIM LAVA GROUP	3565.68	0.56	37.76	3603.99	0.99	0.00	0.01	А
SKYE LAVA GROUP	1629.82	187.60	1.22	1818.64	0.90	0.10	0.00	А
MULL LAVA GROUP	1561.39	3.70	4.53	1569.62	0.99	0.00	0.00	А
CLYDE PLATEAU VOLCANIC FORMATION	940.22	136.64	17.42	1094.28	0.86	0.12	0.02	А
ARBUTHNOTT-GARVOCK GROUP	37.18	241.03	606.69	884.91	0.04	0.27	0.69	С
LITTLE MINCH SILL COMPLEX	600.29	0.00	0.00	600.29	1.00	0.00	0.00	А
RESTON GROUP	0.00	0.00	595.23	595.23	0.00	0.00	1.00	С
LOWER DEVONIAN ROCKS (UNDIFFERENTIATED)	0.00	52.04	492.01	544.06	0.00	0.10	0.90	С
LORN PLATEAU VOLCANIC FORMATION	2.35	0.00	368.56	370.91	0.01	0.00	0.99	С
UNNAMED IGNEOUS INTRUSION OF UNKNOWN AGE	359.98	0.27	1.93	362.18	0.99	0.00	0.01	A
BORROWDALE VOLCANIC GROUP	6.91	11.65	312.17	330.73	0.02	0.04	0.94	С
LANARK GROUP	3.77	231.92	32.46	268.16	0.01	0.86	0.12	В
DALRADIAN SUPERGROUP	0.61	231.73	5.92	238.26	0.00	0.97	0.02	В
INSCH PLUTON	216.03	0.00	0.00	216.03	1.00	0.00	0.00	А
TAYVALLICH VOLCANIC FORMATION	0.00	202.47	0.00	202.47	0.00	1.00	0.00	В
MIDLAND VALLEY CARBONIFEROUS TO EARLY PERMIAN ALKALINE BASIC SILL SUITE	165.78	24.70	0.00	190.48	0.87	0.13	0.00	A
BLACKSTONES BAND IGNEOUS COMPLEX	183.56	0.00	0.00	183.56	1.00	0.00	0.00	А

A.3. All Potentially Suitable Geological Formations

Appendix Table A2. Proportional breakdown of all identified Potentially Suitable Geological Formations



MIDLAND VALLEY SILL-COMPLEX	0.02	178.78	0.00	178.80	0.00	1.00	0.00	В
TYRONE VOLCANIC GROUP	143.41	0.00	0.00	143.41	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, ORDOVICIAN	124.30	15.21	2.89	142.40	0.87	0.11	0.02	А
ARDNAMURCHAN CENTRAL COMPLEX	125.98	15.16	0.10	141.25	0.89	0.11	0.00	А
LIZARD COMPLEX	134.65	0.00	0.00	134.65	1.00	0.00	0.00	А
MORVEN-CABRACH PLUTON	131.51	0.00	0.00	131.51	1.00	0.00	0.00	А
MULL CENTRAL COMPLEX	93.89	7.02	12.03	112.94	0.83	0.06	0.11	А
WHIN SILL COMPLEX	34.64	68.95	0.00	103.59	0.33	0.67	0.00	В
LEWISIANOID GNEISS COMPLEX	0.08	10.56	90.80	101.44	0.00	0.10	0.90	С
SOUTHERN HIGHLAND GROUP	0.00	90.96	5.39	96.35	0.00	0.94	0.06	В
TYRONE PLUTONIC GROUP	92.74	0.00	0.00	92.74	1.00	0.00	0.00	А
KELSO VOLCANIC FORMATION	89.79	0.00	0.00	89.79	1.00	0.00	0.00	А
BORROWDALE SILL SUITE	1.42	8.93	73.21	83.56	0.02	0.11	0.88	С
SKYE CENTRAL COMPLEX	71.53	0.00	4.42	75.95	0.94	0.00	0.06	А
GARLETON HILLS VOLCANIC FORMATION	42.45	31.31	0.00	73.76	0.58	0.42	0.00	А
SHETLAND OPHIOLITE COMPLEX	52.52	18.99	0.00	71.51	0.73	0.27	0.00	А
NEOPROTEROZOIC BASIC MINOR INTRUSION SUITE	0.04	4.29	66.27	70.60	0.00	0.06	0.94	С
HUNTLY-KNOCK PLUTON	67.58	0.00	0.00	67.58	1.00	0.00	0.00	А
BATHGATE GROUP	55.49	3.89	0.00	59.38	0.93	0.07	0.00	А
LOCH MAREE GROUP	0.00	58.19	0.00	58.19	0.00	1.00	0.00	В
NORTH-EAST GRAMPIAN BASIC SUITE	31.73	20.18	0.00	51.91	0.61	0.39	0.00	А
CLACKMANNAN GROUP	48.07	1.96	0.00	50.03	0.96	0.04	0.00	А
BIRRENSWARK VOLCANIC FORMATION	48.95	0.58	0.00	49.52	0.99	0.01	0.00	А
STEWARTRY GROUP	46.54	1.05	0.00	47.59	0.98	0.02	0.00	А
ARGYLL GROUP	0.00	27.55	17.87	45.42	0.00	0.61	0.39	В
SHETLAND GRANITIC SUITE	38.88	4.12	0.00	43.00	0.90	0.10	0.00	А
RUM CENTRAL COMPLEX	39.47	0.00	0.00	39.47	1.00	0.00	0.00	А
EYCOTT VOLCANIC GROUP	0.00	4.29	31.66	35.95	0.00	0.12	0.88	С
TORBAY GROUP	34.57	0.00	0.00	34.57	1.00	0.00	0.00	А
STRATHCLYDE GROUP	4.89	0.72	28.50	34.11	0.14	0.02	0.84	С
FISHGUARD VOLCANIC GROUP	8.27	23.79	0.00	32.06	0.26	0.74	0.00	В
UNNAMED IGNEOUS INTRUSION, DEVONIAN TO CARBONIFEROUS	25.41	6.59	0.00	32.00	0.79	0.21	0.00	A
UNNAMED IGNEOUS INTRUSION, PRE- CALEDONIAN	0.00	0.00	31.49	31.49	0.00	0.00	1.00	С
GURRINGTON SLATE FORMATION	0.63	29.79	0.00	30.42	0.02	0.98	0.00	В
EIGG LAVA FORMATION	26.54	3.53	0.00	30.07	0.88	0.12	0.00	А
BALCREUCHAN GROUP	30.07	0.00	0.00	30.07	1.00	0.00	0.00	А
BALLANTRAE OPHIOLITE COMPLEX	29.42	0.00	0.00	29.42	1.00	0.00	0.00	А
ARNAGE PLUTON	29.31	0.00	0.00	29.31	1.00	0.00	0.00	А
MAUD PLUTON	29.01	0.00	0.00	29.01	1.00	0.00	0.00	А
MIDDLE DEVONIAN SLATES	27.57	0.01	0.00	27.58	1.00	0.00	0.00	А
ARAN VOLCANIC GROUP	1.14	24.30	0.00	25.44	0.04	0.96	0.00	В



UNNAMED METAMORPHOSED IGNEOUS ROCKS, PRE-CALEDONIAN TO CALEDONIAN	0.13	1.45	23.58	25.16	0.01	0.06	0.94	С
SOUTHERN SCOTLAND DINANTIAN PLUGS AND VENTS SUITE	23.51	0.36	0.15	24.03	0.98	0.02	0.01	A
DINANTIAN ROCKS (UNDIFFERENTIATED)	0.00	22.70	0.00	22.70	0.00	1.00	0.00	В
UNNAMED IGNEOUS INTRUSION, DEVONIAN	19.58	3.10	0.00	22.68	0.86	0.14	0.00	А
LOCH SCRIDAIN SILL COMPLEX	2.50	17.59	0.00	20.09	0.12	0.88	0.00	В
TARLAND INTRUSION	19.68	0.00	0.00	19.68	1.00	0.00	0.00	А
GLENCOE VOLCANIC FORMATION	0.00	0.00	19.15	19.15	0.00	0.00	1.00	С
PORTSOY IGNEOUS COMPLEX	18.34	0.33	0.00	18.68	0.98	0.02	0.00	А
CLIFT HILLS 'DIVISION'	1.95	16.52	0.00	18.47	0.11	0.89	0.00	В
SOUTH ARRAN SILLS	7.77	10.07	0.00	17.83	0.44	0.56	0.00	В
SEALYHAM VOLCANIC FORMATION	0.00	0.00	17.69	17.69	0.00	0.00	1.00	С
MILTON ABBOT FORMATION	17.63	0.04	0.00	17.67	1.00	0.00	0.00	А
RHOBELL VOLCANIC GROUP	15.93	0.19	0.00	16.12	0.99	0.01	0.00	А
CANNA LAVA FORMATION	6.52	9.09	0.08	15.68	0.42	0.58	0.01	В
BARRACK HILL ANDESITE MEMBER	0.00	0.00	14.98	14.98	0.00	0.00	1.00	С
LEWISIAN COMPLEX	0.33	13.57	0.66	14.57	0.02	0.93	0.05	В
PEAK LIMESTONE GROUP	14.38	0.00	0.00	14.38	1.00	0.00	0.00	А
ERNAN-GLASS METABASIC SWARM	0.00	14.36	0.00	14.36	0.00	1.00	0.00	В
PRESTWICK-MAUCHLINE SILL-COMPLEX	14.19	0.00	0.00	14.19	1.00	0.00	0.00	А
ST MAGNUS BAY GROUP	1.69	0.00	11.33	13.02	0.13	0.00	0.87	С
RHINNS COMPLEX	0.00	12.41	0.03	12.44	0.00	1.00	0.00	В
HADDO HOUSE PLUTON	11.52	0.00	0.00	11.52	1.00	0.00	0.00	А
SNOWDON VOLCANIC GROUP	11.49	0.00	0.00	11.49	1.00	0.00	0.00	А
UNNAMED SILL, ORDOVICIAN	11.12	0.35	0.00	11.46	0.97	0.03	0.00	А
QUEYFIRTH GROUP	2.70	7.91	0.00	10.61	0.25	0.75	0.00	В
MIDLAND VALLEY SILURO-DEVONIAN FELSIC INTRUSION SUITE	0.00	0.00	10.51	10.51	0.00	0.00	1.00	С
URICONIAN GROUP	4.88	3.84	1.73	10.45	0.47	0.37	0.17	В
SLIEVE GULLION COMPLEX	10.18	0.00	0.00	10.18	1.00	0.00	0.00	А
UPPER DEVONIAN SLATES	6.97	2.95	0.00	9.92	0.70	0.30	0.00	А
TAMAR GROUP	9.88	0.02	0.00	9.90	1.00	0.00	0.00	А
SOUTH HARRIS META-IGNEOUS COMPLEX	0.00	9.36	0.00	9.36	0.00	1.00	0.00	В
ARTHUR'S SEAT VOLCANIC FORMATION	2.52	6.81	0.00	9.34	0.27	0.73	0.00	В
ARGYLL AND NORTHERN HIGHLANDS GRANITIC SUITE	0.27	9.06	0.00	9.33	0.03	0.97	0.00	В
GWNA GROUP	2.88	5.91	0.00	8.79	0.33	0.67	0.00	В
TAPPINS GROUP	8.42	0.00	0.00	8.42	1.00	0.00	0.00	А
TEIGN VALLEY GROUP	4.65	2.85	0.00	7.49	0.62	0.38	0.00	А
UNNAMED IGNEOUS INTRUSION, NEOPROTEROZOIC	7.09	0.00	0.00	7.09	1.00	0.00	0.00	A
BEN HOPE SILL SUITE	0.00	0.00	6.97	6.97	0.00	0.00	1.00	С
JOHNSTON INTRUSIVE COMPLEX	6.39	0.00	0.00	6.39	1.00	0.00	0.00	A



SCOTTISH LATE CARBONIFEROUS TO EARLY PERMIAN PLUGS AND VENTS SUITE	3.24	3.08	0.00	6.31	0.51	0.49	0.00	A
MIDLAND VALLEY SILURO-DEVONIAN MAFIC INTRUSION SUITE	3.13	1.34	1.45	5.93	0.53	0.23	0.24	A
LAKE DISTRICT ORDOVICIAN MAFIC PLUTONIC SUITE	5.34	0.52	0.00	5.85	0.91	0.09	0.00	А
SCOTTISH HIGHLAND ORDOVICIAN MINOR INTRUSION SUITE	0.00	0.27	5.47	5.73	0.00	0.05	0.95	С
GLENCARTHOLM VOLCANIC MEMBER	5.29	0.00	0.00	5.29	1.00	0.00	0.00	А
BLACKWATER PLUTON	5.19	0.00	0.00	5.19	1.00	0.00	0.00	А
EXETER GROUP	5.10	0.00	0.00	5.10	1.00	0.00	0.00	А
LLEWELYN VOLCANIC FORMATION	4.76	0.00	0.00	4.76	1.00	0.00	0.00	А
SCRABO SILL	4.65	0.00	0.00	4.65	1.00	0.00	0.00	А
STAPELEY VOLCANIC MEMBER	0.00	4.46	0.00	4.46	0.00	1.00	0.00	В
COCKERMOUTH VOLCANIC FORMATION	4.41	0.00	0.00	4.41	1.00	0.00	0.00	А
NEOPROTEROZOIC METAMORPHOSED MAFIC AND ULTRAMAFIC MINOR INTRUSION SUITE OF SHETLAND	3.52	0.51	0.37	4.40	0.80	0.12	0.08	A
GARRISON SILL	4.17	0.00	0.00	4.17	1.00	0.00	0.00	А
SOUTHWEST ENGLAND MINOR INTRUSIVE SUITE	2.93	1.23	0.00	4.16	0.70	0.30	0.00	А
NORTH ESK FORMATION [NOT SAME AS NES]	0.61	3.53	0.00	4.14	0.15	0.85	0.00	В
CARBONIFEROUS LIMESTONE SUPERGROUP	0.00	4.05	0.00	4.05	0.00	1.00	0.00	В
LAKE DISTRICT ORDOVICIAN MINOR INTRUSION SUITE	1.26	0.12	2.32	3.70	0.34	0.03	0.63	С
UNNAMED SILL, WESTPHALIAN	3.67	0.00	0.00	3.67	1.00	0.00	0.00	А
OGWEN GROUP	0.26	3.21	0.02	3.49	0.08	0.92	0.01	В
KERSHOPEFOOT BASALT BEDS	3.39	0.00	0.00	3.39	1.00	0.00	0.00	А
DUNNOTTAR-CRAWTON GROUP	0.00	0.44	2.83	3.27	0.00	0.14	0.86	С
BEN NEVIS VOLCANIC FORMATION	0.00	0.00	3.05	3.05	0.00	0.00	1.00	С
NORTH BRITAIN PALAEOGENE SILL SUITE	2.88	0.09	0.04	3.01	0.96	0.03	0.01	А
ROSELAND BRECCIA FORMATION	2.94	0.02	0.00	2.96	0.99	0.01	0.00	А
UNNAMED IGNEOUS INTRUSION, DINANTIAN	2.92	0.00	0.00	2.92	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, WESTPHALIAN	2.80	0.00	0.00	2.80	1.00	0.00	0.00	А
UNNAMED METAMORPHIC ROCKS, NEOPROTEROZOIC	0.00	0.03	2.67	2.70	0.00	0.01	0.99	С
ROWLEY REGIS MICROGABBRO LOPOLITH	2.58	0.00	0.00	2.58	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, CARBONIFEROUS	0.48	2.07	0.00	2.55	0.19	0.81	0.00	В
UNNAMED IGNEOUS INTRUSION, CARBONIFEROUS TO PERMIAN	2.40	0.00	0.00	2.40	1.00	0.00	0.00	A
CRACKINGTON FORMATION	2.34	0.00	0.00	2.34	1.00	0.00	0.00	А
FAIR HEAD SILL	2.30	0.00	0.00	2.30	1.00	0.00	0.00	А
UNST PHYLLITE GROUP	0.00	2.15	0.00	2.15	0.00	1.00	0.00	В
HIGHLAND BORDER COMPLEX	1.91	0.00	0.00	1.91	1.00	0.00	0.00	А
SOUTH OF SCOTLAND GRANITIC SUITE	1.91	0.00	0.00	1.91	1.00	0.00	0.00	А



TREFFYNNON GROUP	0.00	1.90	0.00	1.90	0.00	1.00	0.00	В
RHOSSON GROUP	0.00	1.89	0.00	1.89	0.00	1.00	0.00	В
SKOMER VOLCANIC GROUP	1.22	0.66	0.00	1.88	0.65	0.35	0.00	А
MAGILLIGAN SILL	1.82	0.00	0.00	1.82	1.00	0.00	0.00	А
DARTMOUTH GROUP	1.68	0.00	0.00	1.68	1.00	0.00	0.00	А
GLEN URQUHART COMPLEX	1.66	0.00	0.00	1.66	1.00	0.00	0.00	А
CRAWFORD GROUP	1.64	0.00	0.00	1.64	1.00	0.00	0.00	А
BAIL HILL VOLCANIC GROUP	0.13	1.30	0.20	1.64	0.08	0.79	0.12	В
TISSINGTON VOLCANIC MEMBER	1.61	0.00	0.00	1.61	1.00	0.00	0.00	А
COTTONSHOPE VOLCANIC FORMATION	1.53	0.00	0.00	1.53	1.00	0.00	0.00	А
BUILTH VOLCANIC GROUP	1.29	0.00	0.20	1.49	0.87	0.00	0.13	А
TILLYBRACHTY SANDSTONE FORMATION	0.00	1.43	0.00	1.43	0.00	1.00	0.00	В
UNNAMED IGNEOUS INTRUSION, PALAEOGENE	1.39	0.00	0.00	1.39	1.00	0.00	0.00	А
EASTERN GNEISSES	0.00	1.33	0.00	1.33	0.00	1.00	0.00	В
CLOUSTA VOLCANIC MEMBER	0.41	0.00	0.91	1.32	0.31	0.00	0.69	С
UNNAMED IGNEOUS INTRUSION, LATE SILURIAN TO EARLY DEVONIAN	1.31	0.00	0.00	1.31	1.00	0.00	0.00	A
TREFFGARNE VOLCANIC FORMATION	0.00	0.00	1.31	1.31	0.00	0.00	1.00	С
COALBROOKDALE FORMATION	0.00	0.00	1.29	1.29	0.00	0.00	1.00	С
LOCH BA (CENTRE 3) SUITE	1.24	0.00	0.00	1.24	1.00	0.00	0.00	А
POLYPHANT INTRUSION	1.24	0.00	0.00	1.24	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, CAMBRIAN TO ORDOVICIAN	1.22	0.00	0.00	1.22	1.00	0.00	0.00	A
WESTING GROUP	0.00	0.00	1.12	1.12	0.00	0.00	1.00	С
CALEDONIAN SUPERSUITE	0.15	0.90	0.04	1.09	0.14	0.82	0.04	В
NORTH BRITAIN SILURO-DEVONIAN PLUG AND VENT SUITE	0.45	0.00	0.63	1.08	0.42	0.00	0.58	С
EDAY GROUP	1.06	0.00	0.00	1.06	1.00	0.00	0.00	А
BONSALL MICROGABBRO SILL	0.99	0.00	0.00	0.99	1.00	0.00	0.00	А
KINLET MICROGABBRO SILL	0.99	0.00	0.00	0.99	1.00	0.00	0.00	А
UNNAMED SILL, PALAEOGENE	0.97	0.00	0.00	0.97	1.00	0.00	0.00	А
TREFRIW TUFF FORMATION	0.00	0.93	0.00	0.93	0.00	1.00	0.00	В
CRAIGHEAD VOLCANIC FORMATION	0.80	0.00	0.00	0.80	1.00	0.00	0.00	А
BALLYRAINEY SILL	0.80	0.00	0.00	0.80	1.00	0.00	0.00	А
UPPER LODGE VOLCANIC GROUP	0.00	0.00	0.78	0.78	0.00	0.00	1.00	С
ARRAN CENTRAL COMPLEX	0.64	0.01	0.12	0.77	0.82	0.02	0.16	А
PORTRUSH SILL	0.76	0.00	0.00	0.76	1.00	0.00	0.00	А
CARN LLIDI GABBRO	0.73	0.00	0.00	0.73	1.00	0.00	0.00	А
KINGSTEIGNTON VOLCANIC GROUP	0.73	0.00	0.00	0.73	1.00	0.00	0.00	А
LYDFORD FORMATION	0.70	0.00	0.00	0.70	1.00	0.00	0.00	А
GRIMLEY ANDESITE	0.00	0.00	0.67	0.67	0.00	0.00	1.00	С
LOWER CARBONIFEROUS ROCKS (UNDIFFERENTIATED)	0.00	0.67	0.00	0.67	0.00	1.00	0.00	В



WARREN HOUSE FORMATION	0.00	0.62	0.00	0.62	0.00	1.00	0.00	В
DUNDONALD SILL	0.61	0.00	0.00	0.61	1.00	0.00	0.00	А
UPPER TRAP	0.61	0.00	0.00	0.61	1.00	0.00	0.00	А
LAKE DISTRICT DEVONIAN MINOR INTRUSION SUITE	0.52	0.00	0.04	0.56	0.93	0.00	0.07	А
KIRKLAND FORMATION	0.00	0.52	0.03	0.54	0.00	0.95	0.05	В
ST DAVID'S HEAD GABBRO	0.54	0.00	0.00	0.54	1.00	0.00	0.00	А
NORTH BRITAIN PALAEOGENE PLUG SUITE	0.54	0.00	0.00	0.54	1.00	0.00	0.00	А
TREVOSE SLATE FORMATION	0.05	0.46	0.00	0.51	0.11	0.89	0.00	В
PENDOWER FORMATION	0.47	0.00	0.00	0.47	1.00	0.00	0.00	А
CORKEY ROCKS PLUG	0.47	0.00	0.00	0.47	1.00	0.00	0.00	А
ENNERDALE INTRUSION	0.46	0.00	0.00	0.46	1.00	0.00	0.00	А
SLEMISH PLUG	0.45	0.00	0.00	0.45	1.00	0.00	0.00	А
MOINE SUPERGROUP	0.00	0.00	0.44	0.44	0.00	0.00	1.00	С
LLANBEDROG VOLCANIC GROUP	0.42	0.00	0.00	0.42	1.00	0.00	0.00	А
BARDON BRECCIA	0.00	0.00	0.40	0.40	0.00	0.00	1.00	С
NORWICK HORNBLENDIC SCHIST TYPE 1	0.00	0.40	0.00	0.40	0.00	1.00	0.00	В
MEADFOOT GROUP	0.39	0.00	0.00	0.39	1.00	0.00	0.00	А
HEBRIDEAN PROVINCE	0.06	0.31	0.00	0.37	0.16	0.84	0.00	В
PEMBROKE LIMESTONE GROUP	0.35	0.00	0.00	0.35	1.00	0.00	0.00	А
UNNAMED EXTRUSIVE ROCKS, NEOPROTEROZOIC	0.00	0.00	0.35	0.35	0.00	0.00	1.00	С
WOODEND SERPENTINITE	0.26	0.00	0.00	0.26	1.00	0.00	0.00	А
WILGI GEOS ""GROUP""	0.00	0.00	0.21	0.21	0.00	0.00	1.00	С
POORTOWN INTRUSION	0.18	0.00	0.00	0.18	1.00	0.00	0.00	А
LOCH A MHOID METAGABBRO SUITE	0.00	0.18	0.00	0.18	0.00	0.98	0.02	В
UNNAMED EXTRUSIVE ROCKS, PERMIAN	0.18	0.00	0.00	0.18	1.00	0.00	0.00	А
LEZANT SLATE FORMATION	0.18	0.00	0.00	0.18	1.00	0.00	0.00	А
UNNAMED SILL, DEVONIAN	0.16	0.00	0.00	0.16	1.00	0.00	0.00	А
OATLANDS PLUTON	0.15	0.00	0.00	0.15	1.00	0.00	0.00	А
GRAMPIAN GROUP	0.00	0.00	0.14	0.14	0.00	0.00	1.00	С
POUNDER LANE BASALTIC PYROCLASTIC-BRECCIA VENT	0.14	0.00	0.00	0.14	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, PROTEROZOIC	0.14	0.00	0.00	0.14	1.00	0.00	0.00	А
BALLAGAN FORMATION, CLYDE SANDSTONE FORMATION, STRATHCLYDE GROUP AND CLACKMANNAN GROUP (UNDIFFERENTIATED)	0.14	0.00	0.00	0.14	1.00	0.00	0.00	A
HERMANESS ULTRAMAFIC ZONE	0.00	0.13	0.00	0.13	0.00	1.00	0.00	В
BINNY CRAIG SILL	0.13	0.00	0.00	0.13	1.00	0.00	0.00	А
DUN SCALPSIE BANDED AMPHIBOLITE	0.00	0.00	0.13	0.13	0.00	0.00	1.00	С
LLANWRTYD VOLCANIC FORMATION	0.13	0.00	0.00	0.13	1.00	0.00	0.00	А
APPIN GROUP	0.00	0.00	0.13	0.13	0.00	0.00	1.00	С
STRATHEDEN GROUP AND INVERCLYDE GROUP (UNDIFFERENTIATED)	0.12	0.00	0.00	0.12	1.00	0.00	0.00	А
SHATTERFORD MICROGABBROIC SILL	0.12	0.00	0.00	0.12	1.00	0.00	0.00	А



MOFFAT SHALE GROUP	0.10	0.00	0.00	0.10	1.00	0.00	0.00	А
UNNAMED METAMORPHIC ROCKS, PRE- CALEDONIAN TO CALEDONIAN	0.00	0.00	0.10	0.10	0.00	0.00	1.00	С
BONSALL MOOR BASALTIC VENT	0.10	0.00	0.00	0.10	1.00	0.00	0.00	А
UNNAMED EXTRUSIVE ROCKS, DEVONIAN TO CARBONIFEROUS	0.08	0.02	0.00	0.10	0.80	0.20	0.00	A
UNNAMED METAMORPHOSED IGNEOUS ROCKS, CALEDONIAN	0.00	0.10	0.00	0.10	0.00	1.00	0.00	В
LOWER TRAP	0.09	0.00	0.00	0.09	1.00	0.00	0.00	А
NORTH SANNOX LAVA FORMATION	0.09	0.00	0.00	0.09	1.00	0.00	0.00	А
SCAWT HILL PLUG	0.09	0.00	0.00	0.09	1.00	0.00	0.00	А
ORKNEY DEVONIAN MINOR INTRUSION AND VOLCANIC SUITE	0.08	0.00	0.00	0.08	1.00	0.00	0.00	A
UYEA ""GROUP""	0.00	0.08	0.00	0.08	0.00	1.00	0.00	В
UNNAMED IGNEOUS INTRUSION, TYPE AND AGE UNSPECIFIED	0.08	0.00	0.00	0.08	1.00	0.00	0.00	A
TRELOWGOED VOLCANIC FORMATION	0.08	0.00	0.00	0.08	1.00	0.00	0.00	А
LONDON FIELDS BASALT SILL	0.07	0.00	0.00	0.07	1.00	0.00	0.00	А
BETTON SHALE FORMATION	0.00	0.07	0.00	0.07	0.00	1.00	0.00	В
AMPHIBOLITE OF UNCERTAIN ORIGIN	0.00	0.00	0.06	0.06	0.00	0.00	1.00	С
UNNAMED EXTRUSIVE ROCKS, NAMURIAN	0.06	0.00	0.00	0.06	1.00	0.00	0.00	А
EMBER LANE BASALTIC PYROCLASTIC-BRECCIA VENT	0.06	0.00	0.00	0.06	1.00	0.00	0.00	A
SCOTTISH HIGHLAND SILURO-DEVONIAN CALC- ALKALINE MINOR INTRUSION SUITE (OTHER THAN DYKES)	0.05	0.00	0.00	0.05	1.00	0.00	0.00	A
SCOTTISH COAL MEASURES GROUP	0.05	0.00	0.00	0.05	1.00	0.00	0.00	А
ST BALDRED'S PLUG	0.05	0.00	0.00	0.05	1.00	0.00	0.00	А
MIDDLE DEVONIAN LIMESTONE	0.04	0.00	0.00	0.04	1.00	0.00	0.00	А
MIDLAND VALLEY EARLY CARBONIFEROUS FELSIC SILL SUITE	0.01	0.00	0.02	0.03	0.31	0.00	0.69	С
TOM DUNAN SCHIST MEMBER	0.00	0.03	0.00	0.03	0.00	1.00	0.00	В
BALLAGAN FORMATION	0.03	0.00	0.00	0.03	1.00	0.00	0.00	А
UNNAMED IGNEOUS INTRUSION, ARENIG	0.02	0.00	0.00	0.02	1.00	0.00	0.00	А
IBLE MICROGABBRO SILL	0.02	0.00	0.00	0.02	1.00	0.00	0.00	А
NORTHERN ENGLAND DINANTIAN INTRUSIONS SUITE	0.02	0.00	0.00	0.02	1.00	0.00	0.00	A
BALLAGAN FORMATION, CLYDE SANDSTONE FORMATION AND STRATHCLYDE GROUP (UNDIFFERENTIATED)	0.02	0.00	0.00	0.02	1.00	0.00	0.00	A
ROSEMARKIE METAMORPHIC COMPLEX	0.00	0.00	0.02	0.02	0.00	0.00	1.00	С
UNCLASSIFIED IGNEOUS ROCK, PERMIAN	0.01	0.00	0.00	0.01	1.00	0.00	0.00	А
GLEN SCADDLE INTRUSION	0.00	0.01	0.00	0.01	0.23	0.77	0.00	В
AUCHNAHYLE FORMATION	0.00	0.01	0.00	0.01	0.00	1.00	0.00	В



HARNAGE SHALE FORMATION	0.00	0.00	0.01	0.01	0.00	0.00	1.00	С
MOUNTSORREL COMPLEX	0.01	0.00	0.00	0.01	1.00	0.00	0.00	А
KIRKCOLM FORMATION	0.008	0.000	0.000	0.008	1.00	0.00	0.00	А
BURNING MOUNT PLUG	0.007	0.000	0.000	0.007	1.00	0.00	0.00	А
SIONASCAIG META-OLIVINE-GABBRO SUBSWARM	0.000	0.006	0.000	0.006	0.00	1.00	0.00	В
UNNAMED PLUTON, PERMIAN	0.006	0.000	0.000	0.006	1.00	0.00	0.00	А
MIDLAND VALLEY NAMURIAN TO WESTPHALIAN PLUGS AND VENTS SUITE	0.003	0.000	0.000	0.003	1.00	0.00	0.00	A
LOCH DUICH GNEISSES	0.003	0.000	0.000	0.003	1.00	0.00	0.00	А
FOXLEY TUFF FORMATION	0.003	0.000	0.000	0.003	1.00	0.00	0.00	А
AULDEARN GRANITE PLUTON	0.002	0.000	0.000	0.002	1.00	0.00	0.00	А
BETTYHILL SUITE	0.000	0.000	0.001	0.001	0.00	0.00	1.00	С

A.4. Potentially Suitable Geological Formation Descriptions

Antrim Lava Group

The Antrim Lava Group in Northern Ireland covers parts of Co. Antrim, Co. Londonderry, and Co. Armagh, as well as extending a short distance offshore. It is the largest area of onshore volcanic rocks belonging to the British and Irish Palaeogene Igneous Province, with volcanism starting around 62.6 Ma ²⁰². The group comprises two principal lithostratigraphical units of the Lower Basalt Formation (LBF) and the Upper Basalt Formation (UBF). A total thickness of ~0.8 km recorded in the Lough Neagh Basin, with additional areas of subcropping basalt lying beneath Oligocene age sediments of the Lough Neagh Group. The Antrim Lava Group largely consists of plagioclase-clinopyroxene-olivine-tholeiites, quartz tholeiites and minor tholeiitic andesites, with isolated intrusions of diorite, monzonite and granite ²⁰³. Lava flows typically have avesicular or low vesicularity flow cores that can show columnar jointing and highly vesicular brecciated margins. Individual flows can rarely be correlated more than a few kilometres between outcrops suggesting that flows travelled short distances, with local eruptions from both fissures and vents. The region is cut by strike-slip faults that were active in the Palaeogene and by the Ardglass-Ballycastle and St. John's Point-Lisburn dyke swarms ²⁰⁴.

This study has identified that the Antrim Lava Group has an offshore area of 158 km² and an onshore area of 3446 km², with a total area of 3604 km². A Gross Rock Volume (GRV) of 2883 km³ was calculated using a thickness of 0.8 km and the total area. Geological screening has indicated that the group is composed of 99% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is basalt, and the lava flows have been recorded to be highly vesicular without



significant hydrothermal or geothermal alteration. A mean estimate of 18% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 513 km³ available for CO₂ mineralisation.

Skye Lava Group

The Skye Lava Group is part of the British and Irish Palaeogene Igneous Province, covering the north and west-central parts of the Isle of Skye, Scotland, and extending offshore to the south-west beyond the islands of Canna and Sanday ²⁰⁵. The group has a current approximate thickness of 1.5 km, differing from the original emplacement thickness due to extensional faulting ¹⁸⁶. The lower compound-braided lavas are thin, vesicular and highly fractured olivine-phyric basalts. The transitional mixed sequence marks a transitional eruptive phase from low viscosity compound-braided lavas to simpler tabular lavas with olivine-phyric basalts with occasional flows of basaltic-andesite. The upper tabular-type lava sequence has a more evolved composition that produces thicker flows (>8 m thick) with brecciated margins and massive core zones that can show columnar jointing ¹⁸⁶. In northern Skye the base of the Skye Lava Group consists of hyaloclastites, locally developed pillow lavas, and volcaniclastic sedimentary rocks that mark pauses in the volcanic activity ¹⁸⁶.

This study has identified that the Skye Lava Group has an offshore area of 843 km² and an onshore area of 976 km², with a total area of 1819 km². A Gross Rock Volume (GRV) of 2728 km³ was calculated using a thickness of 1.5 km and the total area. Geological screening has indicated that the group is composed of 90% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is basalt, with several flow morphologies recorded, included highly brecciated and vesicular flows without significant hydrothermal or geothermal alteration. A mean estimate of 18% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 440 km³ available for CO₂ mineralisation.

Mull Lava Group

The Mull Lava Group is part of the British and Irish Palaeogene Igneous Province, covering the north and west of the Isle of Mull, Scotland, as well as extending around the south coast of the island. The group continues offshore, extending to smaller islands to the west including Ulva and Staffa. The Mull Lava Group also outcrops on the Morvern Peninsula and to the east of Ben Hiant on the Ardnamurchan Peninsula. The Mull Lava Group has a thickness of 1.8 km on Mull and 0.46 km on Morvern where the lowest lavas thin to the north ²⁰⁵. The lavas were erupted



from northwest-southeast trending fissures that are now represented by the Mull Dyke swarm. The erupted lavas are tholeiitic basalt, with some rare alkali-olivine basalt flows and more evolved compositions ²⁰⁶. At the base of the group, the Staffa Lava Formation consists of tholeiitic basalts that commonly show columnar jointing. Above, the Mull Plateau Lava Formation consists of brecciated and vesicular olivine basalt and hawaiite lava flows ²⁰⁵. The Mull Central Lava Formation overlies the Mull Lava Group, cropping out within the Mull Central Complex. This formation consists of pillow lavas that have been extensively hydrothermally altered, probably erupted within a water-filled caldera.

This study has identified that the Mull Lava Group has an offshore area of 826 km² and an onshore area of 744 km², with a total area of 1570 km². A Gross Rock Volume (GRV) of 1774 km³ was calculated using a thickness of 1.13 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 99% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is basalt, with some brecciated and vesicular flows recorded and the effects of alteration at the base but not throughout of the group. Without additional data to suggest otherwise, a mean estimate of 18% effective porosity (Φ_e) was taken from analogue data and allows comparison with other Paleogene PSGF. A Theoretical Pore Space (TPS) of 318 km³ was calculated to be available for CO₂ mineralisation.

Clyde Plateau Volcanics

The Clyde Plateau Volcanic Formation crops out in the Midland Valley of Scotland, as part of the Carboniferous age Strathclyde Group, as well as in Cowal and on the Isles of Arran and Bute ²⁰⁷. The formation contains lavas of transitional to mildly alkaline compositions and a range of lithologies, including olivine-basalts, hawaiites, mugearites, trachybasalts, and trachytes. The basalt flows are less altered than other compositions, but albitisation, carbonation, oxidation and zeolitisation are widespread ²⁰⁸. The volcanics were emplaced initially as part of four east-northeast trending linear vent systems before later volcanism became focused at one volcanic centre that is now represented by the Waterhead Central Volcanic Complex. The lavas were mostly erupted subaerially, with some minor subaqueous flows found. Tephra cones are present around some of the volcanic centres. The thickness of the formation varies laterally and is not well constrained but is estimated to be over 0.42 km on the Campsie Fells, over 0.9 km thick in the Renfrewshire Hills and 0.07-0.08 km thick on the Isle of Arran ²⁰⁸.



This study has identified that the Clyde Plateau Volcanic Formation has a total onshore area of 1094 km². A Gross Rock Volume (GRV) of 536 km³ was calculated using a thickness of 0.49 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 86% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is basalt and is recorded as having undergone a range of alteration processes. A mean estimate of 8.5% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 39 km³ available for CO₂ mineralisation.

Little Minch Sill Complex

The Little Minch Sill Complex is composed of Palaeocene microgabbro sills (sub-horizontal sheet-like intrusions) within the Sea of Hebrides Basin, to the west of the Scottish mainland. The Complex outcrops onshore in northern Skye and other nearby islands. The rocks are olivine-microgabbros thought to have been derived from the differentiation of an alkaline basalt magma, and compositional variations between individual sills indicate that there were multiple episodes of magma emplacement ²⁰⁵. Some sills are simple, with only one lithology, while others are composite. The composite sills can show evidence of formation by multiple injections, with chilled margins and rafts of country rock found within the stacks of sills. The onshore sills are columnar jointed and vary from a few metres to ~0.14 km in thickness ²⁰⁹ with an estimated aggregate thickness of >0.25 km ²⁰⁵. The sills show centimetre-scale layering defined by varying proportions of olivine, clinopyroxene and plagioclase ²⁰⁵. The sill complex dips shallowly toward the west and is transgressive, intruding into younger bedrock towards the north.

This study has identified that the Little Minch Sill Complex has an offshore area of 509 km² and an onshore area of 91 km², with a total area of 600 km². A Gross Rock Volume (GRV) of 150 km³ was calculated using a thickness of 0.25 km and the total area. Geological screening has indicated that the group is composed of 100% highly reactive (rank A) lithologies, with no need to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is microgabbro and is without significant hydrothermal or geothermal alteration. A mean estimate of 10% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 15 km³ available for CO₂ mineralisation.

Insch Pluton

The Insch Pluton, northwest of Aberdeen, Scotland, was emplaced in the Ordovician around 470 ± 9 Ma ²¹⁰ and is composed of gabbro and peridotites in three 'stratigraphic' zones, formed



by cumulate fractionation of basalt. The first zone, the Lower Zone, consists of dunites, troctolites, and olivine-gabbros that are amphibolitised in places. The Middle Zone overlies the Lower Zone and is formed of coarse grained cumulate norites and granular gabbros that show little preferred grain orientation or rhythmic variation in mineral proportions ²¹¹. In some areas the Middle Zone gabbros are more porphyritic. The boundary between the Middle and Upper Zones of the pluton is marked by a horizon of cumulus iron-rich olivine that can be traced for over 11 km before becoming truncated by a fault. The Upper Zone of the pluton consists of olivine ferrogabbros and some olivine monzonite and syenite with little visible mineral layering. The olivines and pyroxenes become rapidly more enriched in iron upwards. The Middle and Upper Zones of the pluton show straightforward differentiation to more extreme compositions, with no evidence of magma replenishment seen, suggesting that the intrusion was isolated from the magmatic source during the final stages of crystallisation. The base of the pluton has been gravity modelled to be at 1-5 km depth in the crust ²¹².

This study has identified that the Insch Pluton has a total onshore area of 216 km². A Gross Rock Volume (GRV) of 540 km³ was calculated using a thickness of 2.5 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 100% highly reactive (rank A) lithologies, with no need to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is gabbro that has been geothermally altered and metamorphosed. A mean estimate of 13% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 70 km³ available for CO₂ mineralisation.

Blackstone Band Igneous Complex

The Blackstones Band Igneous Complex is located offshore, around 30 km southwest of Tiree, and forms an area of irregular high relief, with the majority of the complex is hidden by a thick cover of Quaternary sediments ²¹³. Samples indicate that most of the complex consists of gabbro, with small areas of granophyre and intersecting basaltic dykes ²¹³. A significant amount of the Blackstones Band Igneous Complex appears to be cumulates, with some isotopic variations interpreted as due to crustal contamination from the host-rock surrounding the intrusion. The Complex produces a large gravity anomaly and is thought to extend ~22-30 km depth to the base of the crust ²¹⁴.

This study has identified that the Blackstones Band Igneous Complex has a total offshore area of 184 km². A Gross Rock Volume (GRV) of 4773 km³ was calculated using a thickness of 26



km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 100% highly reactive (rank A) lithologies, with no need to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is gabbro that has been geothermally altered and metamorphosed. A mean estimate of 13% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 620 km³ available for CO₂ mineralisation.

Tyrone Volcanic Group

The Tyrone Volcanic Group, in Co. Tyrone, Northern Ireland, consists of volcanic, volcaniclastic and thin argillaceous sedimentary rocks, ironstones, and banded chert 4-5 km thick (Hollis et al., 2014). The group forms the upper part of the wider Tyrone Igneous Complex that represents the metamorphosed and tectonised remnants of an Ordovician Island arc system and subduction-related ophiolite. The Tyrone Volcanic Group is bounded by the Omagh Thrust Fault to the north and the Beleevnamore and Davagh faults to the south. The Tyrone Volcanic Group shows evidence of at least three volcanic cycles with basaltic pillow lavas and tuffs with sedimentary lithologies above ²¹⁵. Locally, there are volcanic breccias composed of rhyolite and dacite fragments that likely formed close to explosive vents. Through time the Tyrone Volcanic Group became more acidic, with the upper part dominated by rhyolites and intermediate-felsic tuffs. The rocks have been metamorphosed to upper greenschist to lower amphibolite grade, changing all pyroxene to amphibole. Large granitic to tonalitic intrusions and a suite of porphyritic dacitic sills and dykes intersect the whole Tyrone Igneous Complex ²¹⁶.

This study has identified that the Tyrone Volcanic Group has a total onshore area of 143 km². A Gross Rock Volume (GRV) of 645 km³ was calculated using a thickness of 4.5 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 100% highly reactive (rank A) lithologies, with no need to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is basalt and is recorded as having undergone a range of alteration and metamorphic processes. A mean estimate of 8.5% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 70 km³ available for CO₂ mineralisation.

Ardnamurchan Central Complex

The Ardnamurchan Central Complex, on the Ardnamurchan Peninsula, Scotland forms the westernmost part of the Scottish mainland. The Central Complex represents a Palaeogene central volcano emplaced into the metamorphic basement, now dissected at around 2 km below



the former land surface and possibly 1.5–3.5 km in thickness ²¹⁷. The Complex consists of many mafic intrusive bodes such as cone sheets, ring dykes and lopoliths, with three distinct centres of activity recognised (Centre 1, Centre 2, and Centre 3). At Centre 1 and on Ben Hiant, the Ardnamurchan Central Complex consists of ~0.2 km of heterogeneous volcaniclastic rocks with clasts ranging from millimeters to tens of metres in size that are derived from the older Mull Lava field beneath ²⁰⁵. On Ben Hiant these rocks have been interpreted as debris flows and avalanche deposits. Andesitic pitchstone with well-developed columnar jointing was intruded into the volcaniclastic rocks, alongside many sheets of microgabbro and quartz-microgabbro.

At Centre 2, four phases of intrusive activity have been recognised, starting with the emplacement of tholeiitic microgabbro cone sheets ²¹⁸. In the second phase, these were intruded by later ring-intrusions including hypersthene-gabbros, olivine gabbros, quartz-microgabbros, a granite, and felsites. The third phase involved the intrusion of more steeply inclined plagioclase-phyric microgabbros. In the final stage of activity more incomplete ring-intrusions where emplaced, mainly of quartz-microgabbro. The Gals Eilean Vent formed at the same time of the younger intrusions seen at Centre 2, consisting of fault-bounded microgabbros and basalt lavas alongside volcaniclastics and volcanic breccias ²⁰⁵. The youngest intrusive centre, Centre 3, consists of gabbro ring-intrusions with an overall 'funnel shape', alongside hybrid intermediate and silicic intrusions derived from the fractional crystallisation of basic magmas and partial melting of the surrounding country rock. The largest intrusion at this centre, the Great Eucrite, is a bytownite olivine-gabbro that shows little internal structure ²⁰⁵. The innermost part of the intrusive centre is formed of amphibole-rich tonalite and quartz-monzonite, likely derived from the fractionation of basic magmas and partial melting of the overlying roof rocks.

This study has identified that the Ardnamurchan Central Complex has a total onshore area of 141 km². A Gross Rock Volume (GRV) of 353 km³ was calculated using a thickness of 2.5 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 89% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is gabbro, with many columnar joints and that has been geothermally altered. A mean estimate of 13% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 41 km³ available for CO₂ mineralisation.


Lizard Complex

The Lizard Complex is composed of mafic and ultramafic rocks on the Lizard Peninsula, Cornwall, thought to vary from 0.4-1.5 km in thickness based on geophysical surveys ²¹⁹. It was thrust onto sediments that now lie beneath during the Variscan collision (~380 Ma), created by the convergence of the continent of Gondwana with Laurentia, Baltica and Avalonia to form Pangaea. The Lizard Complex can be split into three distinct groups of igneous rocks: the Lizard peridotites, the crustal units, and later intrusions related to the emplacement of the Complex on top of the metamorphic basement ¹¹².

The peridotite of the Lizard Complex is mostly partially serpentinised lherzolite with discontinuous layers that are enriched in pyroxene and olivine ²²⁰. The rocks are variably deformed and dynamic recrystallisation processes produce areas of mylonitic peridotite. Amphibole replaces pyroxene in some rocks producing amphibole-bearing peridotites (up to 30% amphibole). The crustal units consist of a variety of rock types including dunites, gabbros, norites and anorthosites that can be intensely mylonitised in places and altered to amphibolite grade. Altered tholeiitic basalt pillow lavas and microgabbro sheeted dykes, representing the upper oceanic crust, are also present. These crustal units are cross-cut by MORB-type dykes. The third distinct group of rocks – later intrusions related to thrusting and emplacement – are mafic to felsic intrusions that form shallowly dipping sheets, concentrated around the contact between the peridotite and the underlying basement rocks ¹¹².

This study has identified that the Lizard Complex has an offshore area of 81 km² and an onshore area of 54 km², with a total area of 135 km². A Gross Rock Volume (GRV) of 128 km³ was calculated using a thickness of 0.95 km (mean value taken from the thickness estimate range) and the total area. Geological screening has indicated that the group is composed of 100% highly reactive (rank A) lithologies, with no need to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is peridotite and serpentinite which has been extensively hydrothermally altered and is fracture dominated. A mean estimate of 1.76% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 2 km³ available for CO₂ mineralisation.

The Shetland Ophiolite

The Shetland Ophiolite Complex comprises mafic and ultramafic rocks which outcrop on the larger islands of Unst and Fetlar and several smaller islands that represent the most northeasterly landmasses in the UK. It represents a slab of oceanic crust and mantle that was thrust



over the metasedimentary rocks to the west in the Ordovician, around 470 million years ago. It is composed largely of serpentinised peridotite, gabbro and microgabbro. The gabbros show well-developed layering, which is characteristic of oceanic crustal material. The base of the slab of mafic ultramafic material is thought to reach a maximum depth of 3 km below the surface ²²¹. It is thought to extend some distance offshore, with geophysical surveys indicating it continues at least 5 km westwards from the east coast of Unst, however it has not been mapped in detail ²²¹.

This study has identified that the Shetland Ophiolite Complex has a *potential* offshore area of 77 km² and an onshore area of 72 km². The offshore area has been estimated on the basis of published information and is not distinguished on the BGS maps, therefore is not shown on Figure 3. A Gross Rock Volume (GRV) of 72 km³ was calculated using a thickness of 1 km (mean value taken from the thickness estimate range) and the confirmed onshore area. Geological screening has indicated that the group is composed of 73% highly reactive (rank A) lithologies, with this number used to correct the GRV for usable volume of rock suitable for absorbing CO₂. The dominant lithology is peridotite and serpentinite which has been extensively hydrothermally altered and is fracture dominated. A mean estimate of 1.76% effective porosity (Φ_e) was taken from analogue data. This calculated a Theoretical Pore Space (TPS) of 1 km³ available for CO₂ mineralisation.

Appendix B. Regulations

B.1. Key definitions

The EC Storage Directive ¹⁴⁵, on which UK legislation is based, introduces some important concepts and definitions that will be relevant in assessing the legislative requirements for deep mineral sequestration. The Directive defines the following components of a storage system (conceptually illustrated in Appendix Figure B1) that are used in the UK legislation:

- 'geological storage of CO₂' means injection accompanied by storage of CO₂ streams in underground geological formations;
- 'water column' means the vertically continuous mass of water from the surface to the bottom sediments of a water body;
- 'storage site' means a defined volume area within a geological formation used for the geological storage of CO₂ and associated surface and injection facilities;



- 'geological formation' means a lithostratigraphical subdivision within which distinct rock layers can be found and mapped;
- 'leakage' means any release of CO₂ from the storage complex;
- 'storage complex' means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations;
- 'hydraulic unit' means a hydraulically connected pore space where pressure communication can be measured by technical means and which is bordered by flow barriers, such as faults, salt domes, lithological boundaries, or by the wedging out or outcropping of the formation;
- 'exploration' means the assessment of potential storage complexes for the purposes of geologically storing CO₂ by means of activities intruding into the subsurface such as drilling to obtain geological information about strata in the potential storage complex and, as appropriate, carrying out injection tests in order to characterise the storage site;
- 'exploration permit' means a written and reasoned decision authorising exploration, and specifying the conditions under which it may take place, issued by the competent authority pursuant to the requirements of this Directive;
- 'operator' means any natural or legal, private or public person who operates or controls the storage site or to whom decisive economic power over the technical functioning of the storage site has been delegated according to national legislation;
- 'storage permit' means a written and reasoned decision or decisions authorising the geological storage of CO₂ in a storage site by the operator, and specifying the conditions under which it may take place, issued by the competent authority pursuant to the requirements of this Directive;
- 'substantial change' means any change not provided for in the storage permit, which may have significant effects on the environment or human health;
- 'CO₂ stream' means a flow of substances that results from CO₂ capture processes;
- 'waste' means the substances defined as waste in Article 1(1) (a) of Directive 2006/12/EC;
- 'CO₂ plume' means the dispersing volume of CO₂ in the geological formation;
- 'migration' means the movement of CO₂ within the storage complex;



- 'significant irregularity' means any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health;
- 'significant risk' means a combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of this Directive for the storage site concerned;
- 'corrective measures' means any measures taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO₂ from the storage complex;
- 'closure' of a storage site means the definitive cessation of CO₂ injection into that storage site;
- 'post-closure' means the period after the closure of a storage site, including the period after the transfer of responsibility to the competent authority.
- 'transport network' means the network of pipelines, including associated booster stations, for the transport of CO₂ to the storage site.

It is worth noting that the definitions of storage site and complex were originally defined with the assumption that storage would be in porous rocks. The concept of the storage complex is very important in that any migration beyond the complex boundary, regardless of whether this means the CO₂ is emitted to the seawater column or atmosphere, or whether it remains within the rock formations is determined to be leakage (Appendix Figure B1). The storage complex boundary is defined and agreed between the permit applicant and the NSTA as part of the Applicant's submission for a storage permit. It is therefore incumbent on the applicant to ensure that their storage complex boundary is defined in such a way as to include the volume of rock within which CO₂, including CO₂-rich fluids, are likely to conservatively migrate.

The CO₂ stream must "overwhelmingly" comprise CO₂. Although there is no predefined minimum CO₂ concentration, in practice, values significantly above 98% are targeted.



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Appendix Figure B1 Illustrative schematic showing the concepts for 3D volumes of a CO₂ storage system, as defined by the EC CO₂ Storage Directive ¹⁴⁵, and the definitions of migration and leakage. Each domain in the illustration represents a 3D component of the total geological system. For explanation of terms see text.

B.2. Storage licence technical programme

A work programme should be included, which should be sufficient to resolve any outstanding uncertainties, to enable the applicant to submit a storage permit application in due course. The work programme should be a firm commitment, and any contingent activities should be clearly identified. Contingent activities include those that would be conducted, depending on the outcome of other activities. For example, additional core analysis would be specified but only undertaken if initial measurements were insufficient to address the identified uncertainty. The work programme is expected to include:

- The number and details of exploration/appraisal wells and any associated injection tests.
 Appraisal wells may seek to reduce uncertainty on the nature of reservoir and seal properties and establish injectivity.
- Details of 2D or 3D seismic data to be acquired, either through purchase of existing data or through the acquisition of new data. The quality of the data should be explained and the source (*e.g.* proprietary or multiclient/speculative)
- Other work which might include:
 - o non-intrusive geophysical surveys,
 - o subsurface studies and modelling



- o seabed, shallow strata, and seep surveys,
- research, and technological development studies such as geotechnical studies, gravity or magnetic surveys, electromagnetic seabed logging, reservoir engineering, Front End Engineering and Design.
- A summary of potential emitters, pipeline routes, nearby petroleum or CO₂ storage licences.

The work programme will be included in the licence and will not be amendable once a licence has been granted.

B.3. Storage Appraisal Components

EARLY RISK ASSESSMENT. Potential threats to containment and uncertainties in defining the proposed storage site and storage complex should be defined early in order that further appraisal is focussed on their reduction. The concepts of a storage site and storage complex, which are fundamental concepts to the regulatory framework, are discussed in Section B.1. The results of the early risk assessment determine the subsequent appraisal activities and also inform the requirements for Measurement, Monitoring and Verification (MMV) Plan and Corrective Measures (CM) Plan.

The output of this phase will be an Early Risk Assessment report containing "an analysis of potential threats to containment and the key uncertainties in defining the proposed Storage Site and Storage Complex. It should also demonstrate that all relevant existing accessible data are compiled and interpreted - if not, then a plan should be presented on how the remaining existing and new data will be integrated." ¹⁵⁷

The findings will be discussed at a workshop with relevant independent peer reviewers and the NSTA, to review work undertaken and discuss subsequent plans.

SITE CHARACTERISATION. All site-specific primary data should be integrated into an evaluation of the proposed site ¹⁵⁷. This will include, inter alia, seismic interpretation and basic reservoir modelling which reflects the latest information and interpreted data available. The reservoir modelling should include multiphase modelling (*i.e.*, CO₂, water, hydrocarbons) to predict the injectivity at the volumes required and CO₂ plume behaviour. Geomechanical characterisation will evaluate caprock integrity, the potential for induced seismicity and fault reactivation, to inform operational parameters (*e.g.* injection rates, pressure limits).



A Site Characterisation report will describe the seismic interpretation, degree of hydraulic connectivity including fault juxtaposition diagrams, fault seal analysis, and evaluation of the heterogeneity in sealing properties along fault juxtapositions; and identification of impermeable baffles or barriers within the Storage Site. It will also describe the sealing capacity of primary and secondary seals and fracture pressure analysis. More detailed assessment of storage resource is expected at this stage. Finally, an above ground evaluation report will detail the transportation and injection facilities, and engagement with other interested parties.

The site characterisation will conclude with a review with NSTA and independent peer reviewers.

ASSESS PHASE. The Assess Phase review provides assurance that the technical work is at a stage to allow progression into the Define phase and optimisation of the Carbon Storage Development Plan, including characterisation of the Storage Site and Storage Complex (See section B.1.). Outputs include the Site and Complex Characterisation Report, which include final results of all subsurface studies and characterisation of the 3D volume; migration models and identification of potential leakage points; dynamic models of CO₂ migration including sensitivities and full uncertainty analysis and range of contingent storage volumes; and the composition of CO₂ stream. The risk assessment will highlight preliminary risks to containment and injectivity, and plans to mitigate these risks, and remaining work to finalise the Containment Risk Assessment. A preliminary Corrective measures plan will be based on the MMV plan. A provisional Closure and Post-Closure Plan will address eventual abandonment, post-closure monitoring and handover.

DEFINE PHASE. The Define Phase is the Storage Permit Application Process and prepares the following documents as part of the Storage Permit Application (see section B.4. for a short description of each document):

- 1. Carbon Storage Project Overview
- 2. Storage Site and Complex Characterisation
- 3. Carbon Storage Development Plan
- 4. Containment Risk Assessment
- 5. Measuring, Monitoring, and Verification Plan
- 6. Corrective Measures Plan
- 7. Provisional Closure and Post-Closure Plan
- 8. Financial Security (not discussed further in this review)



The Define Phase also includes provision of the draft Project Execution Plan and the draft Supply Chain Action Plan. In addition, a summary of how greenhouse gas emissions, including those associated with energy use (for example from CO₂ heating ¹⁵⁷), will be minimised during operation and throughout the project lifecycle, will be required.

B.4. Storage Permit (supplementary information to 3.1.6.)

B. 4.1. CARBON STORAGE PROJECT OVERVIEW

This document summarises the proposed storage project, defines the storage site and storage complex, and the associated CO₂ capture, transport and injection systems, and the stream composition. The reservoir pressure limits, maximum injection rates and pressures. A summary of key interactions with other users of the seabed should be described.

B4.2 STORAGE SITE AND COMPLEX CHARACTERISATION

This document is a critical input to the Storage Permit Application and informs the rest of documents, providing the geological evidence for the definition of the operational boundaries and decisions taken in the design of the storage project. It also provides key evidence that the project will enable permanent storage without leakage. The structure of this document is prescribed by NSTA ¹⁵⁹, which is summarised here:

Subsurface database: Information on the datasets (seismic, wells, third party reports etc).

<u>Regional geology and basin evolution</u>: Summary of regional geology, including a stratigraphic overview, tectonic history and timing of faulting and trap formation. A list of nearby hydrocarbon fields should be included. A description of regional hydraulic connectivity of the aquifer (if relevant) and a history of subsurface hydrocarbon activity is required.

<u>Storage site and storage complex</u>: The spatial extent and rationale for definition should include the proposed storage formation(s), site and complex seals. A summary of lithologies, and their extent into the wider region, including the underburden (Appendix Figure B1).

<u>Seismic interpretation and structural mapping</u>: A fully illustrated description of the data and structural interpretation. Rock physics analysis to determine the feasibility of 4D seismic should be described.

<u>Geological interpretation and storage complex description</u>: Reservoir properties of the storage site and any permeable formations in the overburden should be fully described. Supporting



detailed studies (*e.g.* sedimentology, fault analysis, core analyses, reservoir quality and heterogeneity, capillary entry pressures) should be included for reservoir and caprock.

<u>Petrophysics and fluids</u>: Petrophysical analyses and supporting data, together with special core analysis, fluid analyses and associated phase (PVT) modelling should be fully described. Current and previous fluid contacts should also be documented.

<u>Pore pressure</u>: Interpretation and analysis of pore pressure regime for storage site and complex, including an assessment of expected future pressure evolution during injection, including water extraction for pressure management must be provided.

<u>Geochemistry</u>: Rock and fluid geochemical information, including future impacts of CO₂ injection should be provided. This should include assessments of impacts on caprock, injectivity and long-term trapping, and well cements, including sensitivities to key parameters.

<u>Faults, fractures, and leakage paths</u>: Potential leak paths, including cross- and along-fault leakage, structural spill points, and pathways along wells, must be identified and assessed.

<u>Seismicity</u>: Natural seismicity should be assessed and the risks to site integrity and complex from natural or induced seismicity.

<u>Geomechanics</u>: Assessments of stress regimes, including fracture gradients, fault reactivation studies, and laboratory testing, and the potential impacts of changing pressure and stress regimes, should be provided.

<u>Static modelling</u>: A range of static geological models will be constructed for the site and complex to enable multiple scenarios to be analysed to reflect the range of uncertainties and their impacts on storage capacities.

<u>Dynamic modelling</u>: Simulations of injection and trapping processes should be described and must be of sufficient resolution and spatial coverage to understand responses to injection, including potential leakage pathways. Simulations should cover both short-term (pre- and injection periods) and long-term (post-injection and post-closure). Where relevant (*i.e.* for depleted hydrocarbon fields) production data and pressures should be history-matched to allow further model validation. Coupled models may be necessary to assess thermodynamic and pressure interactions in all domains of the storage site.



<u>Uncertainty analysis framework</u>: The uncertainties in the above assessments should be fully described in each section. Here, their combined effects on both static and dynamic models should be explained.

<u>Storage capacity estimate</u>: The total quantity of CO₂ to be injected and stored should be defined, within the context of the total storage capacity to be expressed as a range with associated probabilities. This should include any secondary storage formations.

B.4.3. CARBON STORAGE DEVELOPMENT PLAN

This document outlines the development of the wells, infrastructure, pipelines and other facilities required. It should include:

- Development plan overview illustrated with maps of well locations and key dates
- Description of storage site and storage complex
- Injection plan, storage capacity and injection profiles
- Storage site and complex pressure forecasts for individual wells and for the storage site and complex. It will include results from the studies described in Section B.4. with key thresholds for safe operation determined.
- Brine production, where necessary, including brine management facilities should be included.
- CO₂ sources and compositions, including impacts on phase behaviour.
- Injection facilities including options for future expansion and third-party access. Treatment facilities, control systems, process flow diagrams will be included.
- Well design and injection technology, including monitoring and intervention technologies.
- Net Zero considerations
- Project planning including a Project Execution Plan and a Supply Chain Action Plan
- Storage site management plan

B.4.4. CONTAINMENT RISK ASSESSMENT

The Containment Risk Assessment is a key document that provides evidence that all risks have been mitigated to an appropriate level. It contains a detailed risk register with links to the MMV



Plan (B.4.5.) and Corrective Measures Plan (B.4.6.) and provides the evidence base for characterisation studies undertaken to support Storage Site and Complex Characterisation.

It will describe the Risk Assessment Methodology, which will be a systematic process of qualitative, semi-quantitative and quantitative risk analysis. It requires external expert input and guidance (peer-review) to ensure appropriate completeness, robustness and quality.

The key components of the risk assessment are:

- Hazard identification and characterisation to include potential leakage pathways, potential magnitude of leaks and the critical elements that might affect these fluxes, secondary effects and hazards to human health or the environment.
- Risk register and analysis containing all identified hazards, risk scenarios, and unmitigated consequences. Risks will be scored and ranked using a risk matrix. It should also contain risk control measures, integrated with the MMV Plan and Corrective Measures Plan. The potential evolution of risk profiles throughout the project lifecycle should also be described.
- Risk evaluation to confirm that there is no significant risk of leakage.

B.4.5. MEASURING, MONITORING, AND VERIFICATION (MMV) PLAN

The MMV Plan should be consistent and integrated with the risk assessment and corrective measures plan. The planned monitoring should enable demonstration of conformance with predictive modelling of future performance, verification of containment, and detection and measurement of any significant irregularity or leakage. It should detail any additional monitoring required if a significant irregularity or leakage is detected. It should provide sufficient monitoring to assess the integrity of the storage complex over the short- and long-term, including the effectiveness of engineered and natural barriers to prevent loss of containment. It will include:

- Plan design as determined by the containment risk assessment with definitions of trigger thresholds for significant irregularities for timely corrective measures. It should be capable of determining changing risk of leakage. It will require implementation of baseline monitoring during project development and operational monitoring. It will anticipate monitoring requirements in the post closure plan.
- Monitoring technologies screening and selection
- Monitoring plan limitations and mitigations



B.4.6. CORRECTIVE MEASURES PLAN

This plan summarises the corrective measures taken if a significant irregularity or leakage is detected. It should be integrated with the containment risk assessment and MMV Plan. It should include a summary of corrective measure scenarios, describing those events which would require corrective measures, and the thresholds or circumstances which would trigger a response. The corrective measures pertaining to each scenario should be described, which may include additional monitoring or other actions, including contingency if initial interventions are ineffective. Details should include the need for Third Party companies.

B.4.7. PROVISIONAL CLOSURE AND POST-CLOSURE PLAN

This is a provisional document that will be revised and updated, as agreed with the NSTA, dependent on subsequent storage system performance. It describes provisional plans for the decommissioning and sealing of the site. It will also include details of the monitoring needed to demonstrate that the storage site and the storage complex will permanently contain the CO₂. This enables subsequent transfer of liability under the termination of licences regulations ¹⁴⁷. It should contain:

- Site closure criteria and conditions
- Post-closure monitoring plan for the minimum post-closure period of 20 years, or less if agreed with the NSTA that the CO₂ will be completely and permanently contained.
- Decommissioning activities in accordance with relevant good practice.



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