Review of the UK's geological potential for the generation and accumulation of natural hydrogen

Decarbonisation and Resource Management programme

Open report OR/25/015

BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

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Foreword

This report is the published product of a study by the British Geological Survey funded by the Department for Energy Security and Net Zero of the UK Government. The report delivers a first of its kind high level, national scale geological map-based assessment of the UK potential for natural hydrogen using a play-based exploration approach.

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Summary for policy makers

Natural hydrogen is a naturally occurring gas, produced by a series of chemical reactions within rock formations, from where it migrates until it is trapped, typically in porous reservoirs beneath less permeable cap rocks. It is a potentially low-carbon alternative fuel/energy carrier that received an increased interest in recent decades as hydrogen has become a potentially important component of the UK's future energy mix.

To date, the potential scale and accessibility of natural hydrogen in the UK has not been well understood. This study provides a high level, national scale geological map-based assessment of the UK potential for natural hydrogen resources using a play-based exploration approach, indicating a potential for source, trap and storage mechanisms. Areas where the timing of hydrogen generation in the subsurface combined with proximity of suitable reservoirs and geological seals may represent attractive exploration targets. Collection of new data or identification of hydrogen shows in the UK were outside the scope of this project.

Distinguishing between two qualitative grades, the report assesses the UK's geological terranes to indicate if there is 'potential' or 'limited potential' for natural hydrogen. Areas given a 'potential' grade are more likely to contain natural hydrogen, but as yet unproved, based on *currently available data* used in this desk-based study**. It does not confirm an area of natural hydrogen or that a location merits future exploration**, only that more detailed investigations are recommended. Areas given a 'limited potential' grade are less likely to contain natural hydrogen but could yet prove otherwise and should not be discounted without further investigation. The results presented in this study are subject to change as new data and research becomes available.

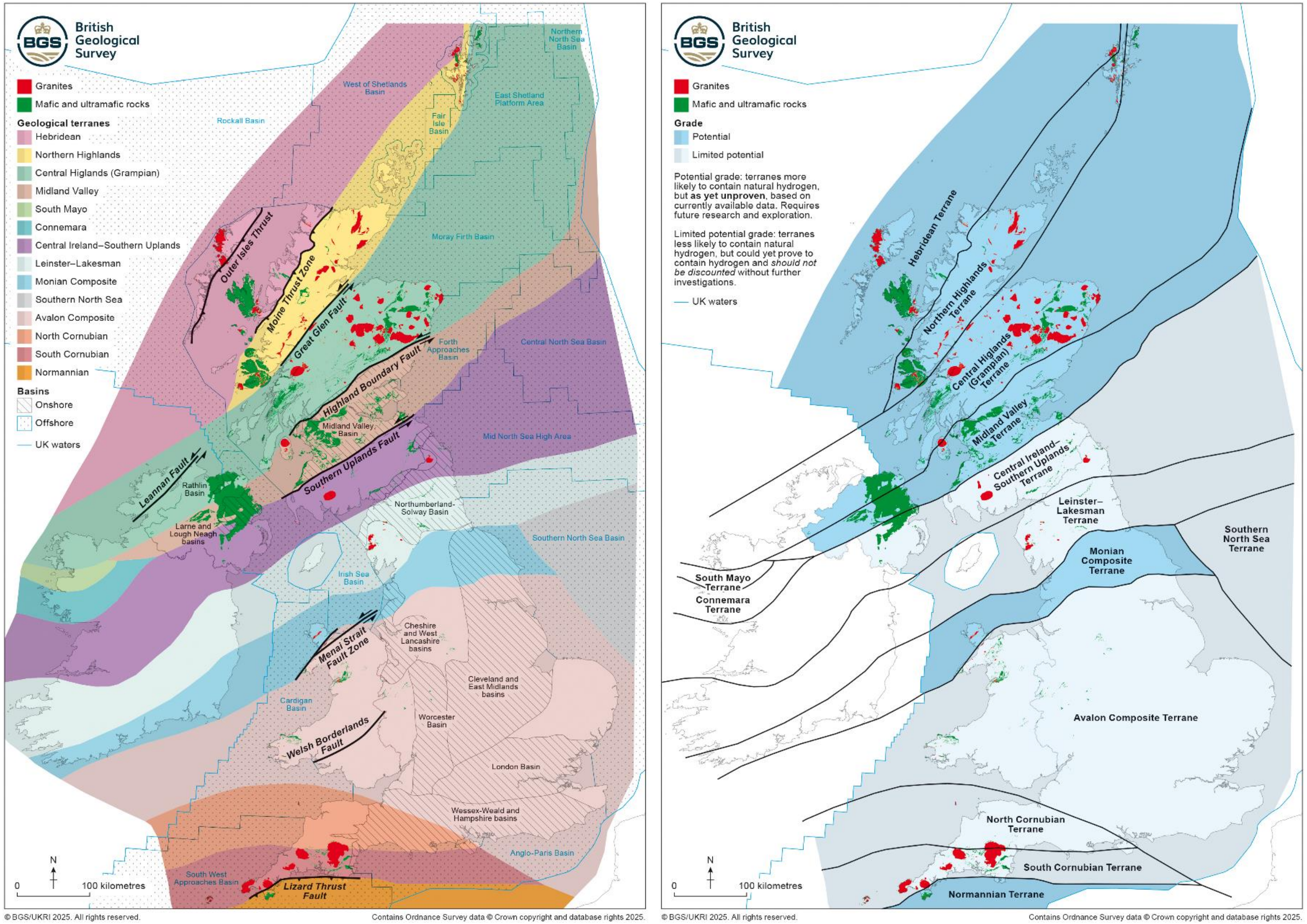
The following geological terranes were given potential grade; the Scottish Hebridean and Northern Highlands terranes, the Northern Irish – Central Scotland Central Highlands (Grampian) and Midland Valley terranes, the Northern Wales / Northern England Monian terrane and the Southern England Normannian terrane (Figure ES1). Each terrane is overlain by a series of on and offshore basins but there is often a large time gap between potential generation and development of suitable reservoir and seals, which has implications for the likelihood of hydrogen accumulation in any significant volumes.

To support this study, information has been collated on the current understanding of natural hydrogen systems, global occurrences and exploration methods. There is a significant lack of published data on natural hydrogen play-systems in the UK, with no current reports showing evidence of hydrogen seeps or accumulations from past drilling programmes. However, there is a vast amount of legacy data that might be relevant to natural hydrogen exploration but, it would require investment to integrate varied databases and datasets held by public bodies (including the British Geological Survey, the North Sea Transition Authority, and the Mining Remediation Authority) and other organisations, as well in peer-reviewed publications and other reports, some of which are commercially confidential. Our understanding on the relevance of this data is currently limited.

More specific investigations are thus needed to fully explore the potential for natural hydrogen in the UK, including the collection of new data as well as the re-assessment of legacy geological, geophysical and geochemical data to screen specifically for prospective areas for hydrogen in the subsurface. The following recommendations are given to address these knowledge gaps and identify potential target areas for further research:

- Identify, appraise and collate relevant legacy UK data to provide a baseline of existing knowledge and open access data.
- Develop a hydrogen add-on element to current gas and water monitoring initiatives undertaken by the Mining Remediation Authority for Mine Water Heat and Gas Leakage Monitoring.

- Establish a national-scale soil gas survey to identify seepage and potential hotspots of natural hydrogen, to better constrain subsurface sources.
- Collect nationwide airborne geophysical (magnetic) survey data to aid understanding of subsurface composition and structure, helping to identify locations of potential sources and reservoirs.
- Establish a laboratory programme to answer key questions about hydrogen play components, such as hydrogen generation reaction rates and volumes, effects of hydrogen on reservoir and seal rocks, and fluid flow through faults and fractures.
- Conduct a nationwide study of present-day and palaeo-heat flow, integrated with the spatial distribution of sources to estimate the age, duration and rate of potential hydrogen generation across the UK.
- Use of geological modelling to numerically describe the subsurface to help derisk exploration, identify potential targets and estimate accumulation volumes.



Executive Summary Figure 1. Maps of geological terranes and potential for natural hydrogen within the boundaries of UK waters. The presence of natural hydrogen has not been established within the UK and areas deemed of interest are **as yet unproven**. Terrane boundaries based on models of Beamish et al., (2016) and Molyneux et al., (2023). Onshore surface outcrops of granite, mafic and ultramafic rocks are shown in green and red and used to indicate likely deeper subsurface extents. Boundaries of offshore sedimentary basins from the North Sea Transition Authority (NSTA) © 2017 Oil & Gas Authority (available under the Open Government Licence). Boundaries of onshore basin from Ireland et al., (2021) and based on British Geological Survey 1:50k Bedrock England, Scotland, Wales; 1:250k Bedrock Northern Ireland; 1:625k Fault data; British Geological Survey ©. All rights reserved.

1 Introduction

1.1 CONTEXT

The United Kingdom's energy mix will undergo a significant shift as it moves away from fossil fuels to meet the UK's 2050 Net Zero carbon obligations. One way to lower carbon emissions is to replace fossil fuel energy sources with low-carbon and renewable alternatives. Where possible, electrification using renewable energy is viewed as a key alternative to the use of hydrocarbons to allow the decarbonisation of key areas such as transport and space heating (Climate Change Committee, 2025). Hydrogen has been proposed as another alternative, low carbon fuel to replace hydrocarbons. The Seventh Carbon Budget published in 2025 foresees hydrogen will play a small but important role particularly in industrial sectors such as ceramics and chemical production which may find it hard to electrify. Hydrogen also has an important role within the electricity supply sector as a source of long-term storable energy and as a feedstock for synthetic fuels. However, there is currently no significant role envisaged for hydrogen in buildings heating or in surface transport (Climate Change Committee, 2025).

Current global consumption of hydrogen is approximately 90 million tonnes per annum (Mtpa). Almost all of it is artificially produced and associated with a significant carbon footprint (McKinsey, 2023) due to the chemical processing (direct release of CO_2), infrastructure and energy required for its production. By 2050 the demand for hydrogen is projected to reach 430 Mtpa, of which low-emissions hydrogen could account for up to 73 to 100 percent (IEA, 2023). Natural hydrogen is seldom 100% pure and often contains carbon dioxide, methane and other gasses. Nevertheless, it presents an attractive proposition for energy companies to invest in to make this natural resource part of the clean energy portfolio globally.

Hydrogen combustion yields only water vapour, and its high energy density by mass makes it suitable for application across multiple sectors (Boretti, 2024). It forms an extremely small highly diffusive molecule, exhibiting low viscosity (Lefeuvre et al., 2022, Aftab et al., 2022). Hydrogen can be artificially produced by electrolysis of water with low-carbon electricity or via steam reforming of methane (natural gas), amongst other methods. Integration of carbon capture and storage with hydrogen production from methane is required for the resultant hydrogen to be considered low-carbon (Antonini et al., 2020).

Hydrogen is also a naturally occurring gas. It is naturally produced by a series of chemical reactions within rock formations, from where it migrates until it is trapped in porous reservoirs beneath less permeable cap rocks. Naturally occurring hydrogen has been reported to accumulate in reservoirs in economically viable quantities (Prinzhofer et al., 2018). However, significantly more research and investigation will be required to fully understand and characterise the formation and preservation of natural hydrogen accumulations within the Earth, and to enable their development as a resource for energy production. This report reviews the current state of knowledge on naturally occurring hydrogen and assesses the potential for UK resources.

1.2 GLOBAL OCCURRENCES AND EXPLORATION

As for hydrocarbons, prospecting for hydrogen requires a good understanding of the geological and structural settings, including the essential components that contribute to the hydrogen systems (sources, pathways, traps and seal). Typically, identification and confirmation of hydrogen resources require drilling into the subsurface to measure gas concentrations at depth. However, in some places, hydrogen gas can be detected by measurement in soil and/or water. These gas occurrences are interpreted as seeps of hydrogen that is leaking from reservoirs at depth. To identify where hydrogen accumulations are most likely to occur, it is necessary to understand the geological hydrogen system (Chapter 2).

Over 300 naturally occurring hydrogen seeps have been reported from various geological settings globally, including those in Canada, USA, Brazil, Mali, Spain, Turkey, Albania, Oman, the Philippines and Australia (Lollar et al., 2014, Prinzhofer et al., 2018, Zgonnik, 2020, Vacquand et al., 2018, Frery et al., 2021, Maiga et al., 2024b, Maiga et al., 2023, Aquino et al., 2025, Maiga et al., 2024a). The Bourakebougou site in Mali was initially drilled in 1987 for water resources, but serendipitously intersected accumulations of natural hydrogen (Prinzhofer et al., 2018). It is currently the only site in the world extracting and using natural hydrogen from the subsurface. Production started in 2012, but the flow rate of hydrogen is small (1500 m^3/day) and the gas is used locally for generating electricity for the village of Bourakebougou (Maiga et al., 2023). The Mali site is considered a large-scale prototype (Gaucher, 2023).

The research into natural hydrogen is gathering pace, with an increasing number of recent publications demonstrating that knowledge is constantly improving. Subsurface understanding of natural hydrogen is still at a developmental stage and discoveries of large accumulations are still relatively rare, with a growing number of companies now actively engaged in exploration. As of 2023, around 40 companies were actively participating in the natural hydrogen sector, compared to just 10 companies in 2020 (International Energy Agency, 2024).

A lack of regulatory frameworks in some countries has slowed down project development, whilst in others, such as Australia, France, Mali, Spain and the US, licensing is well underway (Ball, 2024). For example, in Australia, the Energy Resources Regulations 2013 were amended in 2021 to declare hydrogen as a regulated substance under the Energy Resources Act 2000, meaning that companies are now able to apply to explore for natural hydrogen via a Petroleum Exploration Licence (Government of South Australia, 2021). Further, in 2022, the Oil and Gas Reserves Committee of the Society of Petroleum Engineers (an independent, nonprofit society of 145 countries) advised that the principles of the Petroleum Resources Management System developed for consistent and reliable definition, classification, and estimation of hydrocarbon resources can now be applied to natural hydrogen (Society of Petroleum Engineers, 2022).

To date, hydrogen exploration has been led by start-up companies, but some of the major energy corporations have started to show interest in the technology. For example, Shell, BP and Chevron have joined a consortium led by the US Geological Survey (USGS) and Colorado School of Mines, focusing on studying natural hydrogen. The Brazilian state-owned oil and gas firm Petrobras is also reported to have invested $4 million to research natural hydrogen extraction (H_2 view, 2025). In the province of Saskatchewan, Canada, Max Power Mining company has reported the largest accumulation of high purity (96.4 per cent) natural hydrogen found during oil and gas drilling in the region.

Many of these companies are private enterprises, with several of them having secured substantial funding. In 2023, the US-based company Koloma secured $96.3 million in funding from Breakthrough Energy Ventures (Ball, 2024). Other companies have been able to secure financing and made offerings on the stock markets. The Australian-based Hytera secured AU$5.8 million through the sale of shares on the Australian stock exchange , whilst Gold Hydrogen obtained AU$20 million through an initial sale of shares on the Australian stock exchange in January 2023 and, raised an additional AU$14.8 million following its recent drilling campaign (Ball, 2024). Another company, Helios Aragon is developing Europe's first natural hydrogen production project in northern Spain. They are planning to drill an appraisal well in 2025 to produce hydrogen from the Monzon Field, at an associated cost of €12M (Helios-aragon, 2025).

Globally, several geological surveys have begun undertaking early evaluations of their national natural hydrogen systems and assessments of all available data for prospectivity analysis, including legacy hydrocarbon data. USGS recently published the first publicly available prospectivity map of geological hydrogen accumulations in the United States alongside an interactive map explorer (Gelman et al., 2025). In 2023, the French Geological Survey (BRGM) launched the "'Sous-sol, bien commun' ('Subsurface, a common good') programme, which aims to attain a more integrated vision of subsurface geology and help develop new exploration and exploitation technologies. Natural hydrogen research is one of five key areas of the programme, which is jointly led and funded (€71.4 million over seven years) by BRGM and the French National Centre for Scientific Research, in conjunction with several other academic partners.

In 2024, the Geological Survey of Finland published a map with information on hydrogen occurrences in Finland. However, they acknowledge that more research is needed before natural hydrogen can be exploited (GTK, 2024). Geocenter Denmark, is undertaking data mining to identify possible hydrogen occurrences in the Danish subsurface by using the extensive archive of reports and data held by the Geological Survey of Denmark and Greenland; and developing models for the generation and accumulation of natural hydrogen in the Danish onshore area (Blinkenberg, 2024)

1.3 REPORT AIM

At present, the potential for natural hydrogen in the UK remains largely unknown. Assessing the scale and accessibility of natural resources is crucial for shaping policy and commercial decisions. This study aims to conduct a nationwide assessment of the geological potential for natural hydrogen and to identify where hydrogen accumulations may exist in the UK subsurface. By analysing the existing literature and geological databases, this research will pinpoint prospective geological environments that could serve as target areas for further investigations.

The results from this study will be relevant to colleagues working on a hydrogen production strategy, hydrogen business models and hydrogen regulation. The outputs generated may guide the development of future programmes within the UK Research and Innovation councils, including the Natural Environment or the Engineering and Physical Sciences Research Councils or Innovate UK.

2 Natural Hydrogen Systems

To understand how natural hydrogen is created, transported and stored in the subsurface, it is important to identify the relevant components of the geological system. For this, a 'play-based' exploration model, similar to that of natural hydrocarbon systems, is applied (Boreham et al., 2021, Jackson, 2024). This approach provides an integrated evaluation of each component of a complex, interconnected geological system, including natural hydrogen sources, migration pathways, reservoir formations and seals (cap rocks). For any region to have potential for hydrogen accumulation in the subsurface, all four of these components must be present.

This study is based on existing geological knowledge and data, which were collected for purposes other than hydrogen prospecting. This report can therefore only provide an initial assessment of the potential mechanisms for generation, migration, and accumulation of hydrogen in the subsurface. More targeted data collection will be needed to gain a more detailed understanding of the specific geological factors that control the migration pathways and accumulation mechanisms for hydrogen in the UK subsurface to guide further exploration (Truche et al., 2024).

2.1 SOURCE AND GENERATION

There are two sources of molecular hydrogen (H_2), primordial (primary H_2) which is stored within the Earth's core and secondary, which is generated from chemical and biochemical reactions in the Earth's crust and mantle. Hydrogen can be generated through radiolysis (the breakdown of water by natural radioactivity), oxidation of ferrous iron (Fe^{2+}) by water during serpentinisation of ultramafic and mafic rocks, hydrothermal vents and volcanic degassing, cataclasis (rock fracturing) and others; small amounts are also produced through drilling operations and metal corrosion (Boreham et al., 2021, and references therein). Not all rocks are suitable sources for natural hydrogen. Therefore, the key mechanisms and lithologies are discussed further in this section.

2.1.1 Hydrolysis

Hydrolysis is a reaction of water with a mineral, leading to mineral alteration.

2.1.1.1 ULTRAMAFIC AND MAFIC ROCKS

Hydrolysis of ultramafic rocks that contain magnesium (Mg) and iron (Fe)-bearing (mafic) minerals is called serpentinisation. Serpentinisation is regarded as the most effective, and therefore the most important subsurface process for the generation of natural hydrogen (Smith et al., 2005, Jackson, 2024). It occurs when water interacts with the minerals in ultramafic rocks.

The chemical composition of the mafic minerals in the protolith is important. Namely, those rocks that contain significant proportion of Fe in silicate minerals (particularly, in olivine and/or pyroxene) have the highest potential to generate natural hydrogen. The key process of releasing hydrogen from ultramafic rocks is the oxidation of ferrous to ferric iron (Fe^{2+} to Fe^{3+}) with simultaneous reduction of water to hydrogen, also known as the Schikorr reaction:

$$3Fe^{2+}O \text{ (from olivine or pyroxene)} + H^{1+}{}_2O \text{ (water)} \rightarrow Fe^{2+}Fe^{3+}{}_2O_4 \text{ (magnetite)} + H^{0}{}_2 \text{ (hydrogen)}$$

Serpentinisation produces a new mineral assemblage of serpentine minerals $Mg_3Si_2O_5(OH)_4$ ± brucite $MgOH_2$ ± talc $Mg_3Si_4O_{10}(OH)_2$ ± magnetite Fe_3O_4 (± several minor mineral phases depending on the protolith and the serpentinising fluids' composition, pressure and temperature conditions). Although, most of the Fe^{3+} results in magnetite, some proportion can also be found in the newly formed serpentine, most commonly of the lizardite variety (Bonnemains et al., 2016, Evans et al., 2013). Other minerals including chlorite, talc or brucite can also host iron, both Fe^{3+} and Fe^{2+}, albeit to a lesser extent (Klein et al., 2009, McCollom et al., 2020). Growth of Fe^{3+}- rich lizardite will reduce the amount of magnetite but will have little effect on hydrogen production (Evans et al., 2013). Care must thus be exercised with using magnetite as the only mineralogical proxy for hydrogen generation in a defined system; instead, a combination of petrographic and geochemical studies (Fe speciation in minerals) should be conducted.

The key factors that control the partitioning of Fe and generation of hydrogen during the process of serpentinisation remain poorly understood. These may include the pH and temperature of the water, Fe content and relative proportions of precursor minerals, the silica activity, the evolving oxidation state of the system, and kinetics of component reactions, amongst others (McCollom et al., 2020). Where possible, these factors are summarised below:

Temperature

Hydrogen can be generated at a range of temperatures. It is continually produced by modern water/rock reactions with low salinity fluids under low-temperature conditions (≤50°C) (Miller et al., 2017, Ellison et al., 2021). At shallow subseafloor environments or intermediate depths within the continental crust, the peak temperatures for hydrogen production are estimated at 200 – 315°C (McCollom and Bach, 2009). At high temperatures (approx. >400°C) Mg – olivine (forsterite) is thermodynamically stable and aqueous fluids entering the deeper parts of the Earth with these conditions (e.g. upper mantle or lower oceanic crust), are trapped in olivine as secondary fluid inclusions (Klein et al., 2019). Serpentinisation and thus, hydrogen production is reduced at those conditions.

pH Conditions

Experimental work shows that the transition from mildly alkaline to strongly alkaline (high pH) conditions result in rapid increases in overall reaction rate and the generation of hydrogen. However, the net total amount of hydrogen generated may not vary much as a function of pH, as hydrogen is produced over a shorter span of time under increasingly alkaline conditions (McCollom et al., 2020).

Silica and Iron Content

The chemical composition of natural hydrogen sources undergoing alteration has an important effect on the amount of hydrogen produced, with the low-silica, high-iron ultramafic rocks producing the most hydrogen during serpentinisation (Frost and Beard, 2007, McCollom and Bach, 2009).

Hydrous Fluid System

A key component for serpentinisation to occur is the contact between rock and water to initiate the hydration reaction. The hydrogen production is maximised at a water/rock ratio of around 100, when the Fe^{3+}/Fe_{Total} of the bulk secondary assemblages is around 0.5 and approaches that of magnetite (Templeton et al., 2024). The rate of serpentinisation is strongly controlled by the salinity of the reacting fluid and slows down as salinity increases (Huang et al., 2023). The water must penetrate along joints, fractures and grain boundaries towards depths where the surrounding temperatures are sufficiently high to reach the “target” temperature window for reaction (Evans et al., 2013).

Other

Serpentinisation can take place in deep crustal and mantle levels, margins of oceanic spreading centres, oceanic transform faults and during tectonic processes including the emplacement of mantle rocks and oceanic crust onto continental crust resulting in the formation of ophiolite complexes (Neal and Stanger, 1984). Due to the tendency of fluids to migrate from high to low pressures, the formation and presence of hydrogen gas will increase due to decompression, for example, during tectonic movements (Oze and Sharma, 2007).

Importantly for the serpentinisation potential in the continental crust, the composition of Precambrian continental crust differs substantially from the average composition of continental crust in having a higher proportion of mafic and ultramafic rocks and hence higher FeO contents (Lollar et al., 2014). While the younger Phanerozoic continental crust is composed of 20 per cent mafic/ultramafic rock, the percentage increases to 25 per cent of Proterozoic crust (Precambrian) and between 45 per cent and 51 per cent in Archaean (Precambrian) crust

(Rudnick, 1995). In the UK, the Archean crust is exposed in north-west Scotland and will be considered further in Chapter 3.

2.1.1.2 FELSIC ROCKS

Felsic rocks are enriched in elements such as aluminium, sodium, potassium, and contain less amounts of the iron and/or magnesium bearing minerals typically found in mafic and ultramafic rocks. A typical example of a felsic rock is granite. Natural hydrogen generation associated with granite bodies is typically driven by radiolysis (Section 2.1.2) but hydrolysis of Fe-rich minerals (for example, biotite, amphibole) has also been reported (Murray et al., 2020, Truche et al., 2021, Bourdet et al., 2023). Due to the overall lower proportion of Fe-rich minerals found in granites (Boreham et al., 2021), these rocks are likely to be less important for hydrolysis. In some locations, both radiolysis and hydrolysis are cited as sources of hydrogen, e.g. in the Tickera granite or the Roxby Downs granites of southern Australia (Boreham et al., 2021, Bourdet et al., 2023). The generation of hydrogen attributed to radiolysis in the Roxby Downs pluton is in the range 22 to 32 g/m^3 which is considerably lower than the rate reported for hydrolysis of mafic minerals (such as, amphibole and magnetite) in the same pluton at 323 to 534 g/m^3 (Bourdet et al., 2023).

Evidence from Experimental and Modelling Work

Experimental work by (Truche et al., 2021) shows the hydrothermal breakdown of minerals in granite from the Strange Lake Pluton in Canada to be a plausible hydrogen generation process. Experiments performed at 280 to 400°C under near-neutral to alkaline conditions produced the most hydrogen. (Murray et al., 2020) models the hydrogen generation potential of granite underlying the Soultz-sous-Forêts geothermal site in France, based on the hydrolysis of Fe-rich biotite in fresh (unaltered) granite. At a temperature of 165°C, the rate of generation is about 102 g/m^3 of granite with complete reaction (breakdown of biotite) taking around 150 years. More importantly, three domains with differing generation potential were identified in the granite, highlighting the heterogeneous and complex nature of hydrogen generation in granite bodies.

Whilst experimental models improve our understanding of hydrogen generating processes in granites, it is important to note that such models are constrained by a selected set of conditions of temperature, pressure and fluid composition that may not fully mirror the conditions in natural systems.

Other Considerations

Similarly to serpentinisation, the reaction of Fe in felsic rocks is controlled by several factors, such as temperature, pH, and the water-rock ratio that will control mineral alteration and the type of secondary mineral formation. For example, when biotite, an important Fe-bearing mineral in granites, is altered to the chlorite mineral chamosite, the Fe^{2+} required for generating hydrogen is effectively made unavailable by the reaction, as it becomes ‘locked-up’ in the crystal structure of chamosite. Some mineral alterations may therefore serve as indicators that hydrogen generation has (or has not) taken place at some point in the history of the granite system. The pervasive breakdown of primary minerals along the margins of a fracture, may also increase porosity and therefore surface area, which may increase the overall hydrogen generation potential. Conversely, the creation of secondary minerals also has the potential to impede hydrogen generation by sealing fluid pathways.

2.1.1.3 BANDED IRON FORMATIONS

Banded Iron Formations (BIFs) are Precambrian sedimentary rocks with high Fe content (ranging from about 20 to 40 wt%), and composed of iron oxide layers alternating with silica- and carbonate-rich layers (Klein, 2005). Today, more than 80 per cent of Fe produced throughout the world, particularly in the USA, Australia, South Africa and Brazil, comes from these deposits. Recently, a spatial correlation between BIFs and hydrogen seepages has been observed in several places worldwide, including Namibia and Brazil, with additional suspected seepages reported in the surroundings of BIF-hosted Fe mines in Australia and South Africa (Moretti et al., 2021, Moretti et al., 2022, Geymond et al., 2022, Roche et al., 2024).

A third of the total Fe in magnetite is ferrous (Fe^{2+}) and water – rock interactions can lead to hydrogen - generating redox reactions, similar to those observed in mafic and ultramafic rocks. Collectively, BIFs have been suggested as a new potential source of natural hydrogen in the subsurface and should be targeted during exploration efforts (Geymond et al., 2022). Their presence was also noted at one of the deeper Bourakebougou reservoirs in Mali (Maiga et al., 2024a).

2.1.2 Radiolysis

The decay of radioactive elements such uranium (U), thorium (Th), and potassium (K) in rocks generates α, β, and γ radiation, which breaks apart the hydrogen-oxygen bonds in water and produces molecular hydrogen (H_2). Production of hydrogen via radiolysis requires relatively simple geochemical ingredients — water and radionuclides — that are common on (and within) the Earth. One of the factors affecting the rate of hydrogen generation through radiolysis is the concentration of radionuclides in the component rocks (Lin et al., 2005a). Granitic rocks contain orders of magnitude more thorium and uranium than mafic and ultramafic rocks (Table 1), making them the geochemical foci for the generation of radiolytic hydrogen. The α-particle produced through radiogenic decay is helium (^4He). Helium and hydrogen can thus co-occur in some systems, particularly those enriched in the radioactive elements, such as granites. In addition to granitic rocks, most shales rich in organic matter are also enriched in uranium, and have the potential to generate helium (Gluyas, 2024).

Radiation attenuates energy along its path, i.e. if radiation is emitted from a radionuclide farther from the water interface than the stopping distance then it does not contribute to water radiolysis (Dzaugis et al., 2016). The radiolysis yield will diminish with the slow decay of the radiogenic elements (Lin et al., 2005a) but will increase with higher porewater salinity (Bourdet et al., 2023).

Table 1. Global ranges of uranium and thorium content in common rocks (modified from Tye, 2017).

Igneous rock	Uranium (ppm)	Thorium (ppm)
Syenites and phonolites	0.1 to 26	0.7 to 35 [typically >10 ppm]
Granites, rhyolites	2 to 50	8 to 56
Basalts and other mafic rocks	0.1 to 1	0.1 to 4
Ultramafic rocks	0.001 to 1	<0.1

It must be noted that in any geological system, geochemical reactions are complex and commonly interrelated, and so the oxygen produced though radiolysis can change the system oxygen fugacity and initiate redox reactions (including oxidation of Fe^{2+}, reduction of H_2O, if present) in granitic rocks thus, producing hydrogen by two different methods in one rock body (Dubessy, 1988). Multiple sources for hydrogen have been shown in the Precambrian granites from South Australia, where radiolysis, hydrolysis of mafic minerals and low temperature alteration of magnetite were reported (Bourdet et al., 2023). Radiolytic hydrogen has also been reported in gases from Precambrian Shield groundwaters (Lin et al., 2005b, Lollar et al., 2014) as well as from evaporitic systems, notably in systems that contain potassium-bearing salts (Parnell and Blamey, 2017, Smetannikov, 2011). Trace amount of radiogenic hydrogen resulting from water irradiation associated with potassium decay has been detected in fluid inclusions from samples collected in the Boulby potash mine, Yorkshire, UK (Parnell and Blamey, 2017).

2.1.3 Other Sources

2.1.3.1 Degassing of deep-seated hydrogen from the Earth's core and mantle

Deep-seated hydrogen is regarded as that originating from the Earth's mantle and/or core and is not a result of crustal processes (for example, serpentinisation) (Williams and Hemley, 2001, Zgonnik, 2020). It has been hypothesized that during the Earth's accretion, primordial helium and hydrogen were trapped and stored in the planet's interior as helium and hydrogen solutions and compounds. Helium (high $^3He/^4He$ ratio) can be used as a tracer of mantle-derived input (Güleç et al., 2002, Ballentine et al., 2002).

2.1.3.2 VOLCANIC AND HYDROTHERMAL VENTS

Hydrogen is a common, albeit minor, constituent of volcanic gasses and, is emitted into the atmosphere from degassing of the underlying magma and other processes that might have led to fluid - rock interaction related generation (Klein et al., 2020, Cruikshank et al., 1973). In submarine settings, some hydrothermal vents (high temperature black smoker or low temperature white smokers) currently emit H_2 and hydrogen-bearing fluids, with the gas originating from magmatic degassing and/or the interaction of seawater with mantle-derived ultramafic rocks (Petersen et al., 2011, Hellevang, 2008, Charlou et al., 2000).

2.1.3.3 MECHANOCHEMICAL

Hydrogen can also be generated in active fault zones by mechanochemical breaking (cataclasis) of silicate minerals in the presence of water. Mechanical forces break up silicon-oxygen (Si - O) bonds in silicate minerals, creating radicals that can reduce water to produce hydrogen. In creeping (slow moving) faults, hydrogen may continually be generated, whereas in locked faults, generation is likely episodic and limited to slip events (Klein et al., 2020). Faults are major pathways for hydrothermal fluids, thus hydrogen generation in those settings can be due to a combination of all fluid–rock interaction processes, radiolysis, or mechanochemical formation (Klein et al., 2020).

2.1.3.4 COAL

The first detection of natural hydrogen in history was made by Dimitri Mendeleev who found that gas emerging from a fractured Ukrainian coal seam contained 5.8 - 7.5 per cent hydrogen (Mendeleev, 1888). In coal seams, hydrogen can be generated through the thermal decomposition (pyrolysis) of organic matter or the reaction of water with minerals within the coal (Boruah et al., 2024). However, most of the gas produced by these processes will be methane, rather than hydrogen. Significant concentrations of hydrogen have been detected in gas samples taken from coal mines (Boruah et al., 2024), but whether the hydrogen detected is sourced from coal, or comes from elsewhere and has migrated into the coal basin along faults, is unclear (Zgonnik, 2020).

Some types of coal have a higher hydrogen content than others and therefore, have a higher potential for producing natural hydrogen. Sapropelic coals have a relatively high hydrogen content but are volumetrically minor, local deposits that are thought to represent isolated lakes and channels within peatlands (Rippon et al., 2022). These kind of deposits were exploited locally in the UK during the Industrial Revolution as a source of kerosene or paraffin (Craig and Underhill, 2019), but their laterally restricted nature means that the location of these deposits is not well known in the UK.

Pyrolysis producing hydrogen is most likely to have occurred in seams that have been exposed to particularly high temperatures during their geological history, such as the anthracites occurring in South Wales (Bloxam and Owen, 1985). In fact, pyrolysis of coal has been proposed as the most likely explanation for the presence of hydrogen in the Songliao basin of China (Horsfield et al., 2022, Mahlstedt et al., 2022).

2.1.3.5 CO-PRODUCTION WITH GEOTHERMAL FLUIDS AND/OR LITHIUM.

The co-production of natural hydrogen with helium and/or geothermal power and lithium has been proposed (Gaucher, 2023). For example, the geothermal power plants in Iceland emit a total of 1.2 kt hydrogen per year into the atmosphere (Combaudon et al., 2022). Further techno-economic assessments are needed to understand the generation systems and co-production potential, and to overcome challenges related to the various solid - fluid states of the commodities considered.

2.2 MICROBIOLOGICAL SOURCES AND SINKS

Subsurface microbial communities have been shown to both use and produce hydrogen by various processes, which are often coupled tightly together (Gregory et al., 2019, Lodhia et al., 2024). The existence of hydrogen - utilising subsurface microbial communities and ecosystems hosted in various geological settings (Zgonnik, 2020) may reduce natural hydrogen stores under the right environmental conditions as microorganisms metabolise hydrogen (Gregory et al., 2019, Gregory et al., 2024).

2.2.1 Microbial Processes that Produce Hydrogen

Microbial communities within rocks and sediments can produce hydrogen through a variety of processes including fermentation, nitrogen fixation, anaerobic carbon monoxide oxidation and others (Gregory et al., 2019, Lodhia et al., 2024). Fermentation is usually inhibited by biotic hydrogen production but is balanced by the removal of hydrogen by other microbes, meaning biotic production and consumption of hydrogen are a tightly coupled process. Fermentation of organic material will be most relevant to subsurface environments where there is sufficient organic carbon. In other geological environments with limited organic carbon sources, hydrogen production by fermentation will be less significant (Gregory et al., 2019).

2.2.2 Microbial Processes that Consume Hydrogen

Numerous microbial communities use hydrogen as an energy source (Smith et al., 2005, Kumar et al., 2023). Microbial reactions represent an important sink (a process that absorbs hydrogen) in geological hydrogen migration pathways from depth to the surface and can make detecting hydrogen seeps at the surface challenging (Lodhia et al., 2024). Hydrogen seeps characterised by low hydrogen concentrations likely represent longer migration pathways where, hydrogen is lost due to microbial consumption and other processes. Detection of hydrogen at the surface is most likely at hyperalkaline seeps sourced by deep faults which allow faster hydrogen release, reducing the timescales for biogenic hydrogen consumption (Lodhia et al., 2024). Surface emanations in numerous countries called “fairy circles” are often associated with high hydrogen soil gas measurement (Mainson et al., 2022). The soil at these sites often has reduced fertility which affects the soil microbiota by decreasing the quantity and biomass of bacteria and fungi previously present (Polyanskaya et al., 2017, Polyanskaya et al., 2014).

2.2.3 Limits to Microbial Life

There are several factors influencing and limiting microbial activity. The accepted upper temperature limit to microbial life is 122°C, with some archaea shown to survive at this temperature. Subsurface microbial activity is considered generally possible at temperatures up to 90°C, particularly within hydrocarbon reservoirs; and 61°C within evaporitic repositories and environments with hypersaline groundwater (Gregory et al., 2019). There is concern that microbes could consume or spoil hydrogen stores in low-temperature hydrogen reservoirs and substantially impact yield (Osselin et al., 2022). The impact of the related physical property of pressure is poorly understood, with little to no information about pressure thresholds for microbial life (Lodhia et al., 2024).

In general, microbial life can be found in a pH range of 0 to about 12 (Dopffel et al., 2021), although neutral pH (between 6 and 7) corresponds to the greatest microbial abundance and diversity (Lodhia et al., 2024). Serpentinisation of ultramafic rocks produces challenging conditions for microbes by creating environments with high pH and low levels of electron acceptors, however, microbial communities have been shown to adapt and use hydrogen metabolism under such conditions (Twing et al., 2017). Sulphate-reducing activity has also been demonstrated in environments where serpentinisation is occurring (Gregory et al., 2019).

In evaporitic rocks and highly saline groundwaters, salinity has been documented to severely restrict most microbial activity, however, sulphate-reducing, halophiles or halotolerant microorganisms can be present in salt caverns with conditions that do not completely prevent the possibility of microbial hydrogen consuming activity (Dopffel et al., 2021, Gregory et al., 2024). Low porosity and permeability can also minimize microbial activity due to reduced pore space (Gregory et al., 2024). Changes in reservoir porosity and permeability may occur through the activity of precipitating microbes (such as Fe-reducers) which can further reduce the permeability of porous media (Muhammed et al., 2022).

2.3 SUBSURFACE MIGRATION

Once generated, hydrogen is expelled from the rock and if it is not trapped or metabolised by microbes, it will migrate through permeable rock formations in the Earth's subsurface. The pathways along which hydrogen migrates are a vital part of the hydrogen system, allowing hydrogen to move to shallower levels in the subsurface where it may be trapped by less permeable geological structures or formations. However, if the pathway reaches the surface without encountering such a trap, then hydrogen will be lost to the atmosphere. Since hydrogen is relatively miscible with water under high temperatures and pressures, migration can also occur in aqueous systems in the subsurface, exsolving to a gas phase at shallower depths (Jackson, 2024) as its partial pressure decreases. There are two main processes responsible for the transport of fluid, thus dissolved hydrogen, including diffusion and advection (Etiope, 2023, Lodhia et al., 2024, Lefeuvre et al., 2022).

(i) Diffusion in solution is a process of migration of molecules controlled by concentration and is also affected by solubility, porosity or temperature. Diffusion occurs mainly within seals and is also responsible for the exhalation of biologically - generated hydrogen.

(ii) Advection is a process driven by pressure gradient (advection in solution) or "buoyancy-driven flow", formed in different parts of reservoirs or faults zones.

The transport of fluids in the subsurface is multiscale and occurs either through interconnected pores or through a network of faults or fractures within the rock (Viswanathan et al., 2022). Fluid pathways can exist at the microscale (nanometres to microns), for example at the boundaries between mineral grains or along discontinuities within single mineral grains. It has also been suggested that porous sediments control the vertical hydrogen-bearing gas pathways toward the surface in the Waterberg Basin, Namibia (Roche et al., 2024).

New pathways can open in response to changes in pressure, tectonic activity and changes to the rock volume caused by mineral breakdown reactions — for example, serpentinisation of ultramafic rocks is known to be associated with volume change, as the initially anhydrous rock becomes hydrated.

This can lead to cracking that can aid the removal and migration of fluids, including products formed by the geochemical reaction–hydrogen-bearing fluids. Importantly, fractures are often filled in with the solid product of those geochemical reactions, including serpentine minerals, which narrow the fracture aperture, potentially limiting the fluid flow path surface.

Although fractures make up a very small portion of the subsurface volume, they are often the primary conduits that dominate flow and transport behaviour in subsurface environments and are required for both the input of water for water-rock interactions and the migration of hydrogen through the rock mass (Viswanathan et al., 2022, Jackson, 2024). Some of these pathways, in particular those of tectonic origin are large (kilometre) scale and include shear zones, faults or cooling joints. For example, the Bray fault in the Channel Tunnel (UK) has been proposed as a structural control for hydrogen distribution (Lefeuvre et al., 2024).

The transfer properties of fluid along faults can evolve over time and space (Frery et al., 2015) and are dependent on many parameters, including the internal architecture of the fault or surrounding lithology (Faulkner et al., 2010). Fault segments can become compartmentalised (and act as a reservoir, see 2.4), creating subsurface 'pockets' as interpreted in the Bulqizë chromite mine, Albania (ophiolitic source). Here, an elevated outgassing rate of hydrogen has been reported in recent years through a fault zone (about 10 m wide, with a length varying from 100 m to 1 km, and a maximum height of 5 km) that has been suggested to act as both the pathway and the gas reservoir (Truche 2024). In this specific setting, the configuration and properties of the seal remain uncertain, but the chromite ore body and the necking of the faults may play crucial roles (Truche 2024).

The identification of large-scale structural features is typically based on geological observations at surface and geophysical data at depth. However, relatively little is known about how these structures interact with hydrogen in the subsurface. In some cases, pathways may exist but are not open, as they are sealed by precipitated minerals (for example, quartz, calcite, clays), that will impede the ingress of water. Mineralised systems related to granites may be a useful high-level indicator of fluid movement in the crust, particularly along fractures and faults, for example in south-west England (Edmunds et al., 1989).

2.4 RESERVOIRS, TRAPS AND SEALS

A critical aspect for long-term accumulation of hydrogen in the subsurface is the presence of spatially and temporally relevant geological reservoirs, traps and seals that can accommodate hydrogen that has migrated from the source.

As in hydrocarbon systems, a reservoir is a porous and permeable rock formation where the free or dissolved gas can accumulate. However, reservoirs suitable for trapping or storing hydrocarbons are not necessarily conducive to trapping or storing hydrogen due to its different physical properties and behaviour. Hydrogen accumulation might occur in a variety of different geological systems, including porous sedimentary units (e.g. sandstones), other sedimentary or igneous systems that have been altered and now exhibit secondary porosity, or remain stored within the source due to volume changes (e.g. ophiolites).

In the Waterberg Basin, Damara Belt, Namibia, a series of sedimentary rocks is considered a potential reservoir for hydrogen accumulation (Roche et al., 2024). In the Paris Basin, hydrogen and nitrogen were detected in reservoirs composed of carbonate sedimentary rocks (Lefeuvre et al., 2024). Carbonate rocks are also reported to host natural hydrogen in Bourakebougou, Mali, where the reservoir has largely formed through dissolution of limestone upon interaction with igneous intrusions. Those intrusions have also served as an efficient seal, preventing upward gas migration and retaining hydrogen in the reservoir (Maiga et al., 2024a, Prinzhofer et al., 2018).

Low porosity and permeability barriers (seals) are crucial to preventing hydrogen leakage within the subsurface or to the surface (Maiga et al., 2024a). Evaporite (salt) seals have long been recognised as playing a key role in hydrocarbon systems, due to their low porosity and permeability, and their ability to flow (González-Esvertit et al., 2023) and so “heal” the rock to form effective seals. Indeed, Triassic age salt formations have been proposed as a promising trapping mechanism for hydrogen in the Mauléon Basin, in the northwestern Pyrénées, because of their sealing capability and relatively inert nature with respect to hydrogen (Lefeuvre et al., 2022). Other sedimentary rocks may also be able to effectively trap hydrogen and act as a seal (Roche et al., 2024, Truche et al., 2018) but limited data is available. It has been suggested that if a seal has been effective for hydrocarbons then it is likely to be effective for hydrogen (Salina Borello et al., 2024, Hosseini et al., 2022).

Igneous intrusions have also been reported to act as seals, particularly in the Bourakebougou field in Mali, they are relatively impermeable and having very low fracture density. Intrusions less than <20 m thick are reported to be less effective in trapping hydrogen, whilst those ranging between 20 m and 55 m in thickness appear to retain hydrogen more effectively (Maiga et al., 2024a). Similar intrusions were also reported as a potential barrier to the escape of hydrogen in the Waterberg Basin, Damara Belt, Namibia (Roche et al., 2024). Such large-scale igneous intrusions or similar rocks found within sedimentary rocks may be worth investigating in the context of natural hydrogen plays globally (Maiga 2024).

When combined, an effective reservoir/seal system can trap hydrogen at conditions where microbial activity, fluid-rock interaction and tectonic processes or, a combination of these factors, are minimal or balanced, leading to long-term accumulation and preservation (Maiga et al., 2024a, Roche et al., 2024, González-Esvertit et al., 2023, Lefeuvre et al., 2022, Truche et al., 2018).

2.5 TIMING AND PRESERVATION

Critical to any significant accumulation of hydrogen in the subsurface are:

(i) the timing of generation in relation to the existence of other key components of the hydrogen play-based exploration model (such as, migration, reservoir and trap) and,

(ii) preservation of both the hydrogen accumulation and the accommodating trapping mechanism, with several factors causing loss including seal failure, geochemical reactions and microbial growth.

Simply put, the generation of hydrogen must occur at the right time and in the right place where there are suitable reservoirs, traps and seals within the subsurface. For example, if the reservoir is a porous sedimentary rock, the hydrogen generation must occur after the deposition of both the trapping and sealing lithologies. In addition, the biotic and abiotic removal (chemical reactions and leaks) of the free or dissolved gas must be negligible to enable long-term preservation.

3 UK Geological Potential

Natural hydrogen generation is associated with several distinct rock types that have experienced suitable geological processes. The UK is host to several of these rock types, although as many are particularly old or have experienced an uncertain geological history, the potential for generation of natural hydrogen is generally not well understood. There are considerable uncertainties in migration pathways, trapping mechanisms and the role of microbes in metabolising hydrogen in the subsurface and the UK's potential for natural hydrogen.

Of importance to this study are the several phases of orogenic (mountain building) and rifting (pulling apart) processes that created the UK. They have given rise to a collage of geological terranes, where each is a fault bounded crustal block with a distinct geotectonic history. Over time, the terranes have amalgamated together to form the deep continental basement of the UK, with the oldest in the northwest, becoming younger to the east and southeast. They have been defined from multiple datasets and a variety of detailed field and rock sample studies. For more information on the geological history of the UK, please refer to the Appendix, Section 6.1.

3.1 METHODOLOGY

Exploration for natural hydrogen typically utilises a play-based model that evaluates key components of the system, such as source, reservoir, seal, and is in that sense similar to the exploration for hydrocarbons (see 2.4). This study has taken similar play-based exploration approach (documented in Figure 1) by undertaking a national scale, geological map-based assessment of the UK. The use or interpretation of subsurface data was outside the scope of this project but should be considered to further constrain the distribution of relevant geological units.

In the UK, the sources with the most potential for the generation of natural hydrogen are hydrothermally altered mafic and ultramafic rocks (e.g. **basalts, ophiolites**) and felsic rocks undergoing radioactive decay (e.g. **granites**) (see 2.1). These rocks are found at the UK surface but typically exist at depth in the subsurface. To better understand their distribution, this study has used the concept of geological terranes which subdivides the crust into segments (as discussed above and summarised in Figure 2). This is because the sources of interest are either formed when terranes collide or are formed at depth below the Earth's surface.

This study has used the terrane models of Beamish et al., (2016) and Molyneux et al., (Molyneux et al., 2023) which are based on geological history, major tectonic structures, stratigraphy and magnetic field data. It is important to emphasise that, whilst the terranes cover relatively large areas of the UK, it is likely that only a small percentage of these areas will have rock types suitable for hydrogen generation, migration or trapping.

Possible reservoirs and seals have been defined by the distribution of current onshore and offshore sedimentary basins that overlie terranes hosting potential natural hydrogen sources. The extents of sedimentary basins are recognised to change over geological time, therefore existing basins and the rocks within were used to define the potential ages and extents of reservoir and seal rocks overlying the terranes. The boundaries of offshore sedimentary basins and high level, regional descriptions of ages, type and depositional environments of the sediments within have been taken from data available from the North Sea Transition Authority (NSTA, 2019, NSTA, 2016) © 2017 Oil & Gas Authority (available under the Open Government Licence). Boundaries of onshore basins and high level, regional descriptions of ages, type and depositional environments of the sediments within are from Ireland et al., (2021) and based on British Geological Survey 1:50k Bedrock England, Scotland, Wales; 1:250k Bedrock Northern Ireland; 1:625k Fault data; British Geological Survey ©.

Given the scale of our evaluation and the complex geological history of the UK, several assumptions have been made. Each is an oversimplification and are an optimistic best-case scenario of the possible subsurface geology, and it should be noted that they require further investigation:

- That hydrogen generation started shortly after each terrane was accreted, as this was likely close to peak heat generation.
- That migration has occurred via any permeable conduit through which water is able to penetrate the subsurface. These will be on a range of scales from terrane bounding faults and shear zones, to fault and fracture systems, to stratigraphic boundaries and permeable rock units within the overlying basins. These pathways may not be continually permeable through time or space, and migration may be via several mechanisms.
- That there are a range of suitable trapping mechanisms (structural and stratigraphic traps) present in the overlying basins, that consist of a reservoir and seal rock to accumulate hydrogen, unless proven otherwise.

The timing and preservation of hydrogen accumulations is critical and the most difficult aspect of the assessment to quantify. It should be understood there is a significant amount of uncertainty due to the lack of published data on natural hydrogen systems within the UK. Without additional data, exploration or field testing to determine if there are true active hydrogen systems, the assessments presented in this study are likely to change based on the collection of new data and the greater understanding that future work will give.

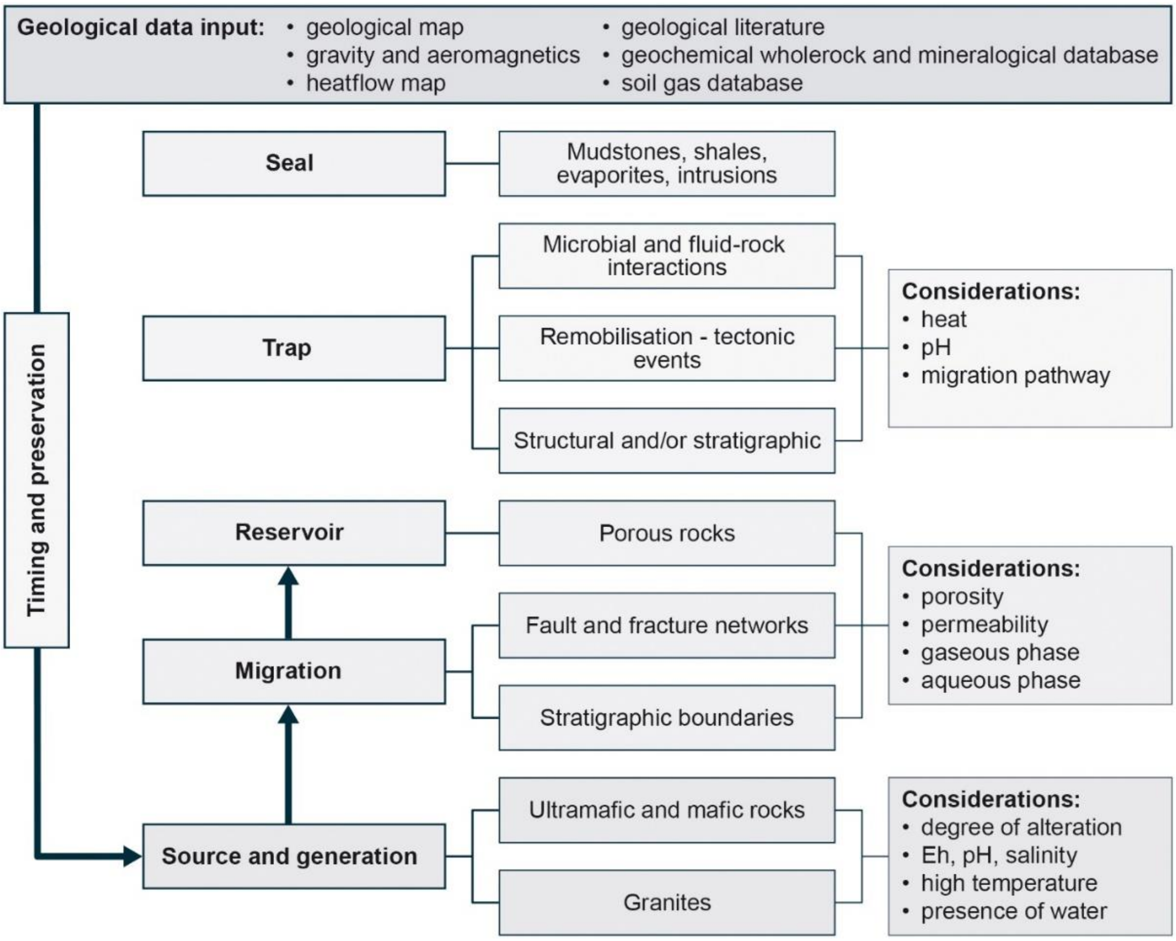


Figure 1. Flow diagram documenting the play-based exploration methodology used in this study to undertake the geological assessment of potential natural hydrogen of the UK. Geological data input is suggestive of datasets that should be used if available.

3.2 TERRANE DESCRIPTIONS

The following subsections summarise the geology of each terrane in turn, from north to south based on the methodology described in Section 3.1. Where possible, the geological information has been used to assess its potential for natural hydrogen using a play-based model.

3.2.1 Hebridean Terrane

Located in Northwest Scotland, the Hebridean Terrane is bounded to the south by the Moine Thrust (Figure 2). Potential sources within the terrane have been identified as Archaean to Paleoproterozoic gneissose basement (the Lewisian Complex), Paleoproterozoic mafic Scourie Dykes and Paleogene central vent complexes, plateau lavas, and intrusive complexes. Hydrogen may have been generated from the hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

The Hebridean Terrane is overlain by the major offshore sedimentary basins of the West of Shetlands and Rockall (Figure 2). These contain Upper Devonian to Paleogene sediments, deposited in aeolian, alluvial, fluvial, coastal, shallow and deep marine environments. Many of these are established reservoirs with good porosity and permeabilities, with documented hydrocarbon accumulations. Effective seals may be provided by Jurassic and Cretaceous mudstones, laterally extensive Palaeocene to Eocene intrusions, lava flows and tuffs. Hydrogen accumulations may also be stored in fracture networks within the gneissose basement.

Migration of hydrogen has been assumed to be through any permeable fault and fracture systems that penetrate deep into the crust, such as the rejuvenated Proterozoic Outer Isles Thrust. Generation of natural hydrogen was likely during the Archaean-Proterozoic when the terrane basement was amalgamated and intruded, and later in the Palaeogene during the North Atlantic Igneous Province (NAIP) regional volcanic event, when heat flow peaked. The terrane has been given a **potential grade**, based on the likely of mafic and ultramafic sources, with possible accumulations in both the gneissose basement and reservoirs within the overlying basins (Table 2). There are significant timing and preservation issues with generation in the Archaean-Proterozoic and trapping mechanisms in the Upper Devonian to Paleogene, but no timing or preservation issues with generation in the Palaeogene.

3.2.2 Northern Highlands Terrane

Southeast of the Hebridean Terrane is the Northern Highlands Terrane which trends north-eastwards from Mull to Shetland and is bounded by the Moine Thrust and the Great Glen/Walls Boundary faults (Figure 2). Possible sources within the terrane are likely to be the Archaean gneissose basement (Lewisian Complex) and extensive Palaeogene mafic intrusive systems. Hydrogen may have been generated from the hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

The overlying sedimentary basins include the West of Shetlands, Fair Isle and the East Shetland Platform Area (Figure 2). These are dominated by Upper Devonian to Paleogene sediments, deposited in aeolian, alluvial, fluvial, coastal, shallow and deep marine conditions. These reservoirs are known to have properties suitable to hold hydrocarbon accumulations and could similarly act as hydrogen reservoirs. Effective seals may be provided by Jurassic to Cretaceous mudstones and Palaeocene to Eocene intrusions, lava flows and tuffs. Hydrogen accumulations may also be stored in fracture networks within the gneissose basement.

Potential migration pathways may occur through the Moine Supergroup that overlies the Lewisian Complex via deep permeable fault and fracture systems. Generation of natural hydrogen may have occurred during the Neoproterozoic to Palaeozoic due to terrane collision, and Palaeogene during the NAIP regional volcanic event. The terrane has been given a **potential grade**, based on the likely availability of mafic and ultramafic sources, with possible accumulations in both the gneissose basement and reservoirs within the overlying basins (Table 2). There are significant timing and preservation issues with generation in the Neoproterozoic to Palaeozoic and later trapping mechanisms in the Upper Devonian to Paleogene, but no timing and preservation issues with generation in the Palaeogene.

3.2.3 Central Highlands (Grampian) Terrane

The Central Highlands Terrane is located across Central Scotland and part of Northern Ireland and is bounded by the Great Glen/Walls Boundary faults to the north and Highland Boundary/Fair Head-Clew Bay faults to the south (Figure 2). Potential sources within the terrane include significant Palaeozoic granitic intrusions that extend deep into and laterally within the crust. The Shetland Unst Ophiolite in the north which was obducted onto the Neoproterozoic to Early Palaeozoic metasediments of the Dalradian Supergroup during the Ordovician. Finally, the terrane has Palaeogene mafic intrusives and plateau lavas. Hydrogen may have been generated from the radiolysis of the granitic material and hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

The most important sedimentary basins are located offshore and include the Northern North Sea, East Shetland Platform and Moray Firth Area, Fair Isle, Forth Approaches, Rockall and Irish Sea (Figure 2). The basins are dominated by significant Devonian to Neogene sediments, deposited in aeolian, alluvial, fluvial, lacustrine, coastal, shallow and deep marine environments. Many of these have proven hydrocarbon reservoirs and could provide similar suitable hydrogen reservoirs. Effective seals may be provided by Late Permian evaporites, Upper Jurassic marine mudstones, and Palaeocene volcanic tuffs and marine mudstones. Hydrogen may also have accumulated in fracture networks within the ophiolitic rocks.

Migration of hydrogen is assumed to be through a range of permeable fault and fracture systems that penetrate deep into the crust. Generation of natural hydrogen may have occurred during the Neoproterozoic to Early Palaeozoic (including Ordovician) due to terrane collision and ophiolite obduction. The terrane has been given a **potential grade**, based on the likely availability of mafic and ultramafic sources, with possible accumulations in both the ophiolitic rocks and reservoirs within the overlying basins (Table 2). However, there are significant timing and preservation issues with generation in the Neoproterozoic to Palaeozoic and trapping mechanisms in the Devonian to Neogene.

3.2.4 Midland Valley Terrane

The Midland Valley Terrane encompasses the Central Belt of Scotland and part of Northern Ireland and is bounded by the Highland Boundary and Southern Uplands faults (Figure 2). It was formed from an Ordovician magmatic arc complex with potential sources that includes ophiolitic and volcanic material. The most notable of these are the Ballantrae Ophiolite Complex and its close analogue, the Tyrone Igneous Complex which indicates potential further ophiolitic material along strike of these complexes or at depth. Emplacement of mafic vents, intrusions and lava flows in the Carboniferous to Permian with the Clyde Plateau Volcanic Formation due to the Variscan orogeny to the south. Hydrogen may have been generated from the hydrolysis of iron-bearing minerals in the mafic and ultramafic material of the various ophiolitic and volcanic complexes.

The terrane is overlain by the offshore basins Northern North Sea, Forth Approaches, Irish Sea and Moray Firth basins and East Shetland Platform Area (Figure 2). These contain Devonian to Neogene sediments that were deposited in aeolian, alluvial, fluvial, lacustrine, coastal, shallow and deep marine environments and may prove to be suitable reservoirs. Effective seals may be provided by Late Permian evaporites, Upper Jurassic marine mudstones and Palaeocene volcanic tuffs and marine mudstones. Onshore, the Midland Valley Basin (Figure 2) contains Devonian to Carboniferous sediments deposited in alluvial, fluvial and coastal environments which may host suitable reservoir and seal units. Hydrogen may also have accumulated in fracture networks within the ophiolitic complexes.

Migration of hydrogen is assumed to be through a range of permeable fault and fracture systems that penetrate deep into the crust. Generation of natural hydrogen may have occurred during the Ordovician to Silurian and Carboniferous to Permian due to terrane collisions and orogenic processes. The terrane has been given a **potential grade**, based on the likely availability of mafic and ultramafic sources, with possible accumulations in both the ophiolitic complexes and reservoirs within the overlying basins (Table 2). However, there are significant timing and preservation issues with generation in the Ordovician to Silurian and Carboniferous to Permian and trapping mechanisms in the Devonian to Neogene.

3.2.5 Southern Uplands Terrane

The Southern Uplands Terrane underlies Northern Ireland and Southern Scotland and is bounded by the Southern Upland Fault and Iapetus Suture (Figure 2). The terrane consists of Mid Ordovician to Mid Silurian granite bodies intruding into oceanic sediments that formed an accretionary complex system related to the Ballantrae Ophiolite Complex. Later igneous activity includes the Carboniferous to Permian Clyde Plateau Volcanic Formation and limited Palaeogene mafic intrusions. Hydrogen may have been generated from the radiolysis of the granitic material and hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

The major sedimentary basins are located offshore in the Forth Approaches, Irish Sea, Central North Sea basins, and the Mid North Sea High Area (Figure 2). These contain Devonian to Neogene sediments deposited in aeolian, alluvial, fluvial, lacustrine, coastal, shallow and deep marine environments and may prove to be suitable reservoirs. Suitable seals may be provided by Late Permian evaporites, Upper Jurassic marine mudstones, Palaeocene volcanic tuffs and marine mudstones. Onshore, the Northumberland-Solway basin (Figure 2) hosts Devonian to Carboniferous sediments deposited in fluvial, deltaic and shallow marine environments and may also be suitable as reservoirs. Devonian and Permian igneous rocks, and Carboniferous mudstones could prove suitable seals.

Hydrogen may have migrated through the Iapetus Suture and other deeply penetrating fault and fracture systems. Generation of natural hydrogen may have occurred during the Mid-late Silurian and Carboniferous to Permian due to terrane collisions and orogenic processes. The terrane has been given a **limited potential grade**, based on the relatively limited availability of granitic, mafic and ultramafic sources, although reservoirs within the overlying basins existing (Table 2). There are also significant timing and preservation issues with generation in the Mid-late Silurian and Carboniferous to Permian and trapping mechanisms in the Devonian to Neogene.

3.2.6 Leinster-Lakeman Terrane

Situated underneath the Isle of Man and Northern England, the Leinster-Lakeman Terrane is bordered by the Iapetus Suture and the combined Wicklow/Dent Line/Stainmore faults (Figure 2). No Precambrian basement has been proven, with the Ordovician to Silurian marine sediments of the terrane intruded by granitic bodies during the Devonian and limited Palaeogene mafic igneous intrusions. Hydrogen may have been generated from the radiolysis of the granitic material and hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

Offshore the terrane is overlain by the Irish Sea, Southern North Sea and Cardigan basins and Mid North Sea Area (Figure 2) which consist of Carboniferous to Palaeocene sediments deposited in alluvial, fluvial, lacustrine, coastal, shallow and deep marine conditions, some of which have proven to be suitable reservoirs for hydrocarbons. Late Permian to Triassic evaporites, Jurassic marine mudstones or Palaeocene volcanic tuffs and marine mudstones may act as suitable seals. Onshore, the Northumberland Solway Basin (Figure 2) contains Devonian to Jurassic sediments deposited in aeolian, alluvial, fluvial, coastal, and shallow marine conditions, which could act as suitable reservoirs. Carboniferous to Jurassic lacustrine, estuarine, deltaic and marine mudstone, Late Permian to Triassic evaporites, and Late Carboniferous to Early Permian igneous intrusions, lava flows, and volcanic tuffs may act as suitable seals.

Migration may have occurred through deep permeable fault and fracture systems or the Iapetus Suture. Generation of natural hydrogen may have occurred during the Devonian due to terrane collisions and orogenic processes. The terrane has been given a **limited potential grade**, based on the relatively limited availability of granitic, mafic and ultramafic sources, despite reservoirs within overlying basins existing (Table 2). There are also significant timing and preservation issues with generation in Devonian and trapping mechanisms in the Carboniferous to Palaeocene.

3.2.7 Monian Terrane

The Monian Terrane underlies Anglesey, North Wales and Northern England (Figure 2). The northern boundary is defined by Wicklow Fault Zone / Dent Line / Stainmore Fault, while the southern boundary is defined by steep sheared structures termed the Menai Strait Fault / Pendle Lineament / Flamborough Head Fault zones. To the east, the boundary defined by Dowsing Fault Zone. The terrane is characterised by a Late Neoproterozoic basement with possible sources including the gabbroic rocks of the Sarn Igneous Complex and amphibolites and blueschists of the Anglesey Mona Complex. Hydrogen may be generated through the hydration of iron-bearing material of these sources.

Overlying the terrane are the Irish Sea and Cardigan Bay basins (Figure 2), which contain Carboniferous to Lower Cretaceous sediments deposited in alluvial, fluvial, lacustrine, coastal, shallow and deep marine environments, which may act as reservoirs. Late Permian to Triassic evaporites, Jurassic marine mudstones and Palaeocene volcanic tuffs and marine mudstones may act as effective seals. Onshore, the Cleveland Basin (Figure 2) contains Carboniferous to Cretaceous sediments deposited in alluvial, fluvial, deltaic, lacustrine, shallow and deep marine environments and may provide suitable reservoirs. Carboniferous to Jurassic deltaic, estuarine, lagoonal and marine mudstones, Permian to Triassic evaporites and Carboniferous igneous rocks may act as seals. Accumulations of hydrogen may exist in fracture networks within gabbroic, amphibolites and blueschists rocks that have formed the basement.

Migration of hydrogen is assumed to be through a range of deep permeable fault and fracture systems. Generation of natural hydrogen may have occurred during the Neoproterozoic due to terrane collisions. The terrane has been given a **potential grade**, based on the likely availability of mafic and ultramafic sources, with possible accumulations in both the basement rocks and reservoirs within the overlying basins (Table 2). However, there are significant timing and preservation issues with generation in the Neoproterozoic onwards and trapping mechanisms in the Carboniferous to Palaeocene.

3.2.8 Avalon Composite Terrane

The Avalon Composite Terrane underlies much of Wales, Central and Southern England and is defined by the offshore Dowsing Fault–South Hewett fault zones that separate it from the poorly known Southern North Sea Terrane (Figure 2). To the south, the terrane is bounded by the Variscan Front and/or Bristol Channel Fault Zone. The terrane is composed of four component Neoproterozoic subterranes: Cymru, Wrekin, Charnwood and Fenland, which may have amalgamated by the Late Neoproterozoic.

Remnants of Neoproterozoic calc-alkaline complexes are thought to represent a record of subduction-related arc magmatism, with gabbroic, dioritic, granodioritic and granitic rocks found in Southern Britain. Potential sources include the hydration of iron-bearing minerals within the Neoproterozoic volcanic and plutonic rocks. However, there is significant uncertainty and lack of data as to the precise composition and variation of the Neoproterozoic at depth.

Various well established and studied on and offshore basins exist within the Avalon Composite Terrane, including the Lancashire, Cheshire, Midlands Shelf, London, Severn, Bristol Channel, Somerset, Worcester, Weald and Wessex basins (Figure 2). These are composed of Devonian to Cretaceous, and in places Eocene, sediments deposited in aeolian, alluvial, fluvial, shallow and deep marine environments which may provide suitable reservoirs. Within these basins, Carboniferous and Jurassic deltaic muds, Triassic evaporites and Carboniferous igneous rocks may provide potential seals.

Migration of hydrogen is assumed to be through a range of deep permeable fault and fracture systems. Generation of natural hydrogen may have occurred during the Neoproterozoic due to multiple subterrane collisions. The terrane has been given a **limited potential grade**, based on the relatively limited availability of granitic, mafic and ultramafic sources, despite reservoirs within overlying basins existing (Table 2). There are also significant timing and preservation issues with generation in Neoproterozoic onwards and trapping mechanisms in the Devonian to Cretaceous.

3.2.9 North and South Cornubian terranes

The Cornubian Terrane underlies Southern England and forms part of the Variscan orogenic belt, a mountain range created during the Late Palaeozoic (Figure 2). The terrane is bounded by the Bristol Channel Fault Zone to the north, roughly corresponding to Variscan Front, and the Lizard-Dodman Thrust to the south. The terrane is thought to have originated peripheral to the Avalon Terrane and lacks exposed rocks older than Devonian with unconfirmed Precambrian basement. Intruding the Devonian–Carboniferous metasedimentary rocks of the terrane are the Permian-aged Cornubian Batholith, which extends from the Isle of Scilly to Dartmoor, constituting seven major exposed granitic plutons. Hydrogen may have been generated from the radiolysis of the granitic material of these sources.

Overlying the terrane are the offshore South-West Approaches and Anglo-Paris basins (Figure 2) which contain Permian to Neogene sediments deposited in aeolian, alluvial, fluvial, shallow and deep marine environments and that provide suitable reservoirs. Upper Permian to Triassic evaporites and mudstones, Upper Jurassic marine mudstones, and Palaeocene volcanic tuffs and marine mudstones may offer potential seals.

Migration of hydrogen is assumed to be through a range of deep permeable fault and fracture systems into overlying or adjacent basins. Generation of natural hydrogen may have occurred during the Neoproterozoic to Devonian due to terrane collisions and orogenic processes. The terrane has been given a **limited potential grade**, based on the relatively limited availability of mafic and ultramafic sources, despite the presence of significant amounts of granitic material and reservoirs within overlying basins existing (Table 2). There are also significant timing and preservation issues with generation in Neoproterozoic to Devonian and trapping mechanisms in the Permian to Neogene.

3.2.10 Normannian Terrane

The Normannian Terrane is located at the southernmost part of Britain, underlying the Lizard Peninsula and the Channel Islands (Figure 2). The terrane is bounded to the north by the Lizard-Dodman. The Lizard Peninsula is ophiolite complex that includes ultramafic and gabbroic rocks, with associated metagranitic and metasedimentary rocks which were obducted onto the Avalonian continental margin following the closure of the Rheic Ocean in the Devonian to Carboniferous. The Rheic Suture is thought to extend offshore along strike WSW-ENE into the Western Approaches and English Channel. Considering the exposure of the well-developed Lizard ophiolite along the Rheic Suture, other equivalent structures may exist along strike of the suture. Hydrogen may have been generated from the radiolysis of the granitic material and hydrolysis of iron-bearing minerals in the mafic and ultramafic material of these sources.

The offshore South-West Approaches and Anglo-Paris Basin (Figure 2) overlie the terrane and contain Permian to Neogene sediments deposited in aeolian, alluvial, fluvial, shallow and deep marine environments and may act as reservoirs. These basins also contain Triassic evaporites and mudstones, Upper Jurassic marine mudstones and Palaeocene volcanic tuffs and marine mudstones that could act as seals. Hydrogen accumulations may also be present in fracture networks within the ophiolitic complex.

Migration of hydrogen is assumed to be through the Rheic suture and a range of deep permeable fault and fracture systems. Generation of natural hydrogen may have occurred from Devonian onwards due to terrane collisions and orogenic processes. The terrane has been given a **potential grade**, based on the likely availability of granitic, mafic and ultramafic sources, with possible accumulations in both the ophiolitic complex and reservoirs within the overlying basins (Table 2). There are also significant timing and preservation issues with generation from Devonian onwards and trapping mechanisms in the Permian to Neogene.

3.2.11 Southern North Sea Terrane

The Southern North Sea Terrane is located on the east coast of the UK and is divided from the Leinster-Lakes and Avalon terranes by the Stainmore and Dowsing fault zones respectively (Figure 2). The pre-Silurian basement of the terrane is deeply buried by thick, post-Devonian sediments, however, the few boreholes that have intersected basement in the Mid-North Sea High produced Silurian-Devonian metamorphic ages. These suggest the area was part of the wider Caledonian Orogeny and could record the ‘soft collision’ of Avalonia with Baltica. Modelling of geophysical data has shown numerous deeply buried granites, likely associated with their onshore Late Silurian–Carboniferous equivalents. Hydrogen may be produced from hydration of iron bearing minerals and radiolysis of hydrogen at depth from buried granites. However, little is known about the lithological control, extent or composition at depth.

The overlying Southern North Sea Basin (Figure 2) contains thick Carboniferous to Neogene sediments that were deposited in aeolian, alluvial, fluvial, coastal, shallow and deep marine settings and may act as reservoirs. Late Permian to Triassic evaporites, Jurassic marine mudstones or Palaeocene volcanic tuffs and marine mudstones may act as suitable seas.

Migration of hydrogen is assumed to be through a range of deep permeable fault and fracture systems into overlying basin. The terrane has been given a **limited potential grade**, based on the unknown availability of mafic and ultramafic sources and that despite extensive good offshore reservoirs and seals which have been proven as part of a world class hydrocarbon system, they may not be effective for hydrogen (Table 2). Generation is estimated to be pre-Devonian which indicates a significant timing and preservation gap as overlying sedimentary reservoirs are much younger.

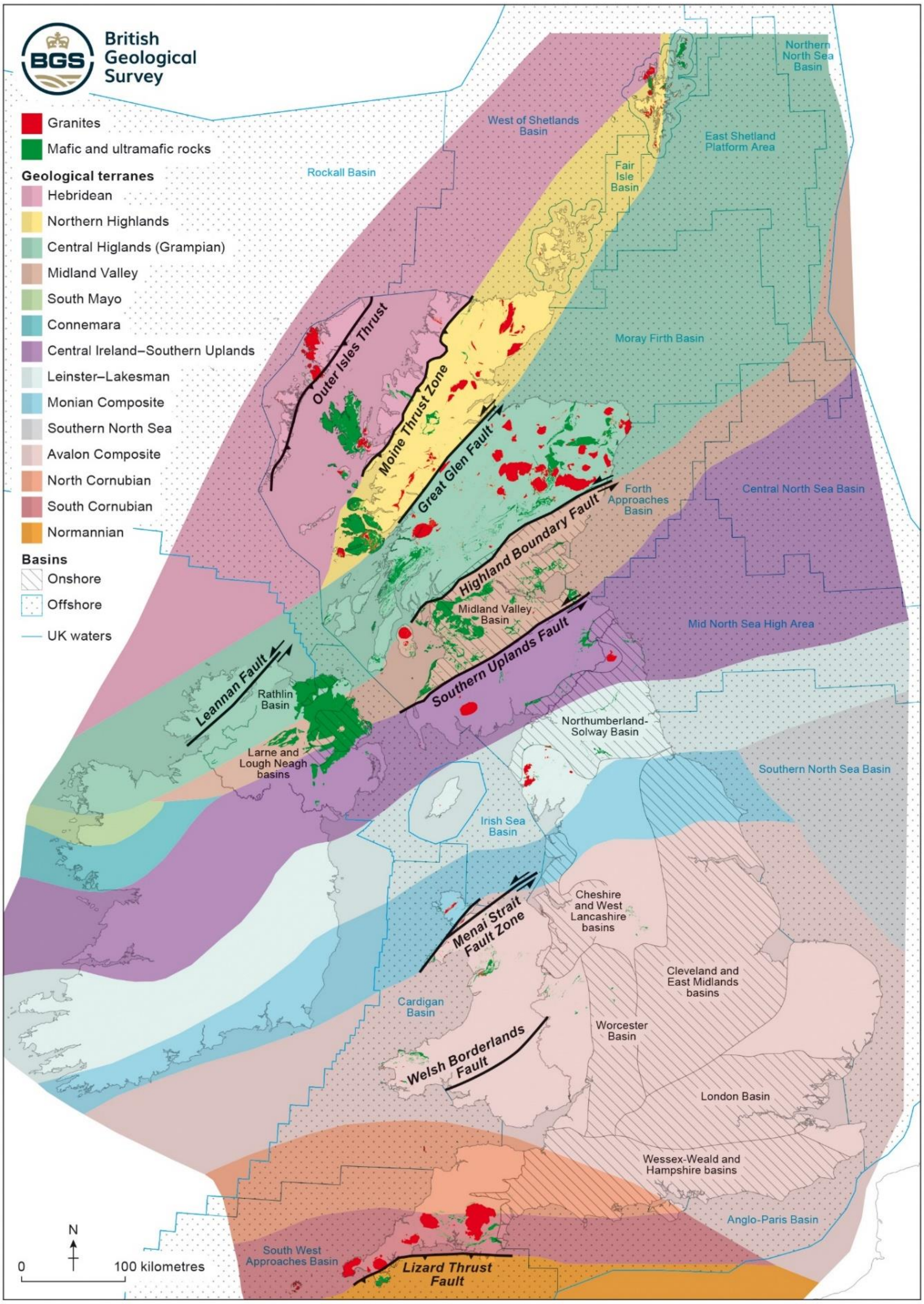


Figure 2. Summary map of geological terranes of the UK based on models of Beamish et al., (2016) and Molyneux et al., (2023). Onshore surface outcrops of potential sources of natural hydrogen, including granite, mafic and ultramafic rocks and their likely deeper subsurface extents, are shown in green and red. Boundaries of offshore sedimentary basins from the North Sea Transition Authority NSTA © 2017 Oil & Gas Authority (available under the Open Government Licence). Boundaries of onshore basin from Ireland et al., (2021) and based on British Geological Survey 1:50k Bedrock England, Scotland, Wales; 1:250k Bedrock Northern Ireland; 1:625k Fault data; British Geological Survey ©. All rights reserved.

3.3 NATURAL HYDROGEN ASSESSMENT

The results of the national scale assessment for potential natural hydrogen in the UK can be seen in Table 2 and Figure 3. There is potential for source, trapping and storage mechanisms distributed throughout the UK, although this is not uniform. Therefore, we have distinguished between two qualitative grades for each geological terrane of the UK: potential and limited potential.

- Areas given a '**potential**' grade are to highlight those that are more likely to contain natural hydrogen based on good source potential, reservoir, trap and seal availability, but may have timing and preservation issues. It does not confirm an area of natural hydrogen or that a location merits future exploration natural hydrogen or that a location merits future exploration, only that more detailed investigations are recommended.
- Areas given a '**limited potential**' grade are to indicate those less likely to contain natural hydrogen based on moderate to low source potential, reservoir, trap and seal availability, that will also have timing and preservation issues. These areas could yet prove to be of interest and should not be discounted without further investigations.

The crustal geology of the Scottish Hebridean, Northern Highlands, Central Highlands (Grampian) and Midland Valley Terranes, the Northern Wales / Northern England Monian Terrane and the Southern England Normannian Terrane suggest the potential for greater natural hydrogen sources although individual accumulations are expected to be spatially dispersed. Each terrane is overlain by a series of onshore and offshore basins but there is often a large time gap between potential generation and suitable reservoir and seals development. The consistent methodology for the appraisal of potential generation and preservation of accumulations is required to move forward and help with any economically viable exploration. It should be noted that the results presented here are based on *currently available data* used in this desk-based study and are subject to change as new data and research becomes available.

Table 2. Summary table of natural hydrogen potential for each geological terrane.

Terranes	Potential Sources	Possible Generation	Possible Storage	Grade
Hebridean Terrane	Gneissose basement, mafic volcanic rocks and intrusives	Archaean-Proterozoic? Paleogene	Upper Devonian to Paleogene	Potential
Northern Highlands Terrane	Gneissose basement and mafic intrusives	Neoproterozoic, Palaeozoic, Palaeogene	Upper Devonian to Paleogene	Potential
Central Highlands (Grampian) Terrane	Granitic and ophiolitic rocks, mafic volcanic rocks and intrusives	Neoproterozoic, Palaeozoic	Devonian to Neogene	Potential
Midland Valley Terrane	Ophiolitic rocks, mafic volcanic rocks and intrusions	Ordovician to Silurian, Carboniferous to Permian	Devonian to Neogene	Potential
Southern Uplands Terrane	Granite rocks, mafic volcanic rocks and intrusions	Mid-late Silurian? Carboniferous-Permian	Devonian to Neogene	Limited Potential
Leinster-Lakeman Terrane	Granite rocks, limited mafic intrusions	Devonian	Carboniferous to Palaeocene	Limited Potential
Monian Terrane	Gabbroic, amphibolites and blueschists rocks	Neoproterozoic onwards	Carboniferous to Palaeocene	Potential
Avalon Composite Terrane	Gabbroic, dioritic, granodioritic and granitic rocks	Neoproterozoic onwards?	Devonian to Cretaceous	Limited Potential
North and South Cornubian Terranes	Granite rocks	Neoproterozoic to Devonian?	Permian to Neogene	Limited Potential
Normannian Terrane	Ophiolitic, ultramafic and gabbroic rocks	Devonian onwards	Permian to Neogene	Potential
Southern North Sea Terrane	Granite rocks	Pre-Devonian?	Carboniferous to Neogene	Limited Potential

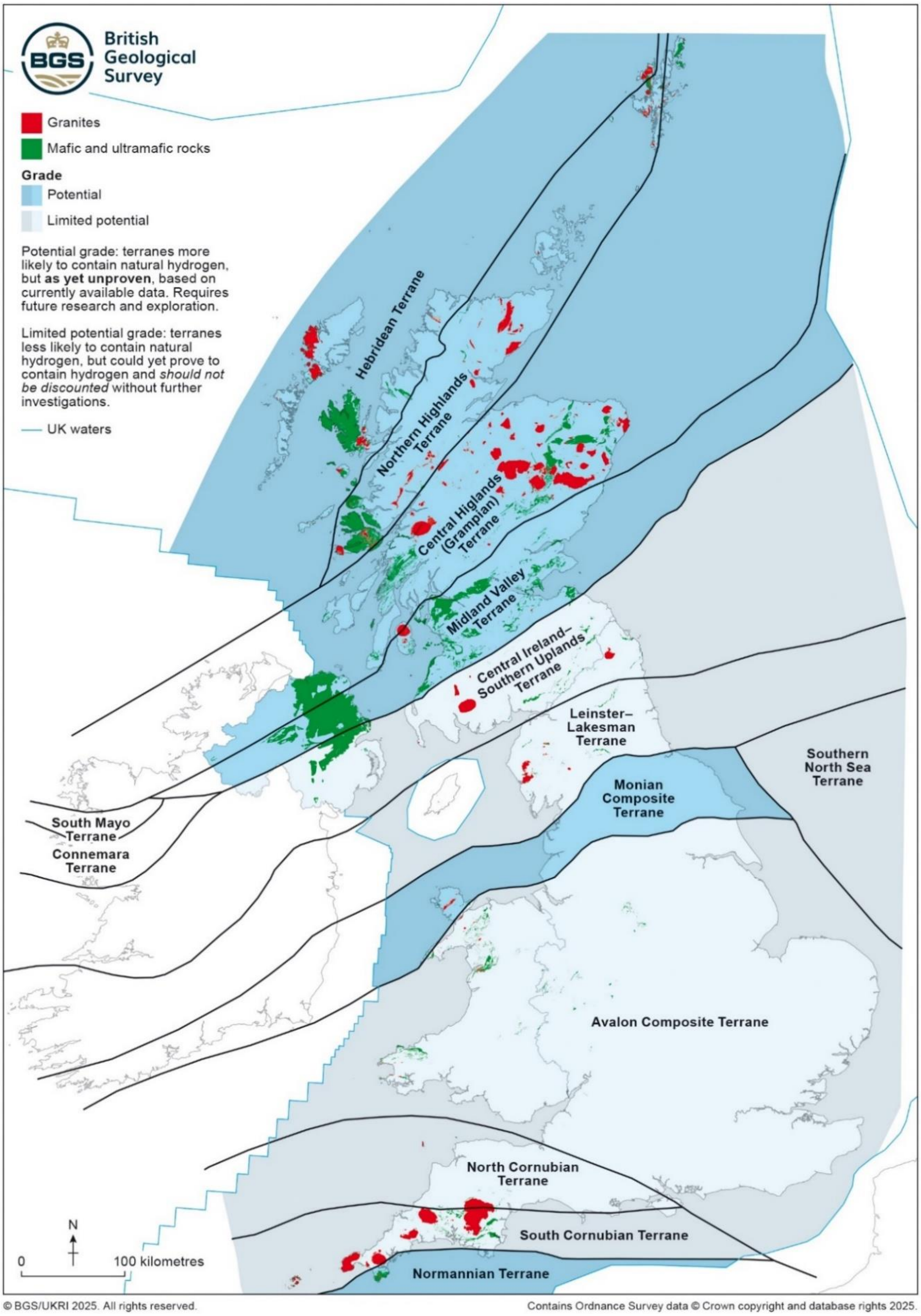


Figure 3. Summary map of the potential for natural hydrogen based on the distribution of geological terranes within the limits of UK waters. The presence of natural hydrogen **has not been established** within the UK and those areas highlighted as more likely to contain hydrogen are based on assumptions using currently available data. Terrane boundaries are based on models of Beamish et al., (2016) and Molyneux et al., (2023). Onshore surface outcrops of potential sources of natural hydrogen, including granite, mafic and ultramafic rocks and their likely deeper subsurface extents, are shown in green and red and are based on British Geological Survey 1:50k Bedrock England, Scotland, Wales; 1:250k Bedrock Northern Ireland; ©. All rights reserved.

4 Detection, Data and Proxies

Hydrogen can be found in at least three main forms: (i) as a dissolved gas, (ii) as a gas in inclusions, and (iii) as a free gas. Although, exploration is currently focussing on hydrogen in free gas form, the occurrences of other forms in geological systems are of interest for research and could also be used to identify areas where sources of hydrogen are present (Patonia, 2024).

Natural hydrogen exploration requires a data-driven approach that includes the re-assessment of legacy data (such as, geological, geophysical and geochemical) and collection of new data (such as, magnetic surveys or gas measurements in soils and over other seeps) to screen for prospective areas for hydrogen exploration in the subsurface. The former is suitable as a first assessment at larger (national / regional) scale and incurs considerably lower cost. The latter provides more certainty for the selected areas of focus but is notably more expensive as new drilling, sample collection and analysis are required. The data required can be divided into two main categories:

(i) direct evidence for hydrogen generated in the subsurface based on direct measurements

(ii) indirect evidence, inferred from the existence of natural hydrogen play components that could theoretically lead to the generation and accumulation of hydrogen in the subsurface

The direct evidence encompasses data from surface seeps and hydrogen measurements collected during soil-gas surveys, in mines or exploratory wells for hydrocarbon industry. It must be noted that some hydrogen detected in soils or during drilling can have an anthropogenic origin, for example, related to the corrosion of steel casing or drill-bit metamorphism, or mechano-radical generation due to drilling effects and Fe production/reduction.

Indirect evidence is an umbrella term used for all geological, geophysical and geochemical data that can be appraised or otherwise extrapolated in the context of theoretical and analogous systems globally. These include maps of subsurface lithology (source and reservoir targets) and maps architecture (faults and fractures as migration conduits); seismic reflection, magnetic, gravity and radiometric data, neutron porosity logs as well as satellite data showing sub-circular depressions that are often associated with changes in vegetation (SCDs or "fairy circles"). Despite an increasing number of exploratory activities globally, much of the indirect data was collected for purposes other than natural hydrogen exploration and is available through various databases (although not always open access). There is also data obtained by commercial exploration campaigns, but this is rarely in the public domain.

4.1 EXPLORATION METHODS

Identifying and locating natural hydrogen sources has been the topic of numerous studies over recent decades, more so in linking the observations from above the surface to our assumptions about the processes below the surface. Observation within the petroleum and mining industries have alluded to hydrogen being measured in their surveys but such occurrence and data have been poorly recorded. The discovery of hydrogen during prospect drilling in Mali at the Bourakebougou water well in 1987 highlighted that an in-depth understanding of the subsurface geology for this type of exploration was fundamental if we are to exploit this natural resource.

The discovery of submarine hydrothermal vents along the Galápagos spreading centre in the mid-1970s (Neal and Stanger, 1983; Charlou et al., 1996), and subsequent other locations with similar formations highlighted a potential source of hydrogen (Evans et al., 2013). These locations are oceanic in nature and are formed through protolith serpentinisation in the lithospheric mantle. Exploration is still in its infancy with most being at the conceptual stage due to their inaccessible settings (Hutchinson et al., 2024) , with others part of the offshore exploration surveys conducted by petroleum industries.

4.1.1 Direct Data

4.1.1.1 Soil Gas Analysis

Whilst soil-gas sampling has proven successful in detecting hydrogen in the soil, current understanding of hydrogen in the subsurface remains incomplete, with various potential sources of origin (Langhi and Strand, 2023).

Two main features commonly associated with natural seepages are semicircular depressions (SCDs) and fault zones (Langhi and Strand, 2023). SCDs have received significant attention in recent years, under the assumption that continued hydrogen transpiration observed in surface or shallow soil environments may indicate the presence of a larger hydrogen reservoir at depths via which concentrations in the soils are continuously recharged. However, the distribution of hydrogen associated with SCDs and other near surface occurrences requires a more in-depth understanding as the hydrogen may be derived from process of near-surface fermentation (with its proximity to wet-soil) rather than a geological degassing event observed in springs and soils in the absence of other geogenic gases (Etiope et al., 2024).

Elevated concentrations of hydrogen may also be linked to the presence of a basement-rooted fault zone (Dugamin et al., 2019). Gas analyses in geologically relevant areas and the detection of hydrogen concentration anomalies could provide further information of gas upwelling and any alignment to subsurface systems, for example, fault zones. Measurements of hydrogen should be in conjunction with other associated gasses such as CO_2 or CH_4, and more advanced analyses with the inclusion of isotopes and noble gases to characterise geogenic type-sources (Etiope, 2024).

Various techniques and instrumentation to measure the hydrogen concentrations at the surface and in the subsurface are available, including spot surface sampling (flux sensors) and interstitial soil-gas sampling (gas- probes or sensors), which show promising results. The classical approach to spot-surface soil-gas sampling with a portable gas analyser is to target depths between 80 and 120 cm (Frey et al., 2021, 2022; Moretti et al., 2021).

Other technologies, such as the use of continuous monitoring probes (semi-permeable membranes which allow gas flow and, in some instances, the elimination of water during the measuring process) are gaining ground (Prinzhofer et al., 2019). These probes are sited in-situ and are usually linked to other essential equipment such as Raman sensors. They can be worked remotely to allow continuous monitoring of the location. Many of these measuring techniques are used in conjunction with geochemical and geophysical data that complement the characterisation of potential hydrogen sources below the surface.

However, this type of data is somewhat challenging due to the lack of any long-term monitoring campaign that identify hydrogen sources and emissions (Langhi and Strand (2023). Langhi and Strand (2023) indicate that the deployment of spot surface and sampling measurements using portable soil probes and gas sensors (such as, multi-level gas sensors, flux sensors and Infrared instruments) remain one of the more practical and financially viable approaches for the early exploration of possible future hydrogen sites. Combining these approaches with additional long-term monitoring may be a way forward for future hydrogen exploration.

4.1.2 Indirect Data

4.1.2.1 Geophysical Data

Geophysical data relevant to hydrogen exploration includes gravity data, magnetic data, seismic refraction and reflection data. Such data have long been used during hydrocarbon and mineral exploration, with well-defined exploration methodologies, but there are no published criteria for natural hydrogen exploration to date. However, with geophysical data able to produce images of the subsurface, modifications could be made to utilise the data for locating potential hydrogen source and reservoir rocks (Zhang and Li, 2024). Studies using these geophysical methods, or multiple combined techniques, have been used successfully in the interpretation of potential subsurface hydrogen sources (Helios-aragon, 2025).

Gravity data reveals rock density variations, for example, serpentinised ultramafic rocks have strong negative gravity anomalies that may be identified in high-resolution gravity data. Magnetic data also reveals variations in the Earth's magnetic field due to changes in the chemistry or magnetism of the local rocks. The process of serpentinization of ultramafic rocks alters the iron bearing minerals and produces a magnetic anomaly that could be identified on high-resolution magnetic data (Dugamin et al., 2019). Making use of these combined datasets could highlight areas of potential natural hydrogen sources and derisk play-based analysis.

Deep seismic refraction data could be used to facilitate the depiction of metamorphic and basement sources and pre-existing crustal structures that could represent migration pathways. Seismic reflection surveys will likely focus on the overlying sedimentary basins. Use of such data has been successful in the South Nicholson Basin, Northern Territory, Australia to assess both mineral resource and hydrocarbon potential. Boreham et al. (2021) and Geoscience Australia used deep-crustal seismic reflection data to link two Paleoproterozoic provinces and stratigraphy to regions with key rock units, with analysis still to be performed on the recovered gas and gas released from fluid inclusions that have had potential sources explored.

Frery et al, (2021) used both multiphysics imaging and seismic reflection data on SCDs between Moora and Pingarrega in an area of the Dandaragan Trough (an area known for deep serpentinisation of ultramafic rocks and Fe oxidisation of Archaean rocks and mafic dykes) in the North Perth Basin, Western Australia. Combining this data with 79 onsite soil-gas measurements using a GA 5000 analyser coupled with an 80 cm inox tube revealed localised hydrogen concentrations persistent in the external ring of outer SCDs and may focus exploration targets, which could lead to the identification of potential hydrogen sources.

Combined geochemical mapping (archived near-subsurface data files), geophysical data and imagery was also used to assess potential natural hydrogen sources in Quebec (Séjourné et al., 2024). Data was further interpreted using systemic rating method to reduce potential risk of higher costs in exploration effort and enable the identification of locations of potential sources to develop the resource (Séjourné et al., 2024). The application of the rating system and use of this type of data and processes could enable potential source rocks to be identified in the UK.

4.1.2.2 Petrophysical Data

Whilst there are no defined petrophysical log responses, Maiga et al., (2023) reports that the neutron porosity log tool reacted strongly to the presence of natural hydrogen in Bourakebougou, Mali. This subsurface tool is used to estimate porosity by emitting neutrons from a radioactive source; the neutrons collide with hydrogen nuclei in the fluid-filled spaces within the rock and slow down. Due to the presence of additional natural hydrogen, very high porosity values can be recorded.

Other authors have suggested that reengineering mud gas logs which are conducted during the drilling of boreholes could be used to identify natural hydrogen (Strapoc et al., 2022).

Alternatively, the properties of main lithological sources of natural hydrogen could be used to identify areas of interest. For example, serpentinisation of mafic and ultramafic rocks causes a reduction in density (from 3.3 to 2.5 g/cm3), which is typically coupled with a low gamma log values and relatively fast sonic log values (Skelton et al., 2005).

4.1.2.3 Satellite Imagery Data

Satellite imagery can provide information on the distribution of SCDs that have been commonly associated with subsurface accumulations of hydrogen (Zgonnik 2020) and related changes in vegetation (Moretti et al., 2022). These structures are thought to be related to faults that access the deep subsurface and may intersect crystalline basement (Larin et al. 2015). The improvement of the free-access satellite images, such as Google Earth Pro, allows easy mapping of the SCDs (Moretti et al., 2021). In 2019, the European Space Agency (ESA) supported a research project called Sentinel Data for the Detection of Naturally Occurring Hydrogen Emanations (sen4H_2) that aimed to evaluate the contribution of satellite images to the detection and qualification of natural hydrogen emanations on the Earth's surface. Moretti et al. (2022) used satellite imagery data (Landsat multispectral images) and a Digital Elevation Model (DEM) for topography provided by the ESA in locations of known hydrogen seeps to differentiate potential hydrogen emitting sources from other depressions. The DEM is based on the radar satellite data acquired during the TanDEM-X Mission between 2010 and 2015.

4.1.2.4 Legacy Data

The use of historical, or legacy data acquired for exploration programmes other than hydrogen can potentially be useful in identifying hydrogen 'hot spots' but this type of data requires careful evaluation. Data from these records is usually generated from the myriads of globally drilled wells and reservoirs from the extensive exploration of oil and natural gas by the petroleum industry (Gaucher, 2020). Historically, the geochemical data captured from these reports was predominantly hydrocarbons data, for example methane with less emphasis on other gases such as hydrogen. This is due in part to the sensors deployed and the instrument calibration used. Nevertheless, the data from these legacy reports may contain information that could be utilised in ascertaining areas for future hydrogen exploration (Lefeuvre et al., 2024).

Unfortunately, data of this type and age is usually found in formats that are not easily searchable, such as scanned documents, various image formats and PDF images, with it requiring significant time to physically read and record the data in a more usable format. However, Lefeuvre et al. (2024) reports effectively converting legacy PDF imaged documentation from a database into a more accessible and readable formats using optical character recognition (OCR) technology. Applying the OCR technology to their extensive public well database and end of drilling reports, they successfully 'read' and analysed documentation previously thought unusable to identify hydrogen occurrences in wells in the Paris Basin.

4.2 REVIEW OF UK DATA

At the timing of writing, there is no centralised database or a research programme specific to natural hydrogen prospectivity in the UK. There might however be isolated initiatives and interest from research and industry, and it is expected that the next few years will show an increase in publications and relevant data.

Currently, the UK data that *might be relevant* to natural hydrogen exploration remains hidden across varied databases held by public bodies (including BGS, the North Sea Transition Authority (NSTA) and the Mining Remediation Authority (MRA)) and other organisations, as well as in peer-reviewed publications and other reports, some of which are commercially confidential.

Sections 4.2.1. and 4.2.2. are a high-level overview of data that might be an asset to the assessment of natural hydrogen play systems in the UK. However, our understanding on the relevance of this data is limited and requires a concerted effort from industry, academia and other public bodies to identify, quality-assess, categorise and analyse all datasets for more effective and efficient evaluation of the UK's potential for natural hydrogen.

Combining evidence from multiple datasets can enable more efficient and effective natural hydrogen system targeting. This can reduce the time and cost of the initial stages of prospecting and ultimately lead to a lower risk of exploration.

4.2.1 UK Direct Data

Some of the first notifications of hydrogen data in the UK context come from the early 20th century. Greenwell and Elsden (1907) reports levels of stoichiometric hydrogen (in water and other compounds, not free molecular gas) in coal and coke between 1.6 and 5.5 per cent. A more recent study on the evaluation of hydrogen storage potential in the Cousland gas fields in the Midland Valley of Scotland does not report any hydrogen concentrations (Butler and Underhill, 2024, Heinemann et al., 2021 and references therein).

There are also reports from soil - gas surveys conducted in the UK that are held by public sector organisations such as the BGS. The data contained in the reports suggests that hydrogen was measured at more than 10 ppm (less than 8 per cent of the total 252 data points surveyed) with approximately 4 per cent of the data indicating hydrogen concentration at more than 25 ppm level. For comparison, examples reported globally suggest hydrogen at 20 to 3400 ppm (Oman, Zgonnik et al., 2019); 210 to 3700 ppm (USA, Zgonnik et al., 2015); 6 to 8000 ppm (Russia, Zgonnik et al., 2018); 221 to 541 ppm (Brazil, Prinzhofer et al., 2019).

These levels of hydrogen, measured at the surface and within the shallow subsurface would not necessarily indicate a deeper reservoir source and some caution is needed as the location of the measurements coincides with coal mining areas and could be a result of anthropogenic sources such as metal corrosion below the subsurface. One BGS report associated with the site selection and environmental monitoring for shale-gas exploration in the Vale of Pickering (Yorkshire) and Fylde (Lancashire) shows climatological baseline data for a 12 - months period (2014 to 2015), where both methane and carbon dioxide were monitored. This was expanded in November 2015 to include remote air quality monitoring of nitrogen oxides and others, with point measurements of soil gas using a portable GA5000 gas analyser to include hydrogen and radon but the data remains confidential.

In summary, besides the sporadic mentions of hydrogen measurements mentioned above, the UK lacks contextualised regional-scale hydrogen data that could be used as part of the prospectivity analysis.

4.2.2 UK Indirect Data

4.2.2.1 National Geoscience Data Centre

National Geoscience Data Centre (NGDC), hosted by BGS maintains databases of geoscience information on UK onshore and offshore drill-cores and as well as samples from a wide range of projects going back nearly 200 years.

The databases also hold digital lithological descriptions, geophysical, geochemical and mineralogical analyses, as well as near-surface gas data. Some of this data is available open access under the Open Government Licence through BGS's data portals, such as, GeoIndex (https://mapapps2.bgs.ac.uk/geoindex/home.html). Most of the data that is openly available falls under the *indirect data* category and has not been assessed in terms of potential use for natural hydrogen exploration to date (mainly due to it being a relatively new research area and lack of funding). Of specific importance to hydrogen prospectivity are the gravity and magnetic anomalies, structural/tectonic context and the various lithologies that form the components of natural hydrogen plays (Truche and Bazarkina, 2019), besides the evidence of any gas shows.

Geophysical Data

The GeoIndex holds UK aeromagnetic data from the 1960's, and gravity survey data acquired by other organisations, as well as more modern geophysical surveys using low-flying aircraft undertaken for the Tellus Programmes. These are available under the Tellus Data Viewer for Ireland and Tellus South West (https://www.tellusgb.ac.uk/) for Cornwall and some areas in Devon (Tellus, 2013). The Tellus programmes also collected radiometric datasets, available via the same portals.

Lithological Data

There is a vast sample collection held in the National Geological Repository, hosted by BGS, containing rock core and other bedrock material that can be used for laboratory analysis to help understand geological processes associated with hydrogen production, transport and accumulation. Currently, the lithological information is held as part of borehole interpretations as well as in the petrographic descriptions of rock thin sections and embedded in geological map data, with only a proportion of the whole dataset in the public domain.

This dataset also contains materials from the BGS Mineral Reconnaissance Programme which ended in 1997, with geological, geochemical, geophysical, mineralogical and metallogenic information on prospective areas in Great Britain. Some of those areas prospective for minerals coincide with potential source rocks for natural hydrogen and should be re-assessed in that context.

Other datasets held by the BGS

The NGDC is also a repository of data held on behalf of other UK organisations, including the North Sea Transitory Authority (NSTA, formerly the Oil & Gas Authority, formerly the Department of Energy and Climate Change), the Mining Remediation Authority (previously the Coal Authority), and the Geothermal Energy program (Busby, 2010). As such, it might include datasets relevant to the understanding of natural hydrogen plays. Amongst that data, are records from onshore and offshore wells provided to BGS for oil and gas exploration and appraisal wells drilled in the UK and held on behalf of the NSTA. For example, the open access dataset for the UK Continental Shelf offshore hydrocarbon materials contains approximately 12700 wells, including over 300 km of drill-core and 4.5 million samples of cuttings. The onshore dataset contains just over 2100 wells, with approximately 800 having associated samples (Table 3). The relevance of any of this data to natural hydrogen exploration is currently unknown.

Table 3. UK offshore and onshore hydrocarbon wells held by the NGDC.

Hydrocarbon wells (BGS GeoIndex)	Total	Offshore with drill core, bulk samples, cuttings
Offshore	12701	9450
Onshore	2128	809

Vast amount of historical data sets is stored in NGDC as PDFs or scanned images (e.g. historical drilling data for a variety of programmes, including onshore UK hydrocarbon well logs, reports, downhole data). OCR technology and specific keywords (e.g. H_2 or hydrogen) has great potential to streamline data mining and analysis, should natural hydrogen become a subject of UK exploration.

4.2.2.2 UK National Data Repository

The UK National Data Repository (NDR, https://ndr.nstauthority.co.uk/) is a component of NSTA's wider Digital Energy Platform. It holds a vast publicly available database of reports and reviews on offshore current and legacy petroleum projects, and more recently carbon capture and hydrogen storage projects. Data includes geophysical surveys, borehole data, description of hydrocarbon play components, with geological maps and cross sections, information on migration, seal, traps, visualisation of hydrocarbon play components or the assessment of play success and failures. Importantly, some of the review reports also contain interpretation of pitfalls, and as such, the NDR could collectively serve as a knowledge platform to springboard our understanding of natural hydrogen play-systems in the UK. Although, the physical properties of hydrogen are different from those of hydrocarbons, there is a significant amount of knowledge in the hydrocarbon industry that the natural hydrogen exploration efforts could tap into.

4.2.2.3 UK Onshore Geophysical Library

The UK Onshore Geophysical Library (UKOGL, https://ukogl.org.uk/) works with the NSTA to operate as a registered charity with the long-term objective of secure archival storage and open access to onshore geophysical data. It is the archive for all available UK seismic surveys and other technical data that records onshore petroleum projects. Data includes geophysical surveys, borehole data, industry reports, geological maps and cross sections, and supplementary imagery, reports, maps and information. Just as the NDR could provide a repository for offshore knowledge, the UKOGL could provide a wealth of onshore information for natural hydrogen exploration.

4.2.2.4 Mining and Remediation Authority

Information from personal communication with M. C. Daly, Department of Earth Sciences, Oxford University, 2024.

The MRA has no on-going activity related to natural hydrogen potential of the UK. It does, however, have two interfaces with hydrogen that could contribute significantly to the understanding of hydrogen's presence and distribution in the UK through its activities in Mine Water Heat and Gas Leakage Monitoring for Public Safety.

The enquiry into Mine Water Heating is a relatively new initiative and reflects the increasing interest in geothermal energy throughout the UK. The Gas Leakage and Safety Monitoring adopts a risk-based approach to the long-established practice of monitoring gas leaks. The activity covers over 1700 active monitoring points which are in the interest of public safety and mine waste integrity. These activities are important as approximately 20 per cent of the UK is underlain by Carboniferous rocks that may have associated coal, and one in four UK houses sit above known coal deposits. Whilst neither the Mine Water Heating work or the Gas Leakage Monitoring have addressed the presence of natural hydrogen systematically, both could reveal much about the UK's hydrogen potential, and a way to quantify it. Together they represent an opportunity to assess the organic part of the UK's hydrogen potential.

Given the outline of MRA context, there are two immediate lines of investigation possible to create a more systematic understanding of the UK's natural hydrogen resources and their potential; (i) monitored water and gas analysis using existing tools and methods (such as, pressurised samplers to collect water and gas at depth, portable and lab-based gas analysers with electrochemical cells, gas chromatographers and mass spectrometers, amongst others) and (ii) a review of the historic gas database that MRA holds. Besides the 1700 sites currently monitored for water and gas, there are up to 300 more sites that exist and could be sampled. The sites comprise old mine shafts, boreholes, riverbeds and other surface-gas leakage points. Testing these sites would bring a completely new, evidence-based perspective to the UK's potential hydrogen resource base. These two lines of hydrogen enquiry are potential early steps if the UK takes an interest in understanding its hydrogen resource base.

4.2.2.5 Other data in public domain

UK Satellite Imagery

UK satellite imagery is available from Landsat (the US constellation managed by USGS) and Sentinel-2 (managed by the European Space Agency, ESA), and can be accessed openly via the Earth Observation Browser portal (https://apps.sentinel-hub.com/eo-browser/). This data set could be assessed in the context of hydrogen seeps and SCDs.

Natural hydrogen source rock specific data

There is a notable amount of geological data in the public domain collected over the years for different purposes, including mineral exploration data (for example, exploration consultancy organisations), the UK geothermal energy assessment, and research to understand the tectonic regime and geodynamic systems of the UK. This data is available through open access peer-reviewed literature and other reports.

None of this data was collected or interpreted in the context of potential natural hydrogen generation but it could provide relevant information on rock composition, fluid/rock interaction and the timing of the main alteration events (including serpentinisation), collectively aiding data-driven assessments of hydrogen potential. It must be noted that what is available in the public domain is generally related to surface samples, which might not reflect the rock composition at depth relevant for hydrogen generation and accumulation.

There are granitic bodies in the UK where the necessary requirements for hydrogen generation via hydrolysis or radiolysis could be met, including those in the Cornubian terranes in south-west England, the Central Highlands (Grampian) Terrane in north-east Scotland, and the Weardale Granite in the Leinster–Lakeman Terrane in northern England. The Central Highlands Terrain, Midland Valley Terrain or Normannian Terrain also contain a variety of ultramafic and mafic rocks that might have contributed to the generation of hydrogen through hydrolysis.

The public domain holds data on mineralogy, degree of alteration of both granitic and ultramafic systems (including serpentinisation), magnetic anomalies or heat flow. These datasets are collectively important to evaluate the likelihood for hydrogen generation in the subsurface. However, to date, there has been no systematic assessment of such data in the context of hydrogen generation in the UK subsurface. It must be noted that:

- most of mineralogical data originates from outcrop samples and might not be fully representative of subsurface lithologies.
- magnetic anomaly measurement (in nanotesla units, nT) can be used as an indicator for the presence of magnetite in the subsurface. This is particularly relevant to ultramafic rocks, as magnetite is a product of serpentinisation and, thus is strongly correlated with the system's potential for generation of natural hydrogen via hydrolysis. However, (i) there are other mineral-hosts of oxidised iron (Section 2.1.1) and (ii) subsequent hydrothermal alteration of serpentinites can lead to a substantial reduction of magnetite concentration (Hodel et al 2017). Both aspects can lower the magnetic susceptibility of the rock, which can lead to a potential false negative in terms of the magnetite/serpentinisation/hydrogen generation relationship.
- the rate of fluid-rock interactions increases at higher temperature; hence the subsurface heat flow can be used as one of potential indicator of regions where, hydrolysis might have been more effective. However, when put into geological timescale of hydrogen generation and accumulation, more rapid reactions are not always desired, especially where suitable reservoir rocks and seals are not present during hydrogen production.

5 Summary

Natural hydrogen has seen a recent increase in interest as a potential primary low-carbon energy source. It is produced by fluid-rock interactions in the subsurface, when optimal geological parameters are met, and is reported to accumulate in commercially viable volumes for example, Bourakebougou, Mali (Prinzhofer et al., 2018). To understand how natural hydrogen is created, transported and stored in the subsurface, it is important to identify and understand each of the contributing elements. For this, a 'play-based' exploration model, similar to that of natural hydrocarbon systems, is typically applied (Boreham et al., 2021, Jackson, 2024). This is an integrated evaluation of each component of the complex, interconnected geological system and encompasses natural hydrogen sources, migration pathways, reservoirs and seals.

This report presents the first UK geological [1]prospectivity analysis for the potential of natural hydrogen in the subsurface, based on the integration of basic components of natural hydrogen play with the UK geology.

5.1 KEY FINDINGS

5.1.1 UK Geological Potential

This assessment of the UK using a combination of the underlying geological terranes and overlying sedimentary basins has indicated that there is significant potential for source, trapping and storage mechanisms of natural hydrogen (Table 2 and Figure 3). However, this is not uniform across the UK and there are several unanswered questions regarding generation, timing and preservation of hydrogen and any current accumulations.

To identify areas that may represent more attractive targets for future investigation and research, but by no means confirming that an area contains natural hydrogen, a qualitative grade of "potential" has been given (Table 2). This is opposed to a "limited potential" grade, which indicates areas that are less likely to contain natural hydrogen (Table 2), yet these could prove to be of interest and should not be discounted without further investigations.

The crustal geology of the Hebridean, Northern Highlands, Central Highlands (Grampian), Midland Valley, Monian and Normannian terranes suggests the potential for greater natural hydrogen sources, although individual accumulations are expected to be spatially dispersed. Each terrane is overlain by a series of on- and offshore basins, but there is often a large time gap between potential generation and suitable reservoir and seal development. A consistent methodology for the appraisal of potential generation and preservation of accumulations is required to move forward and help with any economically viable exploration.

It should be noted that the results presented in this study are based on **currently available** data and will be subject to change as new data and research become available.

5.1.2 UK Data

Collection of new hydrogen data was outside the scope of this project.

There is currently no evidence in the literature to suggest the existence of UK hydrogen seeps, or any significant accumulations noted from past drilling programmes. There are some sporadic statements of several tens of parts per million of hydrogen from few places across the UK. This information is currently held in unpublished soil - gas reports kept by public sector organisations such as the BGS. It must be noted that these surveys have not been targeted or designed specifically to identify natural hydrogen accumulations. The context of this data needs further understanding and verification.

The UK data that might be relevant to natural hydrogen exploration is highly fragmented and not collected or indeed interpreted in the context of natural hydrogen play. It remains hidden across

[1] Hydrogen prospectivity - theoretical possibility or likelihood that hydrogen exist in an area because the geology of this area is permissive or favourable to the formation of hydrogen system

varied databases held by public bodies (such as the BGS, NSTA, MRA and NDR) and other organisations, as well in the public domain as peer-reviewed publications and other reports. There is vast amount of data and knowledge from past minerals and hydrocarbons exploration programmes, collectively forming a potential asset for the assessment of natural hydrogen play systems in the UK. Our understanding of the relevance of this data and knowledge is limited and requires a concerted effort from industry, academia and other public bodies to identify, quality-assess, categorise and analyse all datasets for more effective and efficient evaluation of UK's potential for natural hydrogen.

Natural hydrogen exploration requires a data-driven approach that includes the collection of new data and the re-assessment of legacy geological, geophysical and geochemical data to screen for areas prospective for hydrogen in the subsurface. Re-assessment allows a focus on exploration targets at a considerably lower cost (in terms of both finance and time) than new drilling and sample collection with little prior knowledge of regional potential. Experience and knowledge gained from reviewing existing UK direct and indirect data can be used to design future exploration strategies and set research and innovation priorities.

5.2 RECOMMENDATIONS

In undertaking this study, several significant knowledge gaps have been identified, limiting data-driven screening for hydrogen in the UK subsurface. These recommendations have the potential to fill the knowledge gaps and incentivise UK policymakers, academia and industry to undertake further exploration to gain better understanding of the UK's potential for natural hydrogen. In addition, terranes given a 'potential' grade may serve as geographical areas of interest for some of the recommendations.

5.2.1 Appraisal of Legacy Data

An appraisal of all relevant legacy datasets (for example by using OCR technology on historical drilling data for a variety of programmes, including well logs, reports, downhole data) will help to identify, quality assess and collate potentially relevant data sources and undertake data mining and compilation studies in the context of the natural hydrogen play model in the UK. We also recommend disseminating such data through an open access platform, where possible, to aid interested parties in decision making for their exploration efforts. USGS's natural hydrogen prospectivity map explorer could serve as a good example of such an undertaking (Gelman et al., 2025).

5.2.2 Add-on measurements to current monitoring

Development of hydrogen add-on element to current gas and water monitoring initiatives undertaken by Mining Remediation Authority for Mine Water Heat and Gas Leakage Monitoring.

5.2.3 National Scale Soil-Gas Survey

A nationwide soil-gas survey can help to identify seeps and potential hotspots of natural hydrogen. Since anthropogenic hydrogen may be generated artificially during the sampling process and can be part of the system, it is recommended that further investigations, such as mineralogical and isotopic analyses of the hydrogen and associated compounds should be carried out in conjunction with soil-gas surveys to better constrain possible sources of hydrogen in the subsurface (Langhi and Strand, 2023).

5.2.4 Geophysical Studies

A nationwide airborne geophysical survey (magnetic and gravity data) will greatly improve understanding of subsurface composition and structure and form a key assessment component in the development of natural resources exploration programmes. Several mineral and energy exploration companies have previously undertaken such surveys across some parts of the UK, and new surveys alongside existing data would be the most effective way to understand and manage natural hydrogen.

It is worth noting that some of the potential sources of natural hydrogen are also host rocks for critical metals and potential reservoirs for carbon mineralisation. There is potential that data may provide useful in the integrated exploration of the subsurface.

5.2.5 Laboratory-scale Analytical Programme

5.2.5.1 Mineralogical and petrographic studies

Mineralogical and petrographic studies are recommended as part of integrated workflows to understand all lithological components of a hydrogen play. These include characterising the types of natural hydrogen source and their potential to contribute to hydrolysis and/or radiolysis, the characterisation of fluid pathways (faults and fractures), and the composition and hydrogen-retarding properties of the seals.

5.2.5.2 Fluid-rock interaction experiments

Experimental studies are recommended to simulate natural processes to understand and quantify the rate of reactions that can produce hydrogen. Experimental work can be designed to answer questions related to hydrogen play components, including the generation potential of specific lithologies under conditions relevant to a selected subsurface system, fluid movement through fractures, or testing the properties of seals. The value of experimental applications is to provide an evidence base to inform natural hydrogen system modelling.

5.2.6 Analysis of Timing and Preservation

5.2.6.1 Heat flow studies for hydrogen generation

Heat flow studies could include a nationwide study of present-day and palaeo-heat flow using downhole (borehole) temperature, laboratory and geochemical data. Analyses could include calculations of paleo-geothermal gradients and past heat flow values from vitrinite reflectance (organic matter) data derived from subsurface samples. Where this can be integrated with the spatial distribution of possible natural hydrogen sources, it will help estimate the age, duration and rate of potential hydrogen generation.

5.2.6.2 Geological Modelling

Geological modelling can be used to numerically describe the subsurface by incorporating direct and indirect data to understand the physical requirement for natural hydrogen, including distribution of source lithologies, reaction rates, palaeo-heat flow, migration, timing and preservation of accumulations. Current case studies of active natural hydrogen systems provide limited information and are not directly applicable to the UK. Understanding how potential systems may work given the complex geological history of the UK, is therefore crucial. Geological modelling could help derisk exploration, identify potential targets and estimate accumulation volumes.

6 Appendix

6.1 UK GEOLOGICAL SUMMARY

The UK has remarkably varied geology considering its size, with an almost continuous rock record from the Quaternary to Cambrian, and interspersed record from Pre-Cambrian to Neoarchean (Figure 4). Palaeomagnetic evidence records that the UK is composed of rocks from two large paleo landmasses, with those that form Scotland and Northern Ireland having originated from the continent of Laurentia and those that form Wales, Northern and Southern England having originated from the continent of Gondwana.

6.1.1 Precambrian

During the Precambrian, Laurentia was close to the equator and rocks of this time predominantly outcrop in the north and west of Scotland and in Northern Ireland (Figure 4) as sediments deposited in terrestrial and deep marine environments, and volcanic rocks that are the remnants of ocean island arcs.

6.1.2 Cambrian-Devonian

The continents of Laurentia and Gondwana were separated by Iapetus Ocean, which began to close by subduction in the late Cambrian. A collision between Laurentia and a volcanic island arc in the mid Ordovician produced the Grampian Orogeny. In the early Ordovician, what would be the southern part of England rifted apart from Gondwana to form the new microcontinent of Avalonia. This continued to drift northwards until the closure of the Iapetus Ocean in the Silurian and produced the Caledonian Orogeny. This collision joined the northern and southern parts of the UK, leading to further deformation, faulting, metamorphism, and emplacement of intrusions in Northern Scotland (Figure 4). The collision of Laurentia with Avalonia and Baltica in the Devonian created the Caledonian Orogeny and produced a new palaeocontinent known as Laurussia. At depth, large plutonic bodies where emplaced (Figure 4), whilst at the surface, the UK experienced a semi-arid, tropical climate with seasonal rainfall.

6.1.3 Carboniferous

During the early Carboniferous, the UK was close to the equator, drifting northwards. Fluctuating sea levels created shallow seas and carbonate deposition, with tropical fluvial environments facilitating significant coal deposition across the UK in the Carboniferous (Figure 4). At the same time, mafic magmatism occurred across Central Scotland. To the south, continental fragments continued to collide creating the Variscan orogeny and the supercontinent of Pangaea, whilst oceanic crust was thrust on to the southern margin of the UK.

6.1.4 Permian-Cretaceous

The semi-arid climate of the UK on the continent of Pangaea allowed for the deposition of sedimentary successions that form many of the Permo-Triassic hydrocarbon reservoirs, including those of the Norh Sea. The rifting of Pangaea in the Jurassic also caused uplift in the North Sea. Towards the end of the Jurassic the climate became increasingly arid with Pangaea continuing to break up during the Cretaceous. A more humid climate developed with rising sea levels allowed for a marine environment to return and extensive carbonate deposition occurred in the south of the UK (Figure 4).

6.1.5 Cenozoic

During the Cenozoic the UK experienced a very warm, semi-tropical climate with large amounts of sediment deposited offshore, with the deposition of onshore sediments mostly restricted to the south of the UK (Figure 4). During the Palaeogene a widespread volcanic event known as North Atlantic Igneous Province (NAIP), and related to an underlying mantle plume, emplaced mafic-ultramafic rocks across Northwestern Scotland and Northern Ireland (Figure 4), with outcrops continuing offshore. These include central vent complexes, plateau lavas, and intrusive complexes. The climate gradually cooled at the UK continued to drift north.

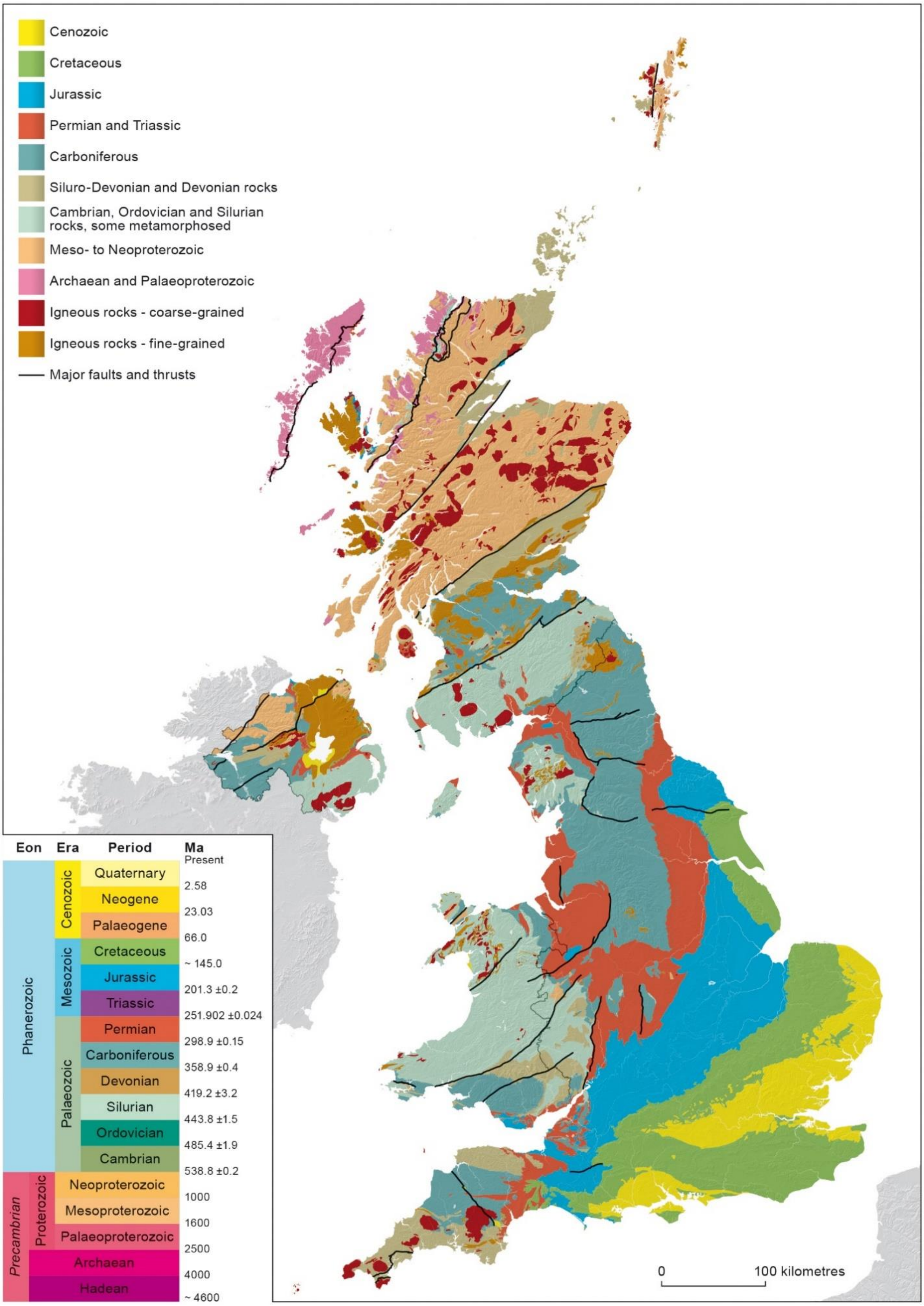


Figure 4. Onshore geological map of UK and major structures, with accompanying geological timescale.

6.2 POSSIBLE UK SOURCES

This section contains additional, detailed information on ophiolites, granites and coals across the UK that is relevant to assessing the lithological potential for the generation of hydrogen. It should be noted that this data is limited to geology that is accessible at outcrop or surface drilling. Caution should be taken when extrapolating this data into the deep subsurface.

6.3 UK GRANITES

Granite bodies in the UK are typically S-type in nature, meaning they formed from the melting of sedimentary source rocks. Although limited in comparison, examples of both A- and I-type granites (those formed by the melting of igneous source rocks) are also known, particularly in north-west Scotland. Almost all the mapped granite bodies in the UK contain Fe-rich minerals (for example, magnetite, biotite, ilmenite and amphibole) that are key for hydrogen generation via hydrolysis. However, the abundance of these minerals will vary not only between different granite bodies but also within a single intrusion.

Varying mineral abundance can be seen in the Shap Granite in northern England, which contains up to 15 per cent biotite (Miles and Woodcock, 2018), whereas the Ballater Granite in north-eastern Scotland contains a lower maximum of 5 per cent biotite (Smith et al., 2002). Granite intrusions are often composite in nature, meaning there may be several different facies of granite present in a single intrusion, with each facies having a slightly different mineralogy. An example of mineralogical variation within a single intrusion is seen in the St Austell Granite in south-west England; here, the composite intrusion comprises biotite granite, tourmaline granite and topaz granite. The topaz granite facies contains little or no mafic minerals (Simons et al., 2017).

There can also be significant variation in the type (biotite → muscovite) and composition (Fe-rich → Fe-poor) of micas encountered in a single intrusion. (Putzolu et al., 2024) reports that the Land's End Granite in Cornwall contains Fe-rich biotite (20.4 to 24.7 wt% iron oxide), phengite (3.36 to 4.87 wt% iron oxide) and muscovite (1.83 to 4.96 wt% iron oxide). It is therefore clear that mineralogical heterogeneity within a granite body will affect the overall hydrogen generation potential.

It is important to note that, for many granite bodies in the UK, mineralogical heterogeneity has only been mapped in two dimensions (at surface) or to relatively shallow depths. Even where relatively deep (more than 2 km) observations have been made, for example via boreholes in the Carnmenellis Granite in south-west England, it is difficult to extrapolate the observations from one or two boreholes to the whole intrusion. A similar situation is observed when considering the potential for radiolysis in granites, in that the distribution of mineral phases that host U, Th and K will not necessarily be uniform. Work by (Beamish and Busby, 2016) states that heat production in Cornish granites is not uniformly distributed, which also indicates a non-uniform distribution of radionuclides in the intrusions.

Fluid-induced alteration of mineral phases within granite intrusions can take place during cooling, by either escaping magmatic fluids or later ingress of meteoric (surface) water. In south-west England, micas (for example, biotite and zinnwaldite) in the granites are known to have reacted with fluids to liberate lithium (Li), with the Li becoming dissolved in deep, circulating fluids (Edmunds et al., 1985). It is therefore expected that those same reactions generated hydrogen. However, this does not imply complete reaction, as there may be parts of the system that remain unaltered.

It is important to note that alteration in granite bodies is typically observed at surface, meaning it is often difficult to know how far into the subsurface the alteration extends. Large-scale structures that are present at depth, such as shear zones, may allow for alteration of granite in the subsurface, but this may only be in discrete regions within the granite body. The degree and extent of deep alteration in the subsurface can be ascertained by drilling or by using geophysics; for example, detailed aeromagnetic surveys (Abdelrady et al., 2023), although such data is limited in the UK.

In the UK, HHP granites (where heat production exceeds 4 $\mu W/m^{-3}$) are known to occur, principally in south-west England, north-east Scotland and parts of northern England (Gillespie et al., 2013, Downing and Gray, 1986). These granite bodies are ‘hot’ due to a combination of geothermal gradient (the change in temperature as a function of depth) and an enrichment in radioactive elements such as U, Th and K. Although no direct correlation is known to exist between heat production and the potential to generate hydrogen, it is reasonable to assume that the process of radiolysis will be more effective in more strongly radioactive granite systems. Therefore, heat production data and geochemical data for U, Th and K may be a useful high-level targeting tool for granites with the potential to generate hydrogen.

It should be noted that, whilst heat production data and bulk geochemical data for U, Th and K do exist for many granite bodies in the UK, it is inconsistent and there are many intrusions for which data is unavailable. The data that is available is also not held in a centralised repository or database, but exists in reports, BGS publications and in academic literature.

It is also useful to note that many of these HHP granite systems are effectively dry; for example, a deep borehole drilled into the Weardale Granite in northern England only encountered water at specific intervals (around 410 m depth), indicating the presence of brine-carrying fractures. However, away from these discrete structures, the granite itself contained very little water (Manning et al., 2007).

A similar situation was observed during the ‘Hot dry rock’ (HDR) research programme that ran in south-west England during the 1970s and 1990s (Edmunds et al., 1989). Here, deep (over 2000 m) boreholes drilled into the Carnmenellis Granite returned very little ‘natural’ fluid, except where deep, north-to-south fractures were intercepted, essentially indicating a dry system. Fluid flow was possible through stimulated fracturing of the rock mass between boreholes and injecting fluids under high pumping pressures (Edmunds et al., 1989).

These examples highlight that discrete, structure-controlled fluid flow can happen at depth within a granite body; however, large parts of the system will remain free of water and therefore the potential for radiolysis and hydrolysis to have taken or to take place is limited.

Assessment of some areas of the UK for geothermal energy potential have focused on granite-related systems. In these areas, some of the key requirements for heat production are also those required for hydrogen generation, including permeability (pathways), input of water and, ideally, some level of radioactivity. Therefore, it stands to reason that areas explored for high-enthalpy geothermal energy may also have potential as sources of hydrogen. The other benefit is that these areas represent locations where the subsurface has been reasonably well characterised, or there are at least deep boreholes that provide some information about these systems at depth.

6.3.1 Granites of Interest

The requirements for hydrogen generation via hydrolysis or radiolysis in granites (pathways; water; mafic minerals; radioactive elements) could, in theory, be met or partially met in many of the UK’s granite bodies. Based on these key requirements, of particular interest are the granite bodies in south-west England and north-east Scotland, and the Weardale Granite in northern England. However, further detailed assessments would be required to fully ascertain the hydrogen generation potential of these bodies.

North-east Scotland

The granites of north-east Scotland have been assessed for their heat production potential (Gillespie et al., 2013) and the granite bodies mentioned in Section 3.2.3. deemed to be HHP. These granites are known to contain between 1.5 and 8 per cent biotite (Smith et al., 2002, Rahmdel, 1987) and minor amounts of other mafic minerals (for example, magnetite).

Geological mapping at 1:50 000 scale shows the granite bodies are locally cut by large-scale faults. During the 1980s, four approximately 300 m-deep boreholes were drilled into the Cairngorm, Ballater, Bennachie and Mount Battock granites to measure heat flow; they also provided useful information about the distribution of radioactive elements and variations in rock composition (Webb, 1984, Webb, 1985, Lee et al., 1984).

Many of these granite bodies are composite in nature and comprise several different facies, each with a different mineralogy (Gillespie et al., 2013).

There is also limited mineralogical information for some of these bodies (for example, the Fearn Granite).

NORTHERN ENGLAND

The North Pennine Batholith is a large (about 1500 km^2), concealed granite body in northern England, comprising several smaller plutons that include the Cornsay, Scordale, Rowlands Gill, Tynehead and Weardale plutons (Kimbell et al., 2010). Being concealed, the volume and structure of batholith has largely been inferred from geophysical surveys (for example, gravity and magnetic surveys). There is also very little detailed mineralogical and petrological information about the granite, with the available descriptions (Dunham, 1965, Manning et al., 2007) coming from only a few deep boreholes that intersected the Weardale Granite.

The granite is biotite bearing, although muscovite is the dominant mica species present (Dunham, 1965). It also contains magnetite and ilmenite. The granite is heat producing, but with values ranging from 3.7 to 4.6 $\mu W/m^{-3}$ (Gillespie et al., 2013), it is not as 'hot' as some of the granites in north-east Scotland or south-west England. Even though the heat production values are lower than in other areas of the UK, a 995 m-deep well was drilled into the Weardale Granite in 2004 to assess its geothermal potential. The aim was to target deep structures that carry warm, circulating brines (Manning et al., 2007).The same brines are currently being explored by Weardale Lithium and Northern Lithium for their potential to produce Li. The fact that these brines are Li-rich implies hydrolysis of mica in the granite has already taken place, but to what extent is unknown.

The Weardale Granite is concealed, being covered by younger sedimentary rocks. The limestone in this area is known to be dissolved (karstic) in places (Cooper et al., 2011), which could potentially be important for trapping of hydrogen. However, the depth to which the limestone units are karstified is unknown. The area is also known to be cut by the large Whin Sill intrusion, which may be another useful trap for hydrogen.

As with other granites in the UK, available evidence suggests hydrogen generation is possible in the Weardale Granite. However, much more detailed geological work would be required to model the subsurface and better understand the scale and nature of deep fracture networks in the granite.

SOUTH-WEST ENGLAND

The south-west region of England is underlain by the Cornubian Batholith, a body of granite with an approximate volume of 40 000 km^3. The batholith is partially exposed at the surface in the form of six distinct granite bodies (Williamson et al., 2010):

- Isles of Scilly
- Land's End
- Carnmenellis
- St Austell
- Bodmin
- Dartmoor

The south-west granites are S-type granites that contain between 5 and 10 per cent biotite and other mafic minerals (for example, ilmenite). The intrusions are composite in nature but dominantly comprise either two-mica granite or biotite granite (Simons et al., 2017).

Geological mapping and geophysical surveys have shown the south-west England region to be structurally complex, being cut by several large fracture systems; some of these structures are known to intersect the granites at depth (Reinecker et al., 2021). The granites are radiogenic and heat producing, and have received significant attention for their geothermal potential (Wheildon et al., 1981, Downing and Gray, 1986, Lee et al., 1987, Sams and Thomas-Betts, 1988, Richards et al., 1991, Beamish and Busby, 2016).

The Carnmenellis Granite in particular has been the focus of past geothermal research via the HDR programme (Andrews et al., 1989, Edmunds et al., 1989, Richards et al., 1989, Savage et al., 1989, Smedley et al., 1989) and more recent geothermal exploration by Geothermal Energy

Lithium. During these periods of research and exploration, several deep (over 2000 m) boreholes were drilled that provide an insight into the subsurface Carnmenellis Granite.

There is also evidence of Li-rich brines circulating at depth in south-west England, indicating that hydrolysis has taken place to liberate Li from mica (Edmunds et al., 1985).

Despite the availability of deep data in south-west England, more work is required to fully understand the hydrogen generation potential, as existing data was collected to assess geothermal potential. It is also worth noting that the ‘basins’ of south-west England have been subject to a complex history of burial, uplift, metamorphism and deformation that may have impacted their potential to trap hydrogen.

6.3.2 UK Ophiolites

Ophiolites are slivers of oceanic lithosphere emplaced onto continents through tectonic processes. Such processes produced the Shetland Ophiolite Complex (Central Highlands Terrain), the Ballantrae Ophiolite (Midland Valley Terrain) and the Highland Border Ophiolite (near the boundary between Midland Valley and Central Highland Terrains) as well as the younger Lizard ophiolite (Normannian Terrain) in Cornwall. Of specific importance to the natural hydrogen prospectivity analysis is the degree and timing of the main serpentinisation events. The UK ophiolites display pervasive and multi-stage serpentinisation with the main serpentinisation events being associated with the onset of obduction throughout to the emplacement of the oceanic lithosphere onto continental margin (Flinn and Oglethorpe, 2005). Where possible the occurrence of chromite (chromitite) should be recorded, based on an observation of co-occurrence of chromite bodies with hydrogen in Albania, Philippines (pers.comm. Aquino, and Truche, 2025). Further information on the mineralogy and magnetic anomalies of ophiolitic rocks is presented below.

Other ultramafic and mafic systems in the UK, that may have served as natural hydrogen source rocks are the extrusive and intrusive complexes of the Palaeogene North Atlantic Igneous Province (NAIP). These include mafic-ultramafic central complexes, notably those of Rum, Ardnamurchan, Mull, Skye and Slieve Gullion. For example, the Rum Igneous Complex consist of thick sequences of layered ultramafic rocks, that based on surface exposures, are reported to contain up to 70 vol % of olivine (Hepworth et al., 2020). This suggests significant potential for ongoing serpentinisation, but further investigations are needed to establish the mineralogy at depth. The NAIP magmatism also resulted in vast 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 (Ritchie et al., 1999). Major gabbroic sill complexes are associated with the plateau lavas and, it would be valuable to assess their potential as hydrogen seal in the system.

The timing plays a critical role in the system potential to accumulate and preserve any gas generated, and if the potential reservoir and seals were not in place at the time of hydrogen generation, the likelihood of large-scale preservation is small. Further work is needed to fully understand the systems across the British Isles, and their interplay beyond the large-scale assessment presented in this report. Indeed, the Lizard Ophiolite Complex is considered a source of hydrogen discovered in Paris Basin, France, with the Bray Fault running across Channel Tunnel as the main pathway (Lefeuvre et al., 2024).

6.3.3 Ophiolites of Interest

6.3.3.1 Northeast Scotland

The Shetland Ophiolite Complex underlies the largest part of the islands of Unst and Fetlar in north-east Shetland. The complex comprises dunites and harzburgites that are intensely serpentinised; primary olivine ± orthopyroxene assemblages are rare. Irregular and laterally discontinuous podiform chromitite seams occur within the peridotites (O'Driscoll et al., 2012). This coincides with a high-amplitude positive magnetic anomaly (over 500 nT) identified in eastern regions of Unst and central Fetlar, overlying the serpentinised ultramafic layers of the ophiolite (Flinn, 2000).

The Shetland Ophiolite Complex was obducted 'cold' (less than 400°C) with a several-kilometre-thick basal layer of harzburgite already pervasively and uniformly lizardite-serpentinised (Flinn and Oglethorpe, 2005). In dunites, the initial serpentinisation resulted in the hydration of olivine and the generation of trails of fine magnetite along the original grain boundaries. This was followed by the recrystallisation of serpentine, sometimes within a shear-stress regime leading to foliated serpentinite. This stage is often associated with the formation of many magnetite veins (Gunn, 1985). Importantly, the recrystallised serpentinites show evidence of interaction with CO_2-bearing fluids as magnesite veins and extensive alteration to carbonate are observed locally. The carbonation stage was followed by low-temperature serpentinisation, demonstrated by late serpentine veins (Gunn, 1985).

Basal portions of the ophiolite have also been intensely, and locally very coarsely, sheared during tectonic processes (Flinn and Oglethorpe, 2005). Consequently, if hydrogen has formed during the early serpentinisation prior to emplacement, the long-term preservation of the gas in the subsurface was likely low, especially in areas that have undergone further tectonic changes or have been otherwise modified in the presence of CO_2-bearing fluids.

6.3.3.2 South-west Scotland

The Ballantrae Ophiolite Complex is located between Girvan and Ballantrae on the shores of the Firth of Clyde, south-west Scotland, and consists of an assemblage of mafic and ultramafic plutonic rocks, basaltic pillow lavas and a range of early Ordovician sedimentary lithologies that crop out over about 75 km^2 (Stone, 1988). The ultramafic rocks have been pervasively serpentinised, probably in the late Arenig (Floian) or earliest Llanvirn (Darriwilian), being penecontemporaneous with the ophiolite’s emplacement (Stone, 1988).

The ophiolite is bound in the south by the Stinchar Valley Fault and crops out in two belts, northern and southern. Significant degrees of compositional and mineralogical transformation associated with chemical reactions triggered by the reaction of fluids (metasomatism) is reported from both belts, indicating the existence of fluid pathways. The northern belt is significantly tectonised, in contrast to the southern body where the tectonic fabric is either non-existent or weak. Chromitite occurs in both belts, at Pinbain Bridge in the north and Poundland Burn in the south (Derbyshire et al., 2019). Magnetic anomalies are also notable in both belts.

Modelling of prominent aeromagnetic and ground-level magnetic anomalies can provide information of the subsurface distribution and depth extension of serpentinite bodies, and suggest that the structure of the Ballantrae Ophiolite Complex’s serpentinites is controlled by a combination of high-angle faulting and folding (Can, 2022). Can (2022) also reports that one of those fault-bounded slices of serpentinite extends down to at least 2.5 km.

6.3.3.3 South-west England

The Lizard Ophiolite Complex is located in Cornwall in south-west England and is one of the best-preserved Variscan ophiolites, probably emplaced in the Devonian. It is younger than the Shetland and Ballantrae ophiolites and displays evidence of a different tectonic provenance. The Shetland and Ballantrae ophiolites are reported to originate from subduction-zone processes, whereas the Lizard Ophiolite Complex has been suggested as a mid-ocean ridge ophiolite (O'Driscoll et al., 2012). Whether this plays any role in the system’s prospectivity for hydrogen is currently not known and further work is required on how and if the initial tectonic setting affects the potential for hydrogen generation.

One well-established way to assess ophiolite tectonic provenance is to examine the chemical composition of chromium-spinel contained within podiform chromitite (O'Driscoll et al., 2012). The idea that the presence of chromite might catalyse hydrogen generation reactions is currently highly hypothetical. Experimental work should be undertaken to test this hypothesis.

The ultramafic rocks of the Lizard Ophiolite Complex are pervasively serpentinised (Power et al., 1997, Mackay-Champion et al., 2024). Based on petrographic analysis and dating of different minerals in paragenetic sequence, it is reported that the main episode of serpentinisation leading to pervasive alteration occurred after the initiation of obduction, and lasted from the late Devonian to the Carboniferous (Power et al., 1997). This episode of serpentinisation resulted in the formation of lizardite and chrysotile and the crystallisation of magnetite and was likely associated with the generation of hydrogen.

Another episode of serpentinisation took place in the late Carboniferous to early Permian and resulted in ubiquitous cross-cutting veins of lizardite and chrysotile, but no magnetite (Power et al., 1997).

Tellus South West's airborne geophysical data, acquired in 2013, provides an overview of magnetic anomalies in south-west England. In the area of the Lizard Ophiolite Complex, the distribution of anomalies generally displays a north-west to south-east trend. Three-dimensional modelling of the Tellus South West aeromagnetic anomaly data shows that the main anomaly over the ophiolite is caused by a wedge-shaped region of high magnetic susceptibility that extends down to depths of about 1.5 km along the eastern coast of the ophiolite (magnetic anomalies of 50 to 130 nT) (Toprak, 2023, Tellus, 2013). Modelling also suggests that the serpentinised peridotites exposed at Coverack extend to depths of at least 2.5 km (Toprak, 2023).

The heat production estimate for the Lizard peninsula is typically less than 1.5 $\mu W/m^{-3}$ (Beamish and Busby, 2016). The Lizard Ophiolite Complex has been suggested as one of possible sources of hydrogen in the Paris Basin, where an OCR programme led to the discovery of multiple wells where hydrogen was detected. The Paris Basin has a lithological and structural inheritance of the Variscan Orogeny, similar to the Lizard Ophiolite Complex.

6.4 OTHER MAFIC AND ULTRAMAFIC ROCKS TO CONSIDER

The UK ophiolitic systems display a high degree of serpentinisation that occurred in early stages of their formation (during obduction), when the reservoir and trap might not have been in place to capture the produced hydrogen. Other mafic and ultramafic systems in the UK that may not be as pervasively serpentinised as the ophiolites and where the serpentinisation might still be ongoing include the intrusive rocks in Ardnamurchan and the islands of Mull, Rum and Skye in Scotland as well as Slieve Gullion in Northern Ireland, which all belong to the NAIP. The Rum Igneous Complex consists of thick sequences of layered ultramafic rocks that, based on surface exposures, are reported to contain up to 70 per cent by volume olivine (Hepworth et al., 2020). Further investigations are needed to establish the mineralogy at depth.

The NAIP magmatism also resulted in vast basaltic plateau 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 kilometres in thickness (Ritchie et al., 1999) but vary significantly across the NAIP. For example, the thickness of the Skye Lava Group was estimated at 1.5 km (Single and Jerram, 2004), whilst 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 (Emeleus, 2005). Major gabbroic sill complexes are associated with the plateau lavas, and it would be valuable to assess their potential as a hydrogen seal in the system.

The Archaean Lewisian Complex exhibits an age and tectonics analogous to the Precambrian shields of Finland and Canada, where dissolved hydrogen concentrations in groundwater were reported (Lollar et al., 2014, Lollar et al., 2007, Kietäväinen et al., 2013). The Lewisian Complex is exposed on the Outer Hebrides and the north-west mainland of Scotland and is dominated by metamorphosed felsic rocks of Precambrian age (Lollar et al., 2014, Lollar et al., 2007, Kietäväinen et al., 2013). The gneisses occur in association with ultramafic, mafic and metasedimentary lithologies, and record a complex history of magmatism, metamorphism and deformation (Guice et al., 2022). The degree of serpentinisation in the complex, as assessed based on surface samples, varies greatly across the region (Guice et al., 2022).

6.5 UK COAL

The UK contains extensive resources of coal, both at surface and in the subsurface. The major coalfields of the UK are of Carboniferous age, with smaller Tertiary lignites in Devon and Northern Ireland and Jurassic bituminous coal deposits in Brora, north-east Scotland. The main coalfields of the UK are located on the eastern, southern and western flanks of the Pennines; some of the largest coalfields are the Nottinghamshire–Yorkshire, South Lancashire, Warwickshire, North and South Staffordshire coalfields. Other important coalfields include South Wales, Kent and those in the Midland Valley of Scotland (Jones, 2006).

Hydrogen has not previously been noted as a major component of UK coal gases: it is not recorded in the extensive work on the properties of British coals by Greenwell and Elsden (1907) and the theses by Creedy, using data from the records of the National Coal Board, lump hydrogen together with argon (Ar) and He as typically comprising less than 0.5 per cent of the composition of British coal gases (Creedy, 1985, Creedy, 1979). It is, however, noted that hydrogen does not adhere well to the surface of coal and may be more likely to be found in adjacent porous rocks such as sandstones (Creedy, 1985).

The ‘gassiest’ UK coals are those in South Wales, followed by South Lancashire, North Staffordshire and Canonbie in Dumfriesshire. North Staffordshire and South Lancashire are also known to have cannel coals with a high stoichiometric hydrogen content, whilst considerable reserves of anthracite are present in South Wales. These are believed to have experienced high temperatures as a result of Variscan orogenic processes. These factors may increase the potential for natural hydrogen generation associated with some coal seams.

7 Glossary

Abiotic	Derived from physical or chemical rather than biological process.
Antiform	A type of fold in the rock that arches upwards
Basalt	A black, fine-grained, basic igneous rock, commonly forming lava flows and consisting of silicate minerals including feldspar and pyroxene
Basement	The oldest rocks recognised in an area, usually a complex mix of metamorphic and igneous rocks that underlies the sedimentary rocks
Biotic/biogenic	Derived from biological rather than physical or chemical processes
Biotite	A dark-coloured, flaky mineral that is a common component of many igneous and metamorphic rocks
CH_4	Methane ('natural gas')
CO_2	Carbon dioxide
Core	The innermost layer of the Earth, divided into an inner and outer core
Crust	The outermost layer of the Earth
Dyke	See **intrusion**
Fault	A plane of weakness in a rock along which displacement has occurred
Fe	Iron
Fe^{2+}	'Ferrous' iron
Fe^{3+}	'Ferric' iron
Felsic	Igneous rocks that are rich in the minerals such as feldspar and quartz
Granite	A coarse-grained, igneous rock consisting of quartz, feldspar and often mica
H_2	Molecular hydrogen
He	Helium
Hydrolysis	The chemical process of breaking down rocks and minerals using water
Igneous	Rocks formed by the solidification of molten rock or magma
Intrusion	A body of igneous rock that has forced itself into pre-existing rocks, either along an existing structural feature (sill) or by deforming and cross-cutting the host rocks (dyke)
Isotopes	Atoms of an element that have the same number of protons but different numbers of neutrons in the nucleus
K	Potassium
Li	Lithium
Lizardite	A hydrated magnesium silicate that is the most common serpentine mineral
Mafic	Igneous rocks that are rich in the minerals such as pyroxene and olivine
Mantle	The main bulk of the Earth, between the crust and the core
Mg	Magnesium
Obducted	The process where oceanic crust is forced up onto a continental plate instead of being subducted down into the mantle

Olivine	Magnesium-iron silicate mineral that is a significant component of the Earth's upper mantle and forms mafic and ultramafic igneous rocks
Ophiolite	The parts of the oceanic crust (and sometimes upper mantle) that were forced up onto a continental plate during obduction
Play	Geographically delineated areas (typically hydrocarbon accumulations) that are defined by their shared geological characteristics (for example, types of source rocks, reservoirs, seals and traps).
Protolith	The original rock before it underwent metamorphism
Pyrolysis	Thermal decomposition of organic matter in the absence of oxygen
Radiolysis	The chemical process of breaking down rocks and minerals using ionising radiation
Radionuclide	An unstable isotope of an element that releases radiation as it decays into a more stable form
Reservoir	A rock formation typically composed of sedimentary rocks that can trap gas or fluid: a key component of a play
Seal	A rock formation that is impermeable and prevents gas or fluid from escaping from a reservoir: a key component of a play
Sedimentary	Rocks formed through the process of deposition of particles consisting of either minerals or rock fragments
Serpentinisation	The hydrothermal alteration process that occurs when ultramafic rocks are transformed into serpentinite
Sill	See **intrusion**
Subduction	The sinking of oceanic crust underneath overriding continental crust at a subduction zone
Tectonic	The structural geological environment and history
Terrane	Blocks of the Earth's crust that share a common geological history, often bounded by major fault systems
Th	Thorium
Trap	A geological structure that allows gas or fluid to accumulate in the subsurface, a key component of a play
U	Uranium
Ultramafic	Igneous rocks that consist almost entirely of magnesium and iron-rich minerals and a silica content typically less than 45 per cent

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The British Geological Survey holds most of the references listed and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://of-ukrinerc.olib.oclc.org/folio/

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