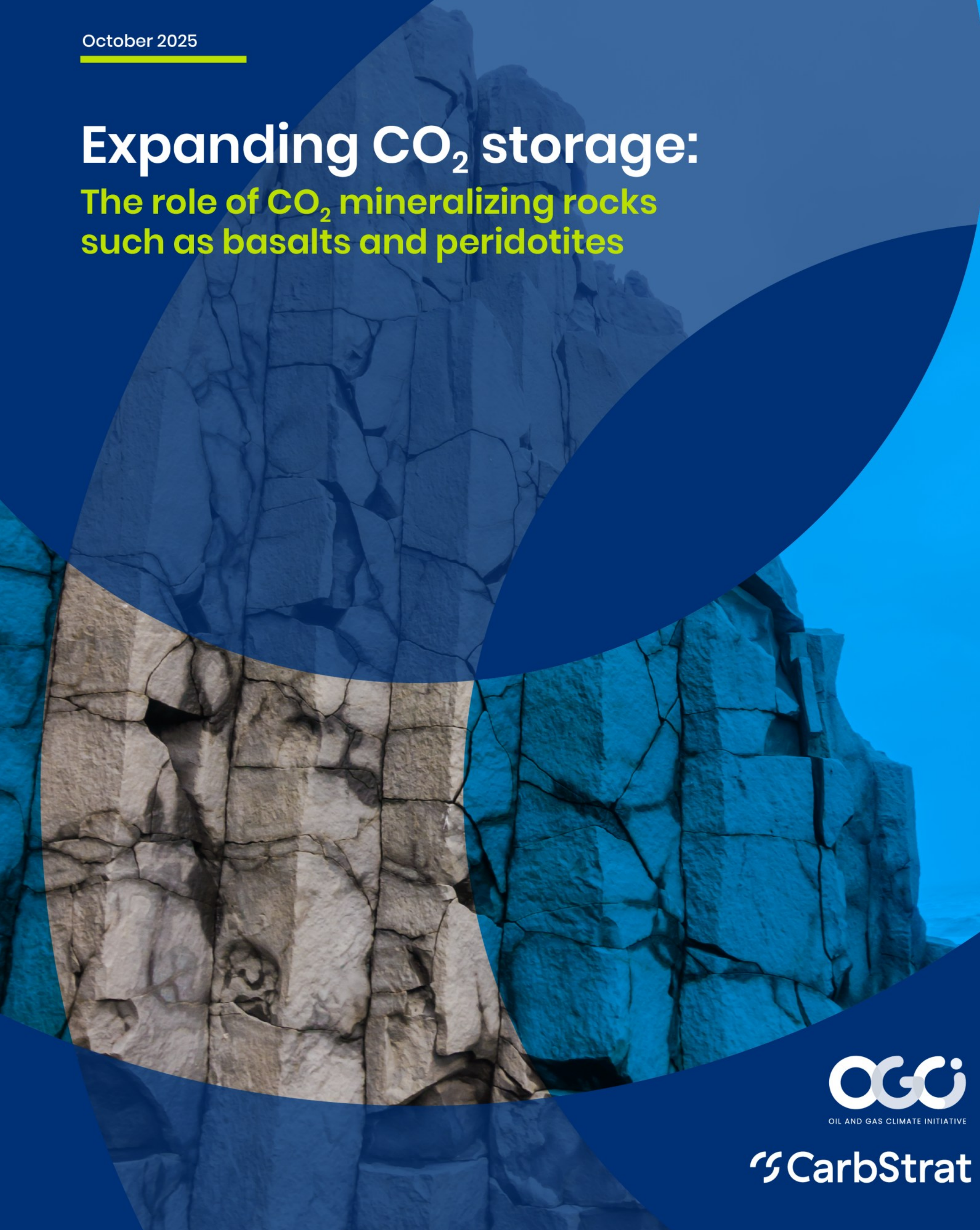
October 2025

Expanding CO_2 storage:

The role of CO_2 mineralizing rocks such as basalts and peridotites



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CarbStrat

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CarbStrat is a boutique consultancy advising on the timely, cost-effective, and sustainable decarbonization of energy and industrial activities. Based in Belgium, we work with clients around the world to address the challenge of managing carbon emissions. Our clients, who include industry, governments, and investors, benefit from our tailored support in navigating the technical, commercial, and policy dimensions of deploying carbon capture, utilization, and storage.

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Executive summary

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), it will be nearly impossible to achieve the Paris Agreement's climate goals without returning carbon to the lithosphere. Recognizing that geological carbon dioxide (CO_2) storage is the most scalable way to return carbon to the lithosphere, countries, regions, and companies have deepened efforts to deploy existing carbon capture and storage (CCS) technologies and to develop new ones.

Today, all large-scale CO_2 storage sites inject CO_2 deep into sedimentary rocks where it is trapped for millennia.[1] Sedimentary rocks are not the only rock types that may be suitable for CO_2 storage, and in the past decade interest has grown in storing CO_2 in igneous and metamorphic rocks.

Many igneous and metamorphic rocks that are rich in magnesium and iron and poor in silica are reactive to CO_2.[2] In nature, exposure to circulating fluids, such as rainwater, seawater, and hydrothermal fluids, dissolves minerals in these rocks releasing magnesium, iron, and other metals. CO_2 can react with the released metals, leading to the formation of carbonate minerals that can trap CO_2 on geological time scales. The results of this process, called carbonation, are readily observed in rocks around the world and carbonation has been the focus of significant scientific research. A critical question today is whether this process can provide a viable and scalable mechanism for CO_2 storage.

Both sedimentary and CO_2-reactive rocks are distributed globally, but they are not always found in the same locations (refer to Figure ES 1). If large-scale CO_2 storage in CO_2-reactive rocks is feasible, then geographies with abundant CO_2-reactive rocks but limited sedimentary rocks would be able to deploy CCS without having to transport captured CO_2 long distances to sedimentary storage sites.

Large-scale CO_2 storage in CO_2-reactive rocks is currently still immature. Over the past 15-20 years, several research consortiums and companies have piloted CO_2 injection into CO_2-reactive rocks in Iceland, Oman, Saudi Arabia, the United States, and the United Arab Emirates. These pilot and small-scale projects have demonstrated that injecting small volumes of CO_2 into these rocks can lead to mineralization over months to years rather than the millennia needed in most sedimentary rocks.[3] For this reason, CO_2 storage in CO_2-reactive rocks is sometimes referred to as mineral storage or mineralization.

The mineralization potential offered by CO_2-reactive rocks is interesting; however, it is important to consider these rocks as a storage resource and not be exclusively focused on their ability to mineralize CO_2. A resource-focused approach is suggested because the rapid rate of mineralization observed at pilot and small-scale sites may not be achievable for large-scale injections. The carbonation process is like a filtration system. It can become less

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[1] This work uses large-scale to describe any storage site with a nominal injection capacity of 100,000 tonnes per year or more.

[2] CO_2-reactive rocks include mafic and ultramafic igneous rocks and the metamorphic rock that form from them. Rock types include basalt, peridotite, gabbro, brucite, and many others.

[3] CO_2 mineralization reactions also occur in sedimentary rock systems over thousands of years. The dominant trapping mechanisms on this injection timescale are structural trapping under a vertical seal, residual trapping by capillary forces, and solubility trapping.

efficient or break down if it is overwhelmed. This can occur above certain temperatures, when there is insufficient water, or if the system becomes blocked or clogged by newly formed minerals. In such circumstances, the rate at which CO_2 is transformed into carbonate minerals will slow down. For example, research suggests that large-scale dense-phase CO_2 injections into CO_2-reactive rocks will mineralize fully after around 500 years.[4] One way to partially mitigate this is to inject CO_2 dissolved in water. Dissolved CO_2 injections improve mineralization efficiency because water plays a role in the carbonation process.

CO_2 mineralization is just one of several mechanisms that traps CO_2 in a storage site. It can be desirable because CO_2 is fixed in mineral form, but it is not strictly necessary so long as containment of injected CO_2 is assured. CO_2, whether injected as a gas or in dense phase, is less dense than reservoir fluids. Owing to its buoyancy, CO_2 migrates upward from where it is injected. As demonstrated by sedimentary CO_2 storage, mineralization is not required to contain CO_2. Sedimentary storage sites rely on a physical trap, in the form of a caprock, to restrict the upward migration of injected CO_2.[5] CO_2-reactive rocks rarely have conventional caprocks, but they can have impermeable zones that can serve as a physical trap. Therefore, mineralization may not always be required for CO_2 to be securely stored in these rocks. As with sedimentary CO_2 storage, containment must be evaluated during resource assessment.

CO_2 storage in reactive rocks is promising, but it requires significant investment in research and development to demonstrate scalability. In Iceland, more than 70 kt of CO_2 has been stored in basalts during around ten years of injection, and a permit has now been approved to inject 106 kt of CO_2 per year across four wells (Carbfix, n.d.). Outside Iceland, no entity has publicly documented injecting more than 1 kt of CO_2 into reactive rocks. Given that most sedimentary CO_2 storage sites inject well over 500 kt CO_2 per year, storage in CO_2-reactive rocks has a much lower technical maturity than sedimentary CO_2 storage.

All projects currently injecting CO_2 into CO_2-reactive rocks dissolve it in water prior to releasing it into the reservoir.[6] This injection style has a higher mineralization efficiency than dense-phase injection and is likely to have lower potential containment risks because the CO_2 is trapped in the water as long as the pressure of the reservoir is high enough. Dissolved CO_2 injections typically use 20-30 tonnes of water to dissolve 1 tonne of CO_2. This greatly increases the injected volume, suggesting that more wells may be required, likely increasing cost and potentially introducing the need for reservoir pressure management. Promising work has been done on the use of seawater or reservoir fluids as the water source, which could reduce water sourcing costs and complexities. This research should continue, given that many large deposits of CO_2-reactive rocks are found in areas with water stress.

Only one project has injected dense-phase CO_2 into CO_2-reactive rocks. That project had encouraging results, suggesting that further dense-phase injection pilots or demonstrations should be considered. At large scale, mineralization rates are expected to be significantly

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[4] Dense-phase CO_2 describes liquid CO_2. If liquid CO_2 is also hotter than about 31°C, it is then in supercritical form. Most sedimentary CO_2 storage sites target dense-phase or supercritical injections because in those phases CO_2 is most compact.

[5] A caprock is an impermeable rock that vertically, and sometimes laterally, seals a reservoir. Common caprock rock types include shale, anhydrite, and salt.

[6] Dissolved CO_2 is what provides carbonated beverages with their fizz. When sealed, a carbonated beverage has a higher internal pressure than our everyday environment. When it is opened, CO_2 bubbles form because the pressure is no longer high enough to keep the CO_2 dissolved. The same principle applies in a reservoir; CO_2 will remain dissolved so long as reservoir pressure is high enough.

slower than those documented by the sole dense-phase injection pilot. Modelling studies suggest that CO_2-reactive rocks can securely trap buoyant dense-phase CO_2 and that mineralization in small fractures can act as a self-sealing mechanism. Therefore, containing dense-phase CO_2 in CO_2-reactive rocks is deemed viable.

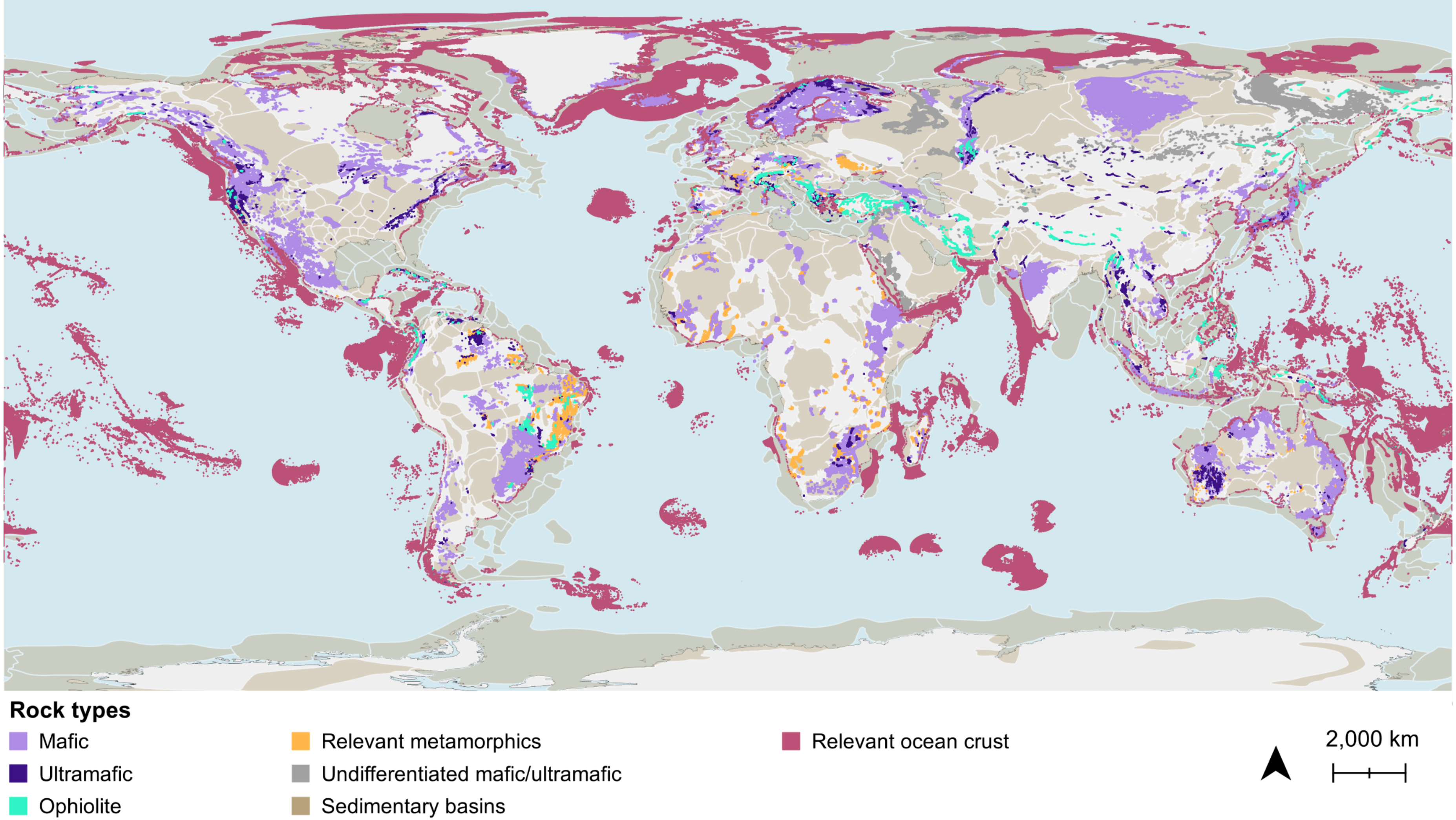
The injection of dissolved CO_2 into CO_2-reactive rocks is more mature than the injection of dense-phase CO_2. Yet it is early days for both. Until storage in CO_2-reactive rocks has been demonstrated at large scale in a range of rock compositions and ages, its technical and economic feasibility will remain an open question.

Initially this work set out to map the distribution of CO_2-reactive rocks and to estimate their global CO_2 storage potential. However, the methodologies currently used to assess the CO_2 storage potential of CO_2-reactive rocks cannot be validated against real world experience gathered at industrial scale projects. That, combined with the substantial data geological data gaps of some regions means that it is premature to global storage potential. Nevertheless, shown in Figure ES 1., large quantities of CO_2-reactive rocks can be found around the world.

CO_2-reactive rocks have the potential to increase the geographic distribution of CO_2 storage. Exploiting them for CO_2 storage would open a new natural resource to economic activity. Taken together, and considering the success of initial pilots, the potential these rocks offer should not be ignored. Continued investment in research, development, and demonstration is advised to improve our understanding of these rocks and their ability to store large amounts of CO_2 for millennia.

There is an urgent need to accelerate development of CO_2 storage infrastructure to support the deployment of CO_2 capture. Sedimentary CO_2 storage is already mature and should be deployed as quickly and widely as possible. However, we are likely to need large-scale CO_2 storage in reactive rocks in the future. Therefore, steps should be taken now to scale up existing activities and develop new projects across all scales.

Figure ES 1. The global distribution of CO_2-reactive rocks compared to the location of sedimentary basins



Notes: Relevant ocean crust is defined as ocean crust outside continental shelves, within exclusive economic zones (EEZs), at less than 3,000 m water depth, and with less than 2,000 m of sediment cover. Ophiolites are geological complexes that include multiple rock types in close geographic association. Refer to Appendix 1 for more information on the mapping.

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Abbreviations and units

ABEX	Abandonment expenditure
CAMP	Central Atlantic Magmatic Province
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
$CO_2(aq)$	Aqueous carbon dioxide
$CO_2(sc)$	Supercritical carbon dioxide
CO_2-EOR	CO_2-enhanced oil recovery
COP26	26th Conference of the Parties (UNFCCC)
COP28	28th Conference of the Parties (UNFCCC)
EC	European Commission
EEZ	Exclusive economic zone
EU	European Union
FEPs	Features, events, and processes
FID	Final investment decision
GIS	Geographic information system
H_2O	Water
H_2S	Hydrogen sulphide
IEA	International Energy Agency
IMA	International Mineralogical Association
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISA	International Seabed Authority
ISO	International Organization for Standardization
LIP	Large igneous province
MI	Mission Innovation
MI-CDR	Carbon Dioxide Removal Mission
NAIP	North Atlantic Igneous Province
NID	National inventory document
OGCI	Oil and Gas Climate Initiative
OPEX	Operational expenditure
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
ρCO_2	Density of CO_2
pCO_2	Partial pressure of CO_2
PNNL	Pacific Northwest National Laboratory
PRMS	Petroleum Resource Management System
ROP	Rate of penetration
SPE	Society of Petroleum Engineers
SRMS	Storage Resource Management System
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate Change

US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WAG	Water-alternating-gas

Units

°C	Degree Celsius
Gt	Gigatonne (billion tonnes)
Gtpa	Gigatonnes (billion tonnes) per annum
K	Kelvin
kg	Kilogram
km	Kilometre
km^2	Square kilometre
km^3	Cubic kilometre
kt	Kilotonne (thousand tonnes)
ktpa	Kilotonnes (thousand tonnes) per annum
m	Metre
m^3	Cubic metre
mD	Millidarcy
MPa	Megapascal
Mt	Megatonne (million tonnes)
Mtpa	Megatonnes (million tonnes) per annum
ppm	Parts per million
s	second
t	Metric tonne

A note on the units used for water in this report

Water injection and production projects typically use volumetric measurements (gallons, litres, m^3) to discuss the amount of water they are handling. However, the scientific literature on aqueous and water alternating gas injections for CO_2 storage in mafic and ultramafic rocks typically use mass when discussing the amount of water used. Additionally, the publicly available permit for aqueous injections in Iceland also uses mass rather than volume when defining the permitted water injection rate.

For this reason, this report primarily uses mass rather than volume to discuss water production and injection. It should be noted that mass is not a perfect metric since the mass of water changes with the amount of total dissolved solids.

A note on terminology used in this report

This report uses conventional geologic terminology throughout. It adheres to standard definitions related to rock type, mineralogy, and formation environment whenever possible. For those who may not be familiar with some of the terminology contained within this work, this box also contains a brief introduction to some of the main geologic terms found within this report, additional information is widely available online from universities, geological surveys, and other reputable sources.

Rocks can be divided into three main classes based on how they formed. They can be further subdivided within those classes based on properties such as grain size, texture, and mineralogy.

Sedimentary rocks such as sandstone, limestone, and shales form when sediments accumulate and then become compacted or cemented together. Sedimentary rocks can be further divided. They can be clastic, having formed from cemented pieces of older rock (e.g. sandstone, conglomerate, and shale); chemical, having formed when minerals precipitate out of solution (e.g. gypsum and anhydrite); or biogenic, having formed from compacted and cemented organic material (e.g. coal, limestone, and chert).

Igneous rocks form when magma or lava crystallizes. Igneous rocks can be further divided into four types based on how they form and how much silica they contain. They can form at the surface of the Earth from cooling lava or deep in the Earth's crust where they can crystallize from cooling magma.

Metamorphic rocks form from other rocks that are exposed to temperature, pressure, and/or fluid circulation. There are a wide variety of commonly known metamorphic rocks, spanning from marble to slate to gneiss. There are several ways to further subdivide metamorphic rocks, but typically they are divided by the degree of metamorphism they have undergone, which is linked to the temperature and pressure they were exposed to.

This work is primarily focused on two types of igneous rocks – **mafic** and **ultramafic** – and the metamorphic rocks that form from them. Mafic and ultramafic rocks are typically dark in colour due to their high concentrations of dark minerals such as olivine and pyroxene. They contain less than 52% silica and are rich in reactive metals like iron (Fe), magnesium (Mg), and calcium (Ca). Basalts and peridotites are examples of mafic and ultramafic rocks, respectively. The two other types of igneous rocks are **felsic** and **intermediate**. Both are typically lighter in colour due to their higher concentration of silica. Due to their lower concentration of reactive minerals, they are less susceptible to chemical or physical changes. Granites and andesites are two common examples of felsic and intermediate rocks, respectively.

This report uses resource-focused terminology to describe CO_2 storage sites and resources rather than referring to different types of CO_2 storage by the geological mechanisms that trap CO_2. Therefore, it refers to mafic and ultramafic CO_2 storage rather than to "CO_2 mineralization" or "CO_2 mineral storage".

Travertine pools formed by surface carbonation. Image by LoggaWiggler via Pixabay.

Chapter 1. Introduction

Key takeaways:

Carbon dioxide (CO_2) storage is possible in a range of rock types. The two most important criteria for CO_2 storage resources are that they support sustained injection of CO_2 and that they can contain injected CO_2 for millennia.

CO_2-reactive rocks, such as mafic, ultramafic, and certain metamorphic rocks, naturally alter when exposed to fluids and CO_2. This chemical process can lead to the precipitation of carbonate minerals, which has prompted researchers to assess their viability as CO_2 storage resources.

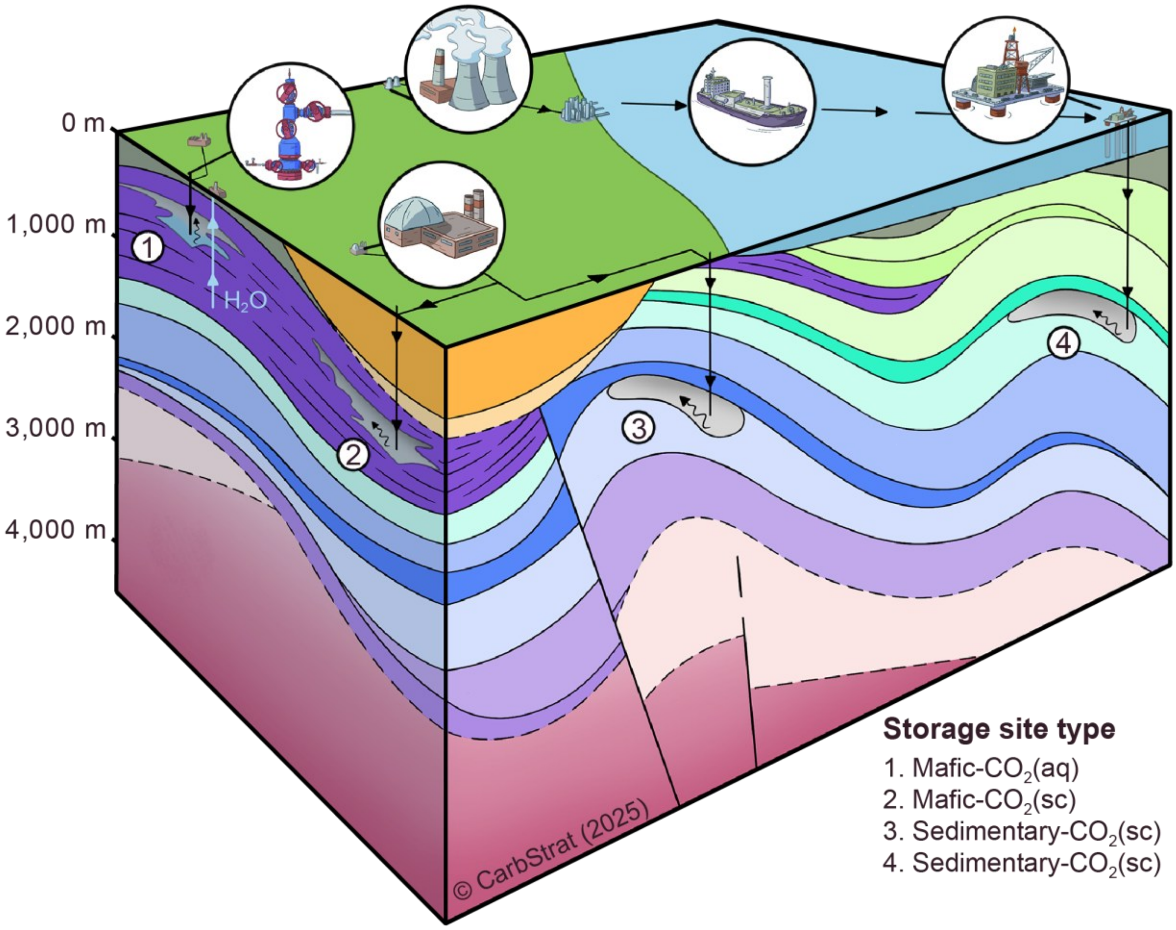
CO_2 storage in mafic and ultramafic rocks has been piloted at a small scale by several companies and research consortiums. The largest permitted site today is significantly smaller than operating sites injecting into sedimentary CO_2 storage resources.

Four main trapping mechanisms enable the physical and chemical containment of CO_2 in reservoir rocks. These trapping mechanisms are the same across rock types, but their overall contribution to storage security and to trapping through time will vary by resource type and injection style.

Interest in carbon management, underpinned by carbon capture, utilization, and storage (CCUS) technologies, surged in the late 2010s. Since then, countries and regions have deepened efforts to deploy CCUS technologies. Technology-based carbon management uses CCUS technologies to enable deep emissions reductions in the industrial and energy sectors and removal of legacy CO_2 from the atmosphere (commonly called carbon dioxide removal [CDR]).

Most energy and climate scenarios see the deployment of CCUS technologies as unavoidable (IEA, 2024; IPCC, 2023; IRENA, 2024). They are an integral part of industrial decarbonization, reducing energy sector emissions and enabling CDR. There is variability between different energy and climate models, but scenarios that align with the ambitions of the Paris Agreement normally consider that over 90% of captured CO_2 is permanently stored in geological formations. Even though the carbon management value chain is still developing, it is generally understood that CO_2 storage is a critical component of the value chain.

Figure 1. Generic schematic of the CCS value chain and CO_2 storage



Notes: CO_2(aq) = aqueous carbon dioxide; CO_2(sc) = supercritical carbon dioxide. Onshore and offshore CO_2 storage are feasible for all resource types. Ultramafic resources have not been included here to reduce figure complexity. In addition to pipeline and ship, CO_2 can be transported by rail, tank truck, river barge, etc.

Permanent storage of CO_2 can be in or ex situ. Ex situ CO_2 storage occurs when captured CO_2 is reacted with other substances to form solid mineral precipitates; examples include

CO_2 curing of concrete and the production of carbonate aggregates.[7] In situ CO_2 storage occurs when captured CO_2 is injected deep underground into a geological formation where it is isolated from the atmosphere for millennia. Geological formations suitable for in situ CO_2 storage have a wide geographic distribution and sedimentary geological formations have the potential to store billions of tonnes (Gt) of CO_2 (OGCI and Halliburton, 2024).

Both types of CO_2 storage have the potential to scale significantly in coming years, but in situ CO_2 storage is less constrained by the total mass of CO_2 that can be sequestered. Ex situ storage is likely to be more constrained due to the scalability of processes and the market uptake of produced materials. In situ CO_2 storage, specifically in mafic, ultramafic, and relevant metamorphic rocks, is the focus of this report.

1.1. Structure of this report

This report aims to provide an in-depth overview of CO_2 storage in mafic, ultramafic, and certain CO_2-reactive metamorphic rocks. Small-scale CO_2 storage in basalts has been piloted or demonstrated in the United States, Iceland, and Saudi Arabia, and small-scale storage in peridotites has been piloted in Oman and the United Arab Emirates. No mafic or ultramafic site has demonstrated sustained CO_2 injection above about 14 kilotonnes per annum (ktpa) CO_2.[8] For comparison, the smallest operating site dedicated to storing CO_2 in sedimentary resources has a nominal injection capacity of 180 ktpa, and many new dedicated CO_2 storage sites are targeting annual injection capacities of 2 megatonnes per annum (Mtpa) CO_2 or more (IEA, 2025; Industrial Commission State of North Dakota, 2021).

Compared to sedimentary CO_2 storage, storage in igneous and/or metamorphic rocks has a lower technology readiness level (TRL). This report assesses the current TRL of CO_2 storage in mafic and ultramafic rocks and explores what may be needed to support the scale-up of this type of injection in the future.

The report is structured as follows:

- **Chapter 1**, this chapter, introduces CO_2 storage and CO_2 storage resources, including the trapping mechanisms that underpin geological CO_2 storage.
- **Chapter 2** outlines the scientific basis of CO_2 storage in mafic and ultramafic rocks. It introduces the different rock types, their mineral assemblages, and their formation environments. It also goes through the chemical reactions that underpin CO_2 storage in mafic and ultramafic rocks.
- **Chapter 3** presents the different types of injection styles that can be used for mafic and ultramafic storage. It outlines documented pilots or demonstration sites and known commercial actors or projects in development. This chapter also compares the current maturity of this type of storage to the maturity of sedimentary CO_2 storage.
- **Chapter 4** provides an overview of the processes used to assess and characterize CO_2 storage resources. It identifies how the Society of Petroleum Engineer's Storage Resource Management System (SRMS) can be adapted or updated to include mafic and ultramafic resources. This chapter also presents a new global map of the

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[7] In 2024 OGCI released a white paper on carbon capture and utilization as a decarbonization lever (OGCI and BCG, 2024).
[8] The 14 ktpa estimate is based on Iceland's annual greenhouse gas reporting. According to the 2024 and 2025 reports, since 2020 Carbfix has been injecting around 12-13 ktpa, but the reports do not specify the number of sites (Icelandic Environment and Energy Agency, 2024, 2025a). In 2025 Carbfix received a permit for an aggregate nominal injection capacity of 106 ktpa CO_2, approved across four wells of different sizes. The largest well has a nominal injection capacity of 47 ktpa CO_2 (Icelandic Environment and Energy Agency, 2025b).

distribution of mafic and ultramafic resources, and a comparison of the methodologies used to calculate mafic and ultramafic resource potential.
- **Chapter 5** focuses on the engineering and technoeconomic aspects of mafic and ultramafic CO_2 storage. It discusses the impact injection style has on site design and it dives into the different cost components. Direct cost estimates are not provided due to significant regional variability in well and drilling costs, but a qualitative discussion of techno-economic factors is included.
- **Chapter 6** explores risks and risk mitigation. It is split into technical and socio-economic risks, with each having several subcategories. The differences in risks between sedimentary and mafic or ultramafic CO_2 storage is discussed, as is the impact that injection style may have on each risk subcategory.
- **Chapter 7** discusses what is needed to scale up mafic and ultramafic CO_2 storage. It outlines continued research needs, and synergies that are present with other energy and energy transition technologies.
- **Chapter 8** brings together the findings of the report and discusses how we move this type of storage from the kilotonne to megatonne scale.

The report is linked to a digital map displaying the distribution of uncharacterized mafic and ultramafic formations that may serve as CO_2 storage resources in the future.

1.2. Rock types suitable for CO_2 storage

Rocks can be divided into three main classes based on how they form:

- **Igneous rocks** form when magma or lava crystallizes. Igneous rocks can be further subdivided according to their mineral assemblage and formation environment. When an igneous rock is composed of < 45% silica it is ultramafic, at 45-52% silica it is mafic, at 52-63% silica it is intermediate and > 63% silica it is felsic (Le Bas et al., 1986). Extrusive igneous rocks form from lava extruded at the surface, or occasionally in shallow dykes and sills. They are commonly called volcanics, typically have a fine-grained texture and include glass. Intrusive igneous rocks crystallize from magma deep underground. Also known as plutonic, these rocks are coarse-grained with large mineral crystals. Well known igneous rocks include granite (felsic, plutonic) and basalt (mafic, volcanic).
- **Sedimentary rocks** form when sediments accumulate and then are compacted and cemented. Sedimentary rocks can be subdivided according to the processes that led to their formation. Clastic rocks, like sandstones and mudrocks, are formed from cemented rock fragments or grains. Biogenic sedimentary rocks, like most carbonates or limestones and coal, are formed from the accumulation of biological material such as plant matter and shells. Chemical sedimentary rocks, like evaporites, form when minerals precipitate out of solution.
- **Metamorphic rocks** form when other rocks are exposed to temperature, pressure, and/or fluid circulation. They can form from either igneous or sedimentary protoliths (parent rock). Sometimes the suffix ortho- is used to describe metamorphic rocks with an igneous protolith and para- is used to describe rocks with a sedimentary protolith. There are a wide variety of commonly known metamorphic rocks, spanning from marble to slate to gneiss.

Total CO_2 storage resources can be broadly divided by rock type. While different rock types have significantly different physical and chemical properties, all CO_2 storage resources must be able to contain injected CO_2 and be sufficiently porous and permeable to support sustained fluid injection. In certain resource types, hydraulic fracturing may be considered to enhance porosity and permeability.

CO_2 storage first started in 1972. At that time, CO_2 was used as a working fluid for CO_2-enhanced oil recovery (CO_2-EOR). During CO_2-EOR operations a portion of injected CO_2 is trapped in the subsurface. In certain countries and under certain reporting frameworks, the resulting trapped CO_2 can be considered stored. Even though between 1996 and 2020, over 75% of CO_2 reported as stored was attributed to CO_2-EOR, today, dedicated CO_2 storage is increasingly the focus (Zhang et al., 2022). Dedicated CO_2 storage sites inject CO_2 into geological formations for emissions reduction or CDR purposes and do not use it as a working fluid. The first dedicated CO_2 storage site entered operations in 1996 and currently around 15 sites are in operation globally with a total nominal injection capacity of more than 12 Mtpa (GCCSI, 2024a; IEA, 2025).[9]

Sedimentary resources have been the primary target for CO_2 storage deployment to date. Oil and gas have been produced from sedimentary reservoirs for over 150 years and much of that subsurface knowledge and expertise is transferable to CO_2 storage. Nevertheless, other rock types can serve as CO_2 storage resources. Recent piloting and small-scale demonstrations have also shown that CO_2-reactive rocks, like basalts and peridotites, are also suitable for CO_2 storage and can more readily trap CO_2 as mineral carbonates.

This report examines non-sedimentary CO_2 storage resources with a specific focus on CO_2-reactive rocks. Mafic rocks, such as basalts, ultramafic rocks, such as peridotites, and certain metamorphic rocks derived from mafic or ultramafic protoliths (parent rock), such as serpentinites, are the most common reactive rocks being explored for CO_2 storage. This work assesses the current maturity of CO_2 storage in these rock types and benchmarks against sedimentary CO_2 storage.[10]

1.2.1. CO_2-reactive storage resources

Natural weathering and alteration of CO_2-reactive rocks prompted scientists to assess whether they could serve as CO_2 storage resources.[11] Today, their use as CO_2 storage resources has been demonstrated at small scale by several start-ups and research groups. The first injection test occurred in 2004 in New Jersey, United States, followed by pilot injections in Iceland (2012-2013), Washington, United States (2013), Oman (2021), Saudi Arabia (2023), and the United Arab Emirates (2023). The largest permitted mafic or ultramafic injection well has a nominal CO_2 injection capacity of 47 ktpa (Icelandic Environment and Energy Agency, 2025b).

Mafic and ultramafic rocks are typically dark-coloured igneous rocks formed from pyroxene and olivine minerals. Poor in silica and rich in iron and magnesium, these rocks readily alter

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[9] The number of operating sites varies according to definitions. At least 10 sites with a nominal injection rate of 100 ktpa (large scale) are in operation today and an additional five sites have a nominal injection rate of 10-100 ktpa. Sites below a 10 ktpa injection rate may be operating in a commercial capacity but have not been included here due to the difficulties in verifying operations. Sites based in the United States permitted via Underground Injection Control (UIC) Class II have not been included here.

[10] Some sedimentary resources may be composed of CO_2-reactive minerals, e.g. a sandstone composed of basalt. These resources are exceptions rather than the rule and will be explicitly noted when relevant. Other rock types, such as carbonates and organic-rich sandstones, may also have some reactivity, but they fall outside the scope of this work.

[11] This work uses “storage resources” as a general term rather than adhering to specific definitions of various “Storage Resources” as defined by the SRMS. Therefore, “storage resources” as discussed throughout this work will not be associated with estimated storable quantities.

when exposed to surface conditions or acidic fluids such as CO_2-rich water. Like all igneous and sedimentary rocks, mafic and ultramafic rocks can be transformed through metamorphic processes. Metamorphic rocks with a mafic or ultramafic protolith, such as those found in ophiolites, can also be CO_2-reactive and are relevant to this study.

This study uses the term "mafic and ultramafic rocks" in a general way to refer to all CO_2-reactive rocks since the term is more immediately understandable than "CO_2-reactive rocks". When specifically highlighting differences between mafic rocks such as basalts and ultramafic rocks such as peridotites, the more specific rock type is referenced. Detailed information on mafic, ultramafic, and relevant metamorphic rocks and their geochemistry is found in Chapter 2.

Additionally, while CO_2 storage in mafic and ultramafic rocks is often referred to as CO_2 mineralization, this report describes CO_2 storage on the basis of the resources being exploited and not the mechanisms which immobilize CO_2 in the storage site. The reasoning behind this is discussed further in Section 3.1.

1.2.2. Sedimentary resources

All large-scale dedicated CO_2 storage sites in operation today inject CO_2 into sedimentary rock formations. Sedimentary saline aquifers and depleted oil and gas fields are the most discussed, and targeted, CO_2 storage resource types.[12] Other sedimentary rocks like deep coal seams and organic shales also have characteristics that allow them to store CO_2, but these two resource types have not been the main target of research, development, or deployment.

Sedimentary saline aquifers and depleted oil and gas fields are porous and permeable sedimentary rocks that are overlain by a caprock or some other type of vertically confining feature. They are distributed around the world in sedimentary basins. Not every saline aquifer or depleted oil or gas field will be suitable for CO_2 storage. Resource-specific assessment is always required.

Operational dedicated sedimentary CO_2 storage sites vary in their size. The Richardton Ethanol CCS project in North Dakota, United States, (previously owned by Red Trail now owned by Gevo) is one of the smallest with a nominal injection capacity of 180 ktpa, and the Gorgon Project in Australia is one of the largest with a nominal injection capacity of 4 Mtpa (GEVO, 2025; Government of Western Australia, 2025).[13] Project developers are increasingly targeting sedimentary resources that can have an annual injection capacity of at least 1 or 2 Mtpa.

In 2024 and early 2025, significant developments in sedimentary CO_2 storage have been seen around the world. Phase 1 of the Northern Lights project in Norway (1.5 Mtpa nominal injection capacity) and the Moomba CCS project in Australia (1.7 Mtpa nominal injection capacity) were commissioned. Additionally, four final investment decisions (FIDs) were taken on storage sites in Europe: Northern Endurance Partnership storage site (4 Mtpa nominal

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[12] Saline aquifers are not exclusively sedimentary; they can also be found in igneous and metamorphic rocks. However, the term is commonly used by the oil and gas industry to describe porous sedimentary formations filled with salty water. This report's use of the term "saline aquifer" has been aligned with how the term is commonly used in CO_2 storage literature. Therefore, any resource specifically identified as a saline aquifer can be considered sedimentary unless noted otherwise.

[13] This report uses nominal injection rate when it provides the permitted annual injection rates, or the ideal annual injection rate announced by a project. There can be major and minor differences between the nominal injection rate of a site and the achieved annual injection.

injection capacity), Phase 2 expansion of Northern Lights (an additional 3.5 Mtpa nominal injection capacity), Liverpool Bay CCS project (4.5 Mtpa nominal injection capacity), and Greensand Future (0.4 Mtpa initial capacity).

The CO_2 Storage Resource Catalogue commissioned by the Oil and Gas Climate Initiative (OGCI) assesses the global distribution of sedimentary CO_2 storage resources and classifies their maturity using the SRMS.

1.3. Trapping mechanisms

There are four main mechanisms that trap CO_2 inside a geological formation or reservoir.[14,15] While these mechanisms are typically described in the context of sedimentary CO_2 storage (Figure 2), they also apply to storage in mafic or ultramafic geologic formations.

- **Structural trapping** is a physical trapping mechanism. Impermeable cap rocks or vertical seals prevent the upward migration of CO_2 or formation fluids. Free-phase CO_2 is typically more buoyant than formation fluids and will rise through a reservoir until it reaches a vertical seal.[16] When CO_2 is injected in aqueous form, structural trapping is not needed to counteract buoyancy the same way it is required with free-phase injections.[17] Structural traps may still be required to ensure that injected fluids do not migrate out of the target storage zone.
- **Residual trapping** is another physical trapping mechanism. Capillary forces can trap small CO_2 bubbles in pores and pore throats during the migration of free-phase CO_2 through the reservoir. This trapping mechanism does not occur widely during aqueous CO_2 injections owing to the absence of free-phase CO_2.
- **Solubility trapping** is a geochemical trapping mechanism. CO_2 dissolves into water and dissociates first into carbonic acid, and then into carbonate and bicarbonate ions (see Section 2.3 for more information). The reaction releases protons and causes the pH to decrease, thereby acidifying the fluid the CO_2 is dissolving into. This reaction occurs inside the reservoir when CO_2 is injected in free-phase. CO_2-enriched formation fluids can be denser than non-enriched fluids, in which case they will slowly sink. Since CO_2 is already dissolved in water in aqueous CO_2 injections, this trapping mechanism will already be in effect upon injection of CO_2-charged water into the formation. For this type of injection, the CO_2-charged fluid will sink if it is denser than formation fluids, but it will float if it is not. The density of the injectant will be dictated by temperature, the density of the fluid dissolving the CO_2, and the mass of CO_2 that is being dissolved.
- **Mineral trapping** is a further geochemical trapping mechanism. Under favourable thermodynamic conditions, acidified formation fluids can dissolve silicate minerals leading to the release of divalent cations (e.g. Fe^{2+}, Mg^{2+}, Ca^{2+}).[18] These react with the carbonic acid and carbonate ions present in solution leading to the precipitation of carbonate minerals (see Section 2.3).

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[14] A reservoir is “a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids” (slb, n.d.-a).

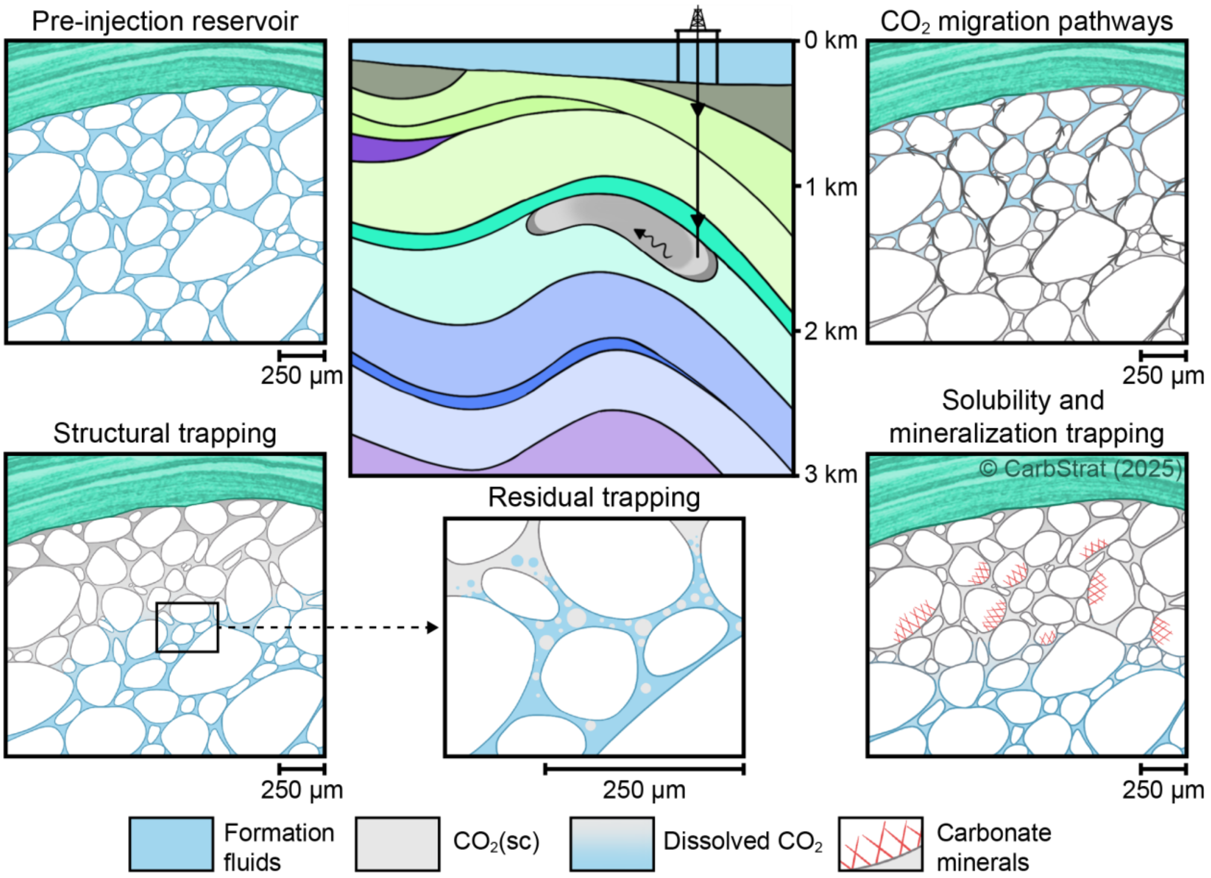
[15] Researchers have proposed that microorganisms that live in the reservoir can incorporate injected CO_2 into biomass, thereby serving as a fifth trapping mechanisms (Daval, 2018; Trias et al., 2017). This is discussed further in Section 7.1.6.

[16] Free-phase CO_2 refers to CO_2 in gaseous, liquid, or supercritical form and is used to distinguish it from CO_2 that has been dissolved in water or otherwise chemically transformed.

[17] Aqueous CO_2 injections refer to injections where CO_2-charged water is the injectant rather than free-phase CO_2. For this type of injection, CO_2 can be dissolved in water either at the surface or within the wellbore.

[18] Divalent cations are ions that have lost two electrons meaning they have a 2+ charge.

Figure 2. Schematic of trapping mechanisms in a saline aquifer



Notes: At the pore scale, buoyancy drives free-phase CO_2 to migrate upward around individual rock grains. Formation fluids containing dissolved CO_2 will slowly sink since the added CO_2 increases the fluid's density.

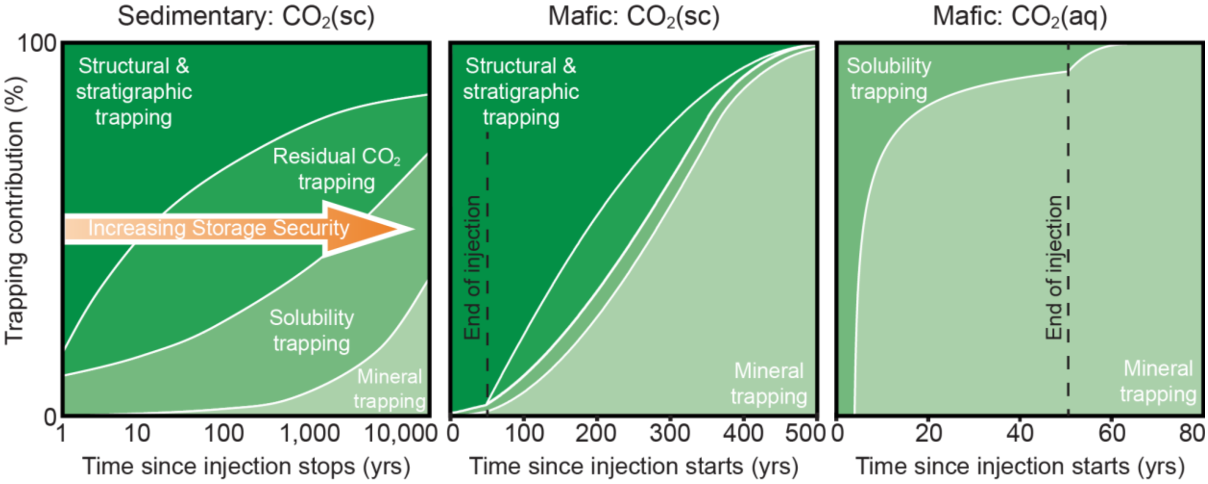
Due to differences in geochemistry, reservoir structure, and other factors, the importance of each trapping mechanism and amount of time post-injection before a specific mechanism becomes the primary trap varies between resource types. Injection style will also influence which trapping mechanisms are engaged.

The 2005 IPCC Report *Carbon Dioxide Capture and Storage* contained a frequently referenced sketch showing the evolution of trapping mechanisms through time following the end of injection at a sedimentary CO_2 storage site (Figure 3, left panel). Several different researchers have investigated how that concept can be adapted to mafic and ultramafic CO_2 storage resources.

Research suggests that trapping mechanisms evolve more quickly in mafic and ultramafic CO_2 storage than in sedimentary CO_2 storage due to the rock's reactivity. To highlight those differences, the centre and right panels of Figure 3 show sketches of trapping mechanisms in mafic and ultramafic rocks and their evolution with time from the start of free-phase CO_2 (centre) or dissolved CO_2 injections (right).

According to numerical modelling, mineral trapping will enter into force much more rapidly in basalt than it does in sedimentary CO_2 storage. Numerical modelling of a 50-year CO_2 storage project injecting 100 ktpa of fluids per km of well array found that when supercritical CO_2 was injected, it took around 500 years from the start of injection to completely mineralize (Postma et al., 2022a). Modelling of an aqueous injection with the same fluid volume found that all injected CO_2 could be mineralized ten years after the end of injection. Across the two models, researchers used the same total volume for fluid injections. As a result of the water used to dissolve CO_2, the modelled aqueous injection stored about 30 times less CO_2 than the modelled supercritical injection. The rapid mineralization rates and dominance of mineral trapping modelled for aqueous injections in the work of Postma et al. (2022a) align with field observations, data, and modelling for the CarbFix1 and CarbFix2 projects in Iceland (Matter et al., 2016; Snæbjörnsdóttir et al., 2017).

Figure 3. Conceptual sketches for storage security and trapping mechanisms through time: Original IPCC figure for sedimentary resources (left); trapping in a basalt reservoir for supercritical injection (centre) and aqueous injection (right)



Left panel: © Intergovernmental Panel on Climate Change (2005). Centre and right panels: CarbStrat (2025). CC BY-SA.

Notes: CO_2(sc) = supercritical CO_2; CO_2(aq) = aqueous CO_2. The panels are conceptual sketches to show how the importance of different trapping mechanisms varies between resource types and injection styles. The importance of different trapping mechanisms will vary between individual resources and injections based on reservoir properties and total amount of injected CO_2. The left panel starts after the end of injection; the centre and right panels include the period of injection due to the rapid evolution of trapping mechanisms during aqueous CO_2 injections into mafic or ultramafic rocks.

Sources: Left: Reproduction of Figure 5.9 from IPCC (2005). Centre and right: Adapted with permission from modelling done by Postma (2022).

Like sedimentary CO_2 storage projects, free-phase CO_2 injections into mafic or ultramafic rocks will initially rely on structural features as their primary trapping mechanism (Figure 4). The rate at which solubility trapping and mineral trapping occur will depend on the amount of CO_2 injected, the amount and rate at which injected CO_2 mixes with formation fluids, and the rate of mineral dissolution. Reservoirs with swiftly moving formation fluids will have increased mixing between formation fluids and injected CO_2. This can lead to more CO_2 dissolving in water, which in turn can impact the rate of mineral dissolution and subsequent carbonate precipitation.

Aqueous CO_2 injections will typically rely on solubility and/or mineral trapping as their primary trapping mechanisms. Sites employing this type of injection strategy will aim to avoid CO_2 exsolution.[19] If CO_2 exsolution were to occur, vertically confining features would be needed to prevent the upward migration of CO_2 due to its buoyancy. Some form of structural trapping mechanisms may still be required to confine the injected CO_2-charged water prior to mineralization so that it cannot interact with subsurface fluids in non-target zones.

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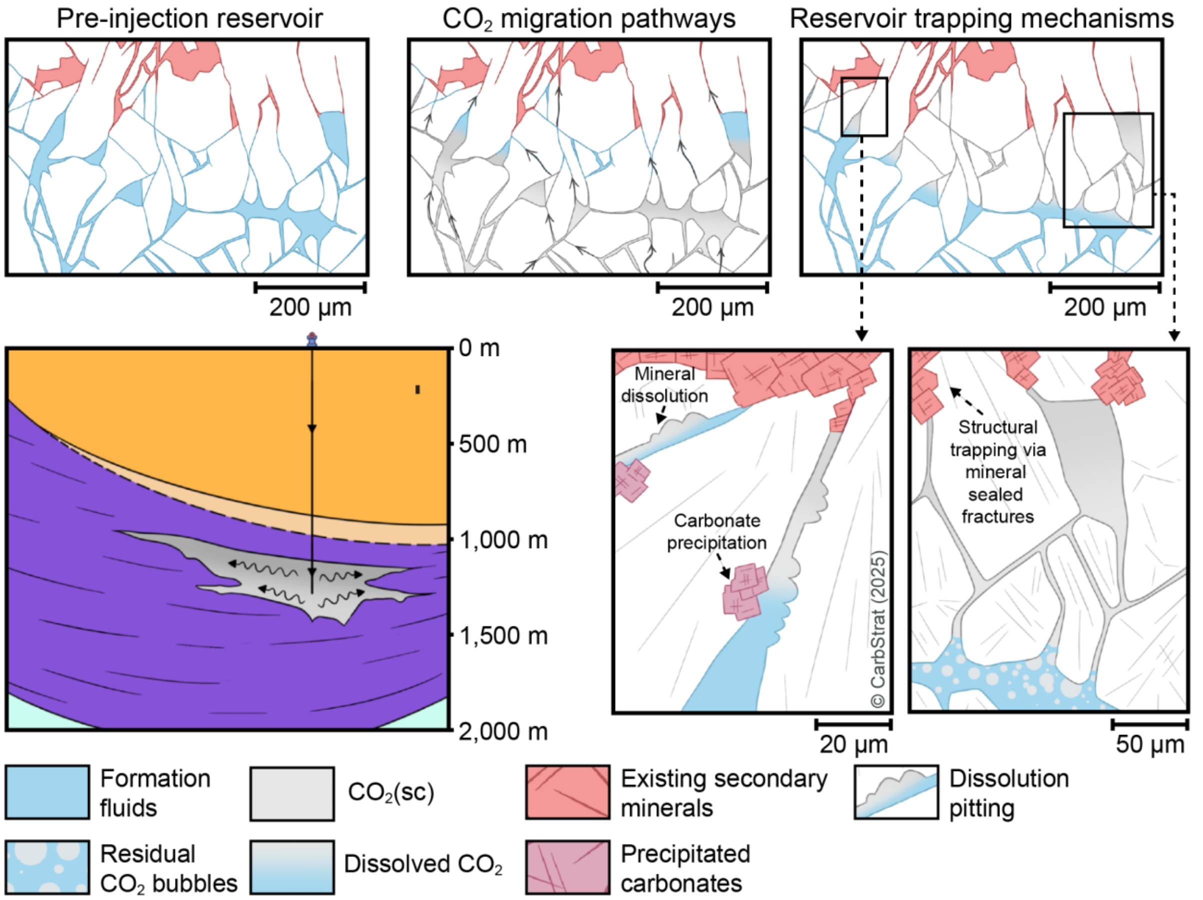
[19] Exsolution occurs when a dissolve gas is released from the fluid it is dissolved in due to changes in temperature, pressure, or other conditions. The bubbles of CO_2 in carbonated beverages are caused by exsolution.

Figure 4. Schematic of trapping mechanisms in a mafic reservoir



Notes: This figure has been developed for a supercritical injection. Aqueous injections will not have residual trapping but will have mixing between formation fluids and dissolved CO_2. Secondary minerals and newly precipitated carbonates can serve as structural traps preventing the upward migration of CO_2.

Basalt cliffs showing columnar cooling joints. Image by Jaesung An via Pixabay.

Chapter 2. The scientific basis of CO_2 storage in mafic and ultramafic rocks

Key takeaways

Mafic and ultramafic rocks rich in olivine and pyroxene are CO_2-reactive. Certain metamorphic rocks, such as brucite, that form when mafic or ultramafic rocks are exposed to elevated pressures and temperatures are also CO_2-reactive.

Formation environment, age, and degree of alteration will influence the porosity and permeability of mafic and ultramafic rocks. In general, rocks formed in the subsurface will have lower primary porosities and permeabilities than those formed from volcanism. Large igneous provinces and ophiolites are two mafic and ultramafic rock sequences relevant to this study. Both will have zonal variability in composition, porosity, permeability.

Weathering, alteration, and other geological processes contribute to the formation of secondary permeability and porosity. Secondary minerals formed by rock alteration processes can coat the surfaces of fractures and vesicles and serve as passivating barriers, reducing dissolution. Depending on the minerals precipitated, secondary minerals can contribute to secondary porosity or clog vesicles and fractures.

When certain minerals within mafic, ultramafic, and relevant metamorphic rocks dissolve they release magnesium, iron, and calcium ions (divalent cations) that can react with dissolved CO_2 to precipitate mineral carbonates. Silicate dissolution is the rate-limiting step in mineral carbonation, although the whole series of reactions from host rock dissolution through to carbonate precipitation is influenced by temperature, pH, and alkalinity.

Exploration, development, and exploitation of the deep subsurface mainly has been driven by the oil and gas sector. Broadly speaking geology can be divided into hard and soft rocks. Igneous and metamorphic rocks are commonly described as hard, while sedimentary rocks are commonly described as soft. As a result of over a century of oil and gas operations, we have a relatively good understanding of reservoir systems in sedimentary rock. That is not the case for hard rock reservoir systems.

Some subsurface projects target hard rock, including mining, exploitation of igneous-hosted petroleum resources, wastewater disposal, nuclear waste disposal, and geothermal energy projects. But there are significantly fewer deep mines, deep research boreholes, and geothermal projects than there are deep oil and gas wells. As of 2019, there were likely fewer than 300 coal and metal mines were operating at depths greater than 1,000 metres (m), but the average depth of oil development wells in the United States have exceeded depths of 1,000 m since before they started collecting data in the 1940s (U.S. Energy Information Administration, n.d.; Xie et al., 2019).

Our comparatively limited understanding of hard rock systems makes it difficult to assess the potential they may offer as CO_2 storage resources. This work focuses on assessing the potential for CO_2-reactive rocks (mafic, ultramafic, and certain metamorphic rocks) to serve as CO_2 storage resources. Intermediate and felsic igneous rocks may also be able to support sustained CO_2 injection and therefore serve as CO_2 storage resources, but they will not exhibit significant potential for mineral trapping.

Box 1. Intermediate and felsic igneous rocks

Intermediate igneous rocks, such as diorite and andesite, are primarily composed of sodic-plagioclase and quartz with mica, amphibole, and potassium felspar accessory minerals. They will have intermediate reactivity and mineral trapping potential when compared to felsic, mafic, or ultramafic rocks. Their mineral trapping potential may be higher than many sedimentary reservoirs since many of them will contain a higher proportion of CO_2-reactive minerals.

Felsic rocks, such as granite and rhyolite, can be referred to as silicic or acidic due to their composition. They are composed of quartz, sodic-plagioclase, and potassium feldspar. Their hardness and low chemical reactivity makes them resistant to weathering and alteration. They are similar in composition to many sandstones, but they are not clastic, so there will potentially be less surface area for CO_2 to interact with. Like sandstone, the mineralization potential offered by felsic rocks is low due to low concentrations of elements, such as calcium, magnesium, and iron, that readily react with CO_2.

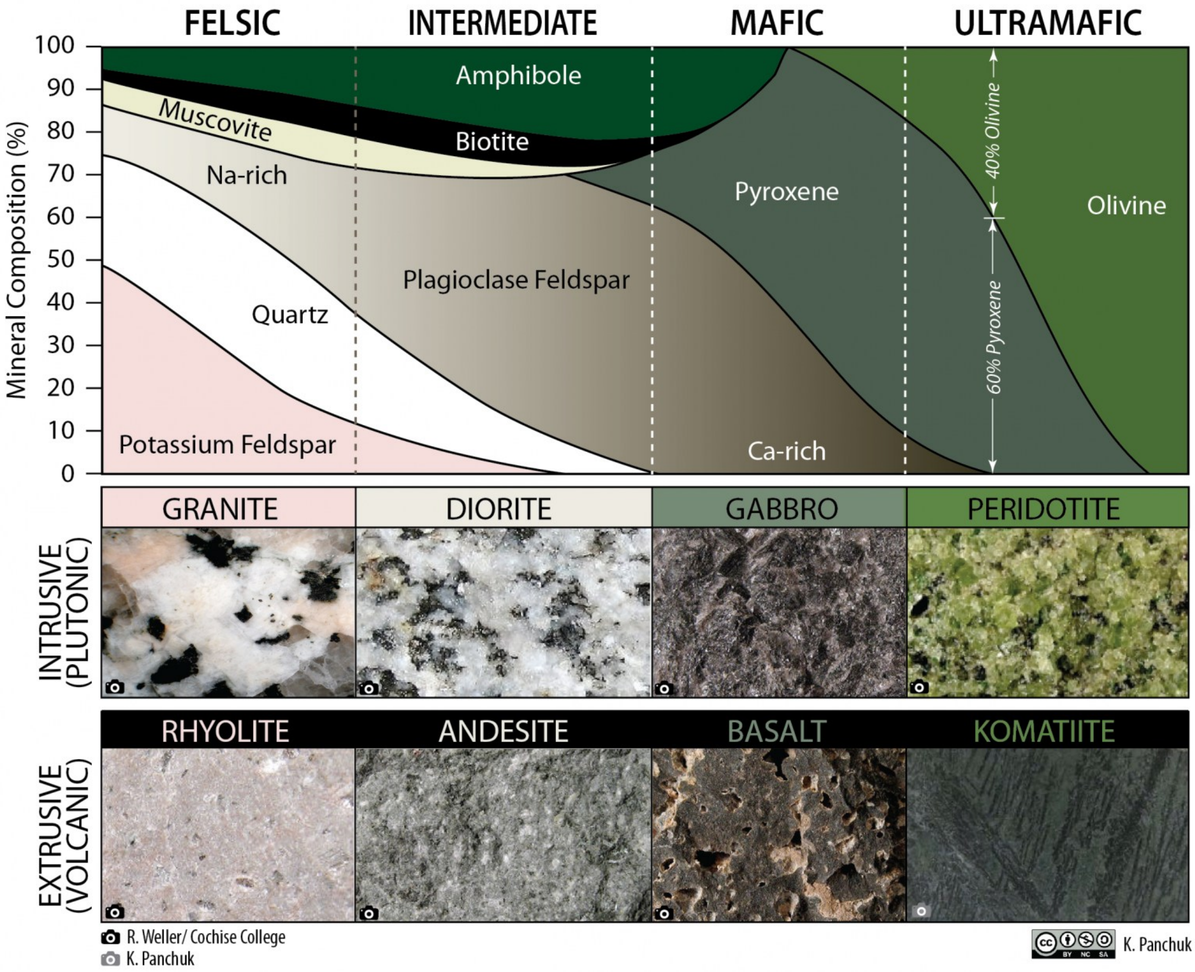
2.1. CO_2-reactive rock types

CO_2-reactive rocks are defined as rocks and rock types that are chemically reactive to CO_2 and the species it forms when dissolved in water (carbonic acid, bicarbonate, and carbonate). Relevant rocks, such as basalt and peridotite, are typically composed of silicate minerals rich in iron and magnesium. Due to their chemical reactivity and susceptibility to weathering, these types of minerals are not frequently preserved in sediments. Instead, they are more commonly found in certain igneous and metamorphic rocks.

2.1.1. Mafic and ultramafic rocks

There are several ways to classify igneous rocks. The simplest method, and the one used in this report, is to categorize them according to their silica content as is done with Bowen's Reaction Series (Bowen, 1922). This method classifies the igneous rocks into four types: felsic, intermediate, mafic, and ultramafic as determined by the minerals that are found within them (Figure 5). Bowen's Reaction Series outlines the order of crystallization of minerals from magmas based on the temperature of crystallization. The temperature of crystallization contributes to the evolution of igneous rocks: ultramafic and mafic rocks are made of minerals that crystallize at the highest temperatures, while felsic minerals crystallize at the lowest temperatures. It should be noted that a mineral's susceptibility to chemical alteration and weathering trends with the temperature of crystallization. Minerals that crystallize at high temperatures, such as olivine and pyroxene, have a higher chemical reactivity and are therefore more susceptible to weathering or alteration than those that crystallize at lower temperatures, such as quartz and potassium feldspar.

Figure 5. Classification diagram for igneous rock types based on mineral assemblage



K. Panchuk. CC BY-NC-SA 4.0. Included with author's permission.

Source: Panchuk (2019).

This work focuses on mafic and ultramafic rocks due to their reactivity. As the names suggest, mafic and ultramafic rocks are rich in magnesium and iron (or ferric) silicates. Mafic and ultramafic rocks are notable for many reasons, including that they are the primary constituent of the ocean crust and that they are found on all seven continents. They initially form when magma cools deep in the Earth's crust or from shallow magmatic intrusions, or extensive volcanism. Once they crystallize, they are exposed to the Earth's geological processes, which can alter them, move them to new places, and/or cause them to be transformed completely into metamorphic rocks. Table 1 provides an overview of the main mafic and ultramafic rocks, their mineral assemblage, and a short description. Most listed minerals are groups rather than specific mineral species since many rock-forming minerals are solid solutions, or mixtures of two or more chemical compounds within a single solid structure.

Table 1. Relevant rock types and information about their mineral assemblages

Category	Rock type	Description	Primary minerals	Common accessory minerals	Alternative terms or subdivisions
Mafic	Basalt	Dark, fine-grained volcanic rock; also found in dykes/sills	Calcic-Pl, Cpx	Ol, Opx, Nph	Tholeiite, Boninite, Hawaiite
Mafic	Gabbro	Dark, coarse-grained plutonic rock	Calcic-Pl, Cpx	Ol, Ap, Mag, Ilm	Norite, Troctolite, Anorthitissite, Theralite
Mafic	Dolerite	Dark, medium-grained plutonic mafic rock	Calcic-Pl, Cpx	Ol, Amp, Fsp	Diabase
Ultramafic	Komatiite	Ultramafic rock with 18-32% MgO	Ol	Px, glass	
Ultramafic	Peridotite	Ultramafic rock with > 40% olivine	Ol	Px, Chr	Dunite, Lherzolite, Wehrlite, Harzburgite
Ultramafic	Pyroxenite	Ultramafic rock with > 60% pyroxene	Px	Amp, Ol	Websterite, Clinopyroxenite, Orthopyroxenite
Ultramafic (exotic igneous)	Carbonatite	Igneous rock with > 50% primary carbonate	Cb		Søvite, Alvikite

Notes: Ol = olivine; Pl = plagioclase; Cpx = clinopyroxene; Opx = orthopyroxene; Nph = nepheline; Amp = amphibole; Mag = magnetite; Fsp = felspar; Chr = chromite; Px = pyroxene; Cb = carbonate; Ap = apatite. Subgroups that include the primary rock type in their name are omitted for brevity; uncommon/rare subgroups are not listed.

Sources: Deer et al. (2013); "Mindat.org" (n.d.); RRUFF Project (n.d.).

Minerals such as olivine, pyroxene, and plagioclase can incorporate multiple elements so long as they have the same electrical charge. For example, iron(II) (Fe^{2+}) has the same charge as magnesium (Mg^{2+}) and calcium (Ca^{2+}). The substitution of different metals into a mineral's crystal lattice can impact its dissolution rate.

Table 2 lists key rock-forming mineral groups or species, their abbreviations, and their chemical formulas. That table provides the endmember species of key mineral groups. Ternary diagrams are used to show the solid solution series and the interrelationship between chemical composition and mineral type or mineral assemblage and rock type. They are readily available online for reference.

Table 2. Primary minerals commonly found in mafic and ultramafic rocks

Group	Abbr.	Formula	Relevant species	Abbr.
Carbonate	Cb	$CaCO_3$	Calcite	Cal
		$MgCO_3$	Magnesite	Mgs

Group	Abbr.	Formula	Relevant species	Abbr.
		$FeCO_3$	Siderite	Sd
		$CaMg(CO_3)_2$	Dolomite	Dol
Plagioclase	Pl	$NaAlSi_3O_8$	Albite (sodic-Pl)	Ab
		$CaAl_2Si_2O_8$	Anorthite (calcic-Pl)	An
Ilmenite	Ilm	$Fe^{2+}TiO_3$	Ilmenite	Ilm
Spinel subgroup	Spl	MgAl2O4	Spinel	Spl
		$Fe^{2+}Cr_2{}^{3+}O_4$	Chromite	Chr
Pyroxene	Px	$MgSiO_3$	Clinoenstatite	Cen
		$Mg_2Si_2O_6$	Enstatite	En
		$FeSiO_3$	Clinoferrosilite	Cfs
		$Fe_2Si_2O_6$	Ferrosilite	Fs
		$Ca_2Si_2O_6$	Wollastonite	Wo
Olivine	Ol	$Fe^{2+}{}_2SiO_4$	Fayalite	Fa
		Mg_2SiO_4	Fosterite	Fo
Feldspathoid		$Na_3K(Al_4Si_4O_{16})$	Nepheline	Nph

Notes: Abbr. = abbreviation. Carbonate is a mineral group in common usage even though it may not be an International Mineralogical Association (IMA) approved mineral group. Carbonate minerals can be primary in certain exotic igneous rocks; they are a main rock-forming mineral in sedimentary rocks such as limestone, and they are a common alteration product. Wollastonite is not technically a pyroxene group mineral, but it is commonly used as an endmember of the pyroxene solid solution series.

Sources: Deer et al. (2013); "Mindat.org" (n.d.); RRUFF Project (n.d.); Warr (2021).

2.1.2. Relevant metamorphic rocks

Soon after a rock forms it becomes exposed to processes that can alter it. Such processes include tectonic events, fluid flow, changing temperature and pressure, and microbial activity. Depending on the amount of temperature, pressure, and fluid circulation it is exposed to a rock may be transformed from an igneous or sedimentary rock into a metamorphic rock. This transformation can be textural and structural, or mineralogical, or both.

Metamorphic rocks are commonly classified according to their grade: low, intermediate, or high. Grades are assigned based on the temperature and pressure that a rock was exposed to when it underwent metamorphism; for example, low-grade metamorphism occurs at low temperatures and low pressures. Since certain minerals form under specific pressure and temperature conditions, metamorphic rocks can also be grouped into facies according to their mineral assemblage.

In this study, relevant metamorphic rocks are those with mafic or ultramafic protoliths. Examples include metabasalts, serpentinites, amphibolites, and eclogites. Due to the wide variety of metamorphic rocks and minerals that can be considered, only some of the most relevant minerals are listed in Table 3. Appendix 1 provides a list of the metamorphic rocks that were used in the mapping portion of this study.

Table 3. Key minerals found in reactive metamorphic rocks

Group	Abbr.	Formula	Common species	Abbr.	Meta. facies
Epidote	Ep	$(Ca_2)(Al_2Fe^{3+})O[Si_2O_7][SiO_4](OH)$	Epidote	Ep	Greenschist, blueschist, amphibolite
Brucite Group	Brc	$Mg(OH)_2$	Brucite	Brc	

		$(Fe^{2+},Ca,Mn,Ni)(OH)_2$	Alt. species		Zeolite, greenschist
Serpentine	Srp	$Mg_3(Si_2O_5)(OH)_4$	Antigorite	Atg	Greenschist, blueschist
			Antigorite	Atg	
			Chrysotile	Ctl	
Amphibole Group	Amp	$Ca_2(Mg_{4.5-2.5}Fe_{0.5-2.5}^{2+})Si_8O_{22}(OH)_2$	Actinolite	Act	Greenschist, blueschist, amphibolite
		$Ca_2(Mg_{5.0-4.5}Fe^{2+}_{0.0-0.5})Si_8O_{22}(OH)_2$	Tremolite	Tr	
		$(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$	Hornblende	Hbl	

Notes: Abbr. = abbreviation; Alt. = alternative; Meta. = metamorphic. Metamorphic facies are mineral assemblages that are characteristic of metamorphic rocks formed under specific temperatures and pressures. They describe the degree of metamorphism and/or identify the protolith. See Table 2 for carbonate minerals.

Sources: Deer et al. (2013); "Mindat.org" (n.d.); RRUFF Project (n.d.).

Box 2. Rock alteration and metamorphism

Water-rock reactions occur when fluids interact with the rock they are circulating through. These reactions play a significant role in numerous geological processes since they are a main driver of rock alteration.

A rock's susceptibility to alteration is dependent on the crystal lattice structure of its constituent minerals. Minerals rich in magnesium and iron, such as olivine and pyroxene, are more susceptible to chemical alteration and physical erosion, while felsic minerals such as quartz are less susceptible. As a result, mafic and ultramafic rocks are often highly altered. Alteration typically increases with age, but not always.

Alteration can produce a wide variety of secondary minerals, depending on the mineralogy of the altered rock and the alteration pathway. In mafic and ultramafic rocks, common secondary minerals include clay, carbonate, zeolite, chlorite, iron or manganese oxide, and serpentine minerals. Alteration, like corrosion, starts on an exposed surface such as along fractures, around mineral grains, and inside vesicles. Alteration products can form protective, passivating layers on mineral grains reducing how much circulating fluids can interact with fresh, unaltered silicate minerals. Additionally, depending on the secondary minerals formed, alteration can lead to either increased or decreased porosity.

Rock alteration and metamorphism go hand in hand. Not all altered rocks have undergone metamorphism, but rock alteration due to fluid circulation often accompanies metamorphism. Metasomatism, a change in the chemical composition of a rock, is a type of metamorphism that occurs when hydrothermal fluids circulate through a rock.

Serpentinization and carbonation are two common metasomatic processes. When fluids circulate through mafic and ultramafic rocks at low to intermediate temperatures (85 to 450°C) primary minerals can dissolve and react with the circulating fluids. This can lead to the precipitation of hydrated minerals such as serpentinite and brucite or mineral carbonates (Wenner and Taylor, 1971). The serpentinization and carbonation reactions are exothermic and result in volume increase and density decrease which can contribute to uplifting large volumes of rock.

2.2. Formation environment

Like all geomaterials, mafic and ultramafic rocks are not homogeneous. In fact, they are typically more heterogeneous than sedimentary rocks. Rock characteristics, including permeability, porosity, and mineral assemblage, can be divided into primary characteristics that stem from formation (i.e. primary porosity, permeability, and primary minerals), and secondary characteristics that are a result of rock alteration, metamorphism, tectonic activity, and other geological processes.

The plutonic igneous rocks that form deep within the Earth's crust are typically coarse-grained. Due to the depth of formation, they often have limited or no primary porosity and low primary permeability. The volcanic igneous rocks that form at or near the surface typically have a fine-grained crystal texture with variable porosity depending on how they were formed (Millett et al., 2024). Due to rapid cooling, volcanic rocks often include volcanic glass, which dissolves more rapidly than most mafic minerals.

Reservoir rocks must be permeable. They must be able to support sustained CO_2 injection and securely trap CO_2. Porosity and permeability will vary between different mafic and ultramafic rock types, across formation environments, and with rock age, though a few general rules of thumb can be applied:

- Plutonic rocks have lower primary porosity and permeability than volcanic rocks.
- Primary porosity in mafic and ultramafic rocks is composed of vesicles (spherical or ellipsoid cavities from trapped gas bubbles) and voids formed during emplacement or magma cooling. As a result, even if total primary porosity is high, the rock may still have low effective primary porosity and low primary permeability due to a lack of connectivity between individual vesicles.[20]
- Secondary porosity is generated by tectonic events, thermal stress, rock alteration, biological activity, fluid flow, etc. It can contribute to secondary permeability by connecting individual vesicles and pores.
- Secondary permeability is typically higher than primary permeability.
- The older the rock, the more likely its pores or fractures will be with filled with secondary minerals. However, this is not always the case and will depend on the diagenetic history of the rock.
- The more reactive the rock, the higher the likelihood that its pores or fractures will be filled with secondary minerals.

Permeability can be measured directly on rock samples or estimated based on material properties. In sedimentary CO_2 storage, initial resource modelling typically uses an idealized permeability derived from porous media models or databases of core measurements. Since mafic and ultramafic rocks function as a hybrid of fractured and porous media, it can be difficult to estimate reservoir-scale permeability. Some experience can be transferred from carbonate-hosted oil and gas reservoirs due to the importance of fracturing, but carbonates are not a direct analogue of crystalline hard rocks. Modelling is discussed in Section 4.1.

CO_2 injection into mafic and ultramafic rocks can impact porosity and permeability since CO_2 and CO_2-charged water can cause primary minerals to dissolve. This can increase secondary porosity and secondary permeability. Chemical species released from the

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[20] Effective pore volume is used here in line with the definition of effective porosity in the slb Energy Glossary.

dissolving rock can react with injected CO_2, water, and other elements in the reservoir to precipitate secondary minerals such as carbonates, zeolites, and clays. Secondary minerals typically have higher volumes than primary minerals, which can lead to a decrease in secondary porosity and secondary permeability. Secondary minerals can also coat surfaces in the rock, leading to passivation.

2.2.1. Large igneous provinces

The 2008 definition of a large igneous province (LIP) applies to igneous formations with an area greater than 100,000 km^2, an igneous volume over 100,000 km^3, an emplacement period of no more than 50 million years, and individual pulses of volcanisms lasting 1 to 5 million years (Bryan and Ernst, 2008). LIPs are important for mafic and ultramafic CO_2 storage because they are large volumes of CO_2-reactive rock (Table 4). All piloting of basalt-hosted CO_2 storage has been in LIPs: the Wallula Basalt Project was in the Columbia River Basalt Group and Carbfix's projects in Iceland are in the North Atlantic Igneous Province.

LIPs are composed of lava flows formed by surface eruptions and sills, and dykes that acted as the plumbing system for the lava. Dykes typically have lower primary porosity and permeability since they formed in the subsurface. Individual flows may have sediment buried between them; this is called interbedding. Some LIPs are better preserved than others; for instance, the Central Atlantic Magmatic Province (CAMP) is heavily eroded, with a maximum remaining thickness of around 500 m, while the significantly older Siberian Traps are much better preserved.

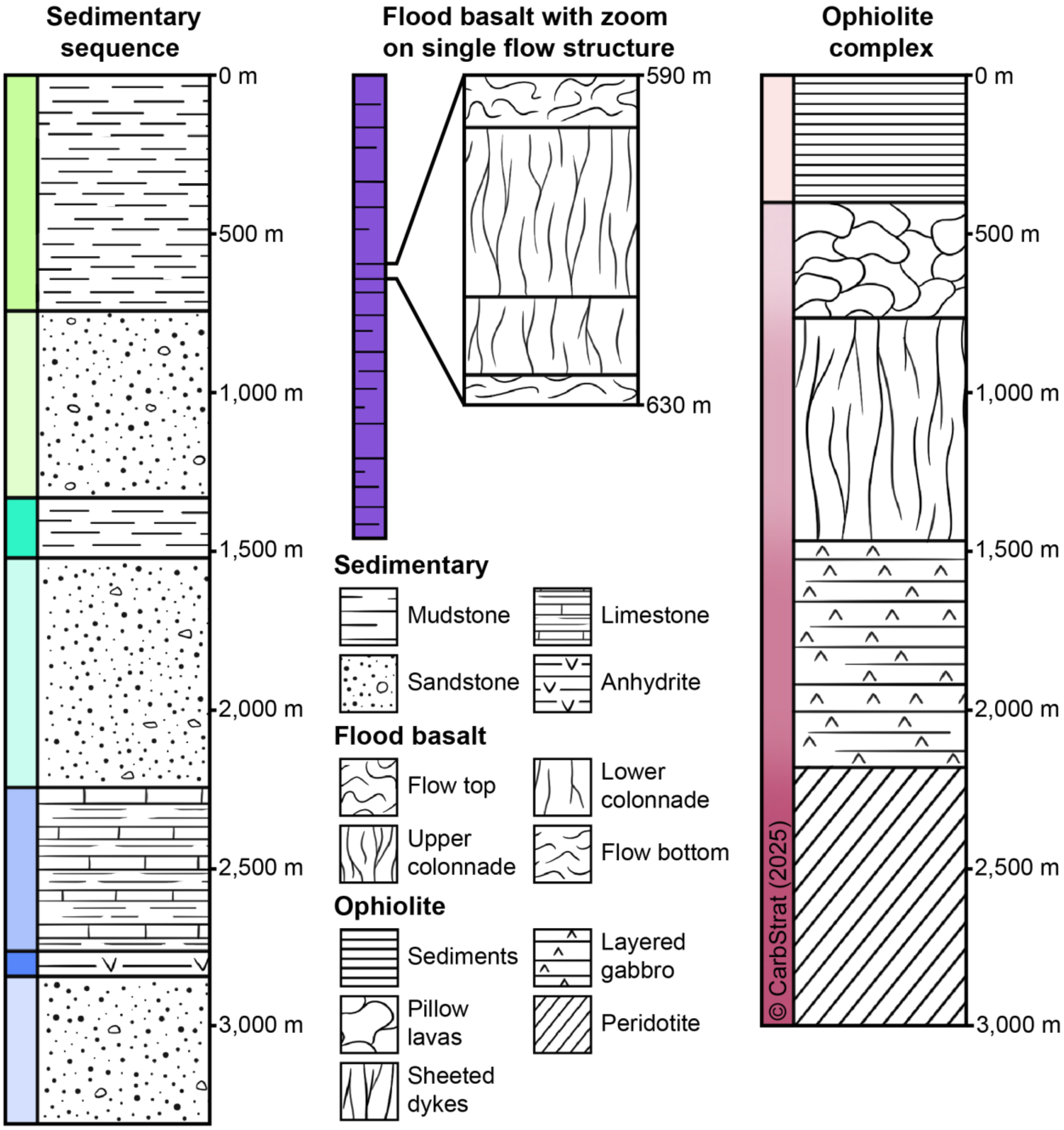
Stacked lava flows such as those found in LIPs can act as reservoirs hosting hydrocarbons and aquifers. The porosity and permeability of mafic or ultramafic rocks in LIPs varies depending on how they were formed. Magma type, lava flow type (related to the underlying dynamics of emplacement), flow structure, pore structure, and secondary processes following their initial formation, all influence porosity and permeability (Millett et al., 2024). Within lava flows, porosity and permeability are typically zoned. Flow tops and bottoms can have porosities in excess of 40% and high permeability ($> 10^{-11} m^2$), but flow interiors are typically much less porous (< 5%) and permeable ($< 10^{-16} m^2$) (Millett et al., 2024).

The Columbia River Basalt Group is one of the youngest and most extensively studied LIPs. Flows in the group can vary in thickness from just a few metres to over 100 m thick. Researchers have described the individual structure of flows that formed it, demonstrating the variability and zonation that exist within a vertical cross section of a single flow (Reidel et al., 2013). The flow structure shown in Figure 6 (centre) is an idealized representation based on vertical cross sections of flows from the Columbia River Basalt Group and the Deccan Traps. Lava flows are typically zoned with an identifiable flow top, interior, and bottom. Contact points between flow tops and flow bottoms are called interflow zones.

- **Flow tops** can be described as having two endmembers: they can be vesicular, with high concentrations of volcanic glass and vesicles slowly transitioning to a fine-grained basalt texture, or they can have breccia overlaying a coherent vesicular basalt (Reidel et al., 2013).
- **Flow interiors** are typically dense basalts with a glassy or fine-grained texture and limited vesicles. They often have cooling joints that can lead to columnar blocking, as observed in the UNESCO World Heritage Site of the Giant's Causeway in Northern Ireland and shown in the photo at the start of this chapter.

- **Flow bottom** structure and composition depend on what the lava encountered as it was emplaced. Flow bottoms can be vesicular with a glassy or fine-grained texture, or they can have more complex structures and textures. If a flow encounters water, it may produce pillow lavas with lobes of basalts rimmed by glassy rock fragments. The term hyaloclastite is specifically used to describe the glassy rocks that form when lava is quenched.

Figure 6. Idealized vertical cross sections of sedimentary resources (left), flood basalts (centre), and ophiolites (right)



Note: Vertical cross sections do not represent a specific resource or lithologic sequence.

Table 4. Locations, ages, and igneous volumes of selected large igneous provinces

Name	Location	Type	Age (Ma)	Area	Max thickness (m)	Lithology from literature	References
Columbia River Basalt Group	North America	C	20	210,000	3,000	Tholeiitic basalt	Bush and Seward (1992); Zakharova et al. (2012)
Afro-Arabian LIP	Arabian Peninsula, Africa	C	30	650,000	3,500	Silicic overlaying intermediate and basaltic rocks	Peate et al. (2005); Prave et al. (2016)
Sierra Madre Occidental	*SW USA, Mexico*	*S*	*30*	*500,000*	*1,000-1,500*	*Primarily silicic (ignimbrites) with intermediate basaltic andesites and some alkali basalts*	*Ferrari et al. (2018); McDowell, (2007)*
North Atlantic Igneous Province (NAIP)	Greenland, Northern Canada, Europe	C	60	1,300,000	10,000	Basalt with some interspersed rhyolite, dolerite dykes and plugs	Ganerød et al. (2010); Rohrman (2022)
Deccan Traps	India	C	70	500,000	1,800	Tholeiitic basalt	Krishnamurthy (2020); Prasanna Lakshmi et al. (2014)
Madagascar Flood Basalt	Africa	C	90	1,000,000	150	Picritic basalt to rhyodacite	Melluso et al. (2001)
Caribbean LIP (CLIP)	Central America, South America	O/C	90	1,540,000	3,000	Basalts, picrites, komatiites	Hauff et al. (2000); Kerr et al. (1997); Sandoval et al. (2015)
Rajmahal Traps	India	C	110	4,100	600	Tholeiitic basalt	Ghose et al. (1996); Singh et al. (2004)
Whitsunday LIP	*Australia*	*S*	*120*	*3,000,000*	*1,500*	*Primarily silicic, but includes basaltic to rhyolitic lavas*	*Bryan et al. (2000)*
Bunbury Basalt	Australia	C	130		40	Basaltic lavas, mafic sills and dykes	Olierook et al. (2015); Zhu et al. (2009)
Comei LIP	South Asia (North of Himalayas)	C	130		600	Basaltic lavas, mafic sills and dykes, layered pyroxenites and picrite porphyrites, and silicic volcanic rocks	Zhu et al. (2009)
Paraná-Etendeka Traps	South America, Africa	C	130	1,300,000	2,000	Tholeiitic basalts with some intermediate and silicic units	Gomes and Vasconcelos (2021); Halder et al. (2021)

Name	Location	Type	Age (Ma)	Area	Max thickness (m)	Lithology from literature	References
High Arctic LIP (HALIP)	Arctic	C	130	7,400,000	5,000	Mafic, composition ranges across formations from basanites to trachy-andesites	Bédard et al. (2021); Kristoffersen et al. (2023)
Karoo LIP	Southern Africa	C/S	180	140,000	2,000	Tholeiitic basalts to basaltic andesites	de Wit et al. (2020); Ivanov et al. (2017); Svensen et al. (2012)
Ferrar LIP	Southern Africa, South America, Antarctica	C/S	180	350,000	1,500	Sills: Dolerite; Lavas: basaltic andesite and andesitic basalt	Halder et al. (2021); Ivanov et al. (2017)
Chon Aike Silicic Province	*South America, Africa*	*S*	*180*	*100,000*	*2,000*	*Primarily rhyolitic with significant ignimbrites, includes basaltic andesites, basaltic trachyandesites and some basalts*	*Foley et al. (2023); Pankhurst et al. (1998)*
Angayucham LIP	Alaska, United States	O/C	200	100,000	> 2,000	Basaltic-gabbroic mid-ocean ridge basalt	Barker et al. (1988)
Central Atlantic Magmatic Province (CAMP)	North America, South America, Africa, Europe	C	200	7,000,000	500	Tholeiitic basalts to basaltic andesites	Marzoli et al. (2018, 1999)
Siberian Traps	Russia	C	250	3,470,000	3,600	Tholeiitic basalt, dolerite sills, some silicic floods	Krivolutskaya and Rudakova (2009); Lightfoot et al. (1990); Svensen et al. (2018)
Emeishan Traps	China	C	260	250,000	5,000	Basalts, dolerite, ultramafic rocks, and syenites	Shellnutt (2014); Xu et al. (2001)
Tarim LIP	Central Asia	C	280	250,000	780	Basats, rhyolites, ultramafic	Halder et al. (2021); Liu and Leng (2020); Yang et al. (2013)
Qiangtang-Panjal LIP	Central Asia	C	280	40,000	2,000	Alkali and tholeiitic basalts with mafic dykes, includes rhyolitic sequence	Dan et al. (2021)
Skagerrak-Centered LIP	Northern Europe	C	300	800,000	1,500	Basaltic lavas, mafic dykes	Neumann et al. (2025); Torsvik et al. (2008)

Name	Location	Type	Age (Ma)	Area	Max thickness (m)	Lithology from literature	References
Kennedy–Connors–Auburn Province	Eastern Australia	S	320	570,000		Rhyolite ignimbrite	Chen and Xu (2021)
Tianshan LIP	China	C	330		1,000	Includes ophiolite body	Xia et al. (2012)
Kola-Dnieper	Europe (Baltics)	C	380	2,960,000		Syenites, carbonatite intrusions, dolerite dykes, some tholeiitic basalt	Arzamastsev et al. (2010)
Yakutsk-Vilyui LIP	Russia	C	380	1,150,000	300	Trachybasalts to trachyandesites, tholeiitic basalt, associated diamondiferous kimberlites and volcanogenic sedimentary sequences	Kiselev et al. (2014)
Magdalen Basin	Eastern Canada	C/S	380			Tholeiitic to alkalic basalts	La Flèche et al. (1998)
Suordakh Event	Russia	C	440	400,000		Basalt to picro-basalts	Khudoley et al. (2013)

Notes: Ma = Million years; SW USA = Southwest United States; LIP = large igneous province; C = continental; O = oceanic; S = Silicic. Listed age is the oldest age associated with the LIP and only LIPs or large flood basalts younger than 500 Ma appear here. Greenland is excluded because insufficient information was found. Italic text denotes silicic large igneous provinces, which have been included here because they often include some basaltic sequences. The Rajmahal Traps does not meet the size definition for an LIP but has been included here due to limited sedimentary CO_2 storage resources in India. Blanks indicate where an area or thickness could not be found or if there was significant disagreement between sources.

Sources: Composition, age, and thickness from the references listed in the table. The list of LIPs under 500 Ma was compiled from Bryan and Ernst (2008); Ernst et al. (2021); Ernst and Buchan (2004).

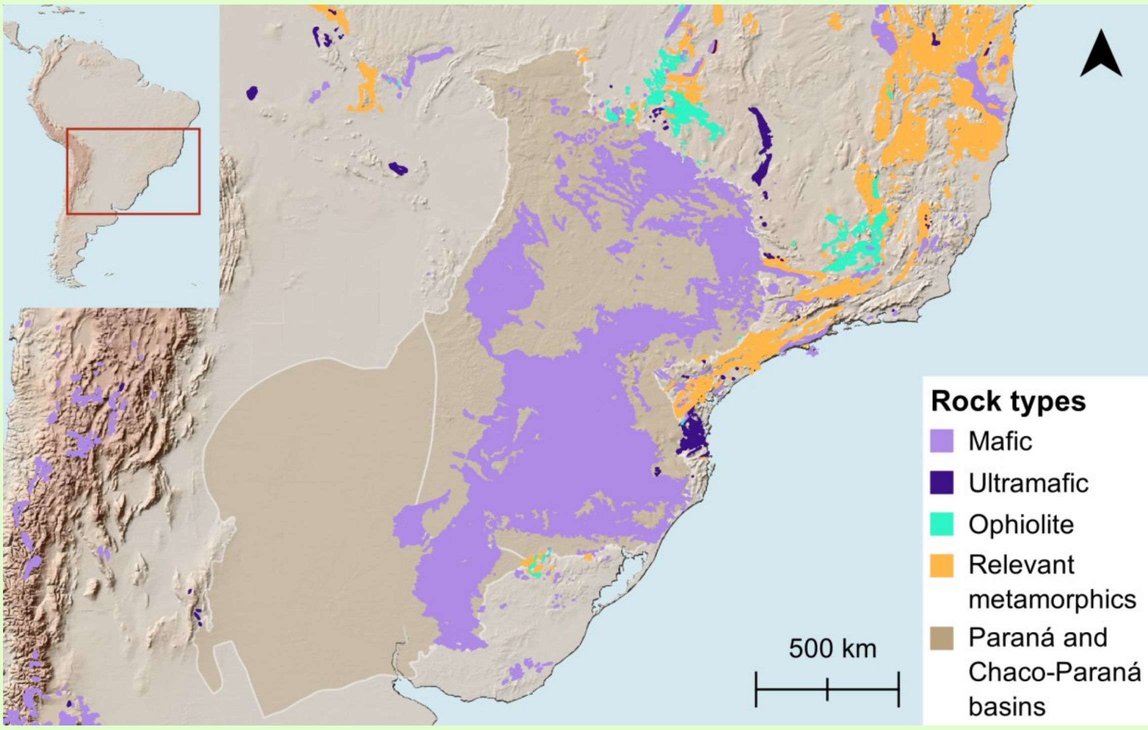
Box 3. Mafic–sediment interbedding and lava reservoirs in Brazil

Magmatism during the rifting of West Gondwana in the early Cretaceous led to the formation of the Paraná-Etendeka LIP (Figure 7). The LIP, which makes up some of the upper intervals of the Paraná Basin, includes lava flows which act as reservoirs and a dyke swarm that served as the LIP's plumbing system. It is part of an igneous hosted petroleum system (Ren et al., 2020; Rossetti et al., 2019, 2025).

The lavas flows found in the LIP range in composition from basalt to basaltic andesite. They are found at surface and extend into the subsurface for up to nearly 2,000 m (Gomes and Vasconcelos, 2021). Certain sections of the volcanic flows have high porosities of between 10-20% and relatively high permeabilities in the order of 100-1,000 millidarcies (mD) (Rossetti et al., 2025). Due to their thickness, porosity, and permeability, CO_2 storage in the Paraná-Etendeka lava flows may be possible. This is currently being investigated by researchers. In early 2025, a project, led by Professor Chang of Universidade Estadual Paulista "Júlio de Mesquita Filho" (unesp), was actively drilling shallow wells to characterize core samples in advance of a shallow injection test planned for later in 2025 (CNPq, 2025; Sidik, 2025).

In other regions of the Paraná Basin, such as Barra Bonita gas field, diabase dykes are interbedded with sediments hosting oil or gas. Since these plutonic rocks are relatively impermeable, pools of natural gas were able to accumulate below them (Ren et al., 2020). This suggests that sediments interbedded with mafic dykes may be targets for hybrid mafic CO_2 storage where the mafic rock serves as a caprock rather than the storage target.

Figure 7. Potential resource distribution in central South America



Sources: Sedimentary basins: Robertson Tellus (CGG) (2009). Rock distribution: Geological Survey of Brazil (SGB) (2004); Gómez et al. (2019). Elevation: Danielson and Gesch (2011).

2.2.2. Ophiolite complexes

Since ophiolites are visible on the surface, they act as natural laboratories where scientists can observe carbonation, serpentinization, and other low-temperature alteration processes. Because of their scientific importance and their close geographic grouping of multiple rock types, many regional geological maps will specifically identify ophiolites.[21]

Ophiolites can be found around the world, but notable examples include the Troodos Ophiolite in Cyprus, Samail Ophiolite in Oman, Dun Mountain Ophiolite in New Zealand, Bay of Islands Ophiolite in Canada, and Macquarie Island, Australia. These rocks are sections of oceanic crust and upper mantle that have been uplifted and exposed. They offer a window into the upper mantle and into crust-forming processes. Due to their uplift and subsequent weathering, not every part of the sequence is visible at each ophiolite, but the general sequence is seafloor sediments, pillow lavas, sheeted dyke complexes, intrusive gabbro, layered gabbro, and peridotites (Figure 6, right).

The mafic and ultramafic rocks found in ophiolites are typically metamorphosed to various degrees. Porosity and permeability will vary across the different zones of an ophiolite. Primary porosity and permeability are generally low in peridotites, gabbros, and sheeted dyke complexes, although fracturing, alteration, and faulting can contribute to secondary porosity and permeability. Primary porosity and permeability are typically higher in pillow lavas due to the presence of inter-pillow hyaloclastites. Secondary porosity and permeability will vary across the different rock types in an ophiolite sequence but will commonly occur via large fractures and faults. Secondary mineral infilling of fractures can include natural carbonate minerals, clays, zeolites, and other alteration products. In the ultramafic portions of ophiolites, fractures will be the main fluid transport pathways.

Project developers targeting peridotites will need to have a thorough understanding of the fracture network to ensure that fractures that cross the target injection reservoir do not provide a pathway for injected fluids to migrate to the surface. These rocks do not have conventional caprocks that can serve as a passive containment barrier. A more active approach to containment assurance, such as additional subsurface monitoring, may be required. If hydraulic fracturing is used to enhance permeability, operators need to be aware of the stress regime of the target reservoir and ensure that fracturing does not create potential leakage pathways to surface or non-target zones.

Box 4. Ophiolites and ultramafic rocks in SE Europe and SW Asia

High elevations and mountainous terrain can render resources inaccessible or make it significantly more complex and expensive to reach them. Under the Storage Resource Management System (SRMS), resources that cannot be developed for storage are defined as Inaccessible Storage Resources. Some of these resources may be developable in the future, but others may not be due to physical or societal constraints.

In the late Mesozoic and early Cenozoic, the African, Arabian, Indian, and Cimmerian plates collided with the Eurasian and Anatolian plates. This caused the Alpine orogeny, or mountain-building event. The resulting Alpide belt of mountains stretches from Spain to Indonesia. It includes the Alps, Himalayas, and several other mountain ranges.

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[21] The mapping work linked to this study refers to ophiolites as a “rock type” for simplicity.

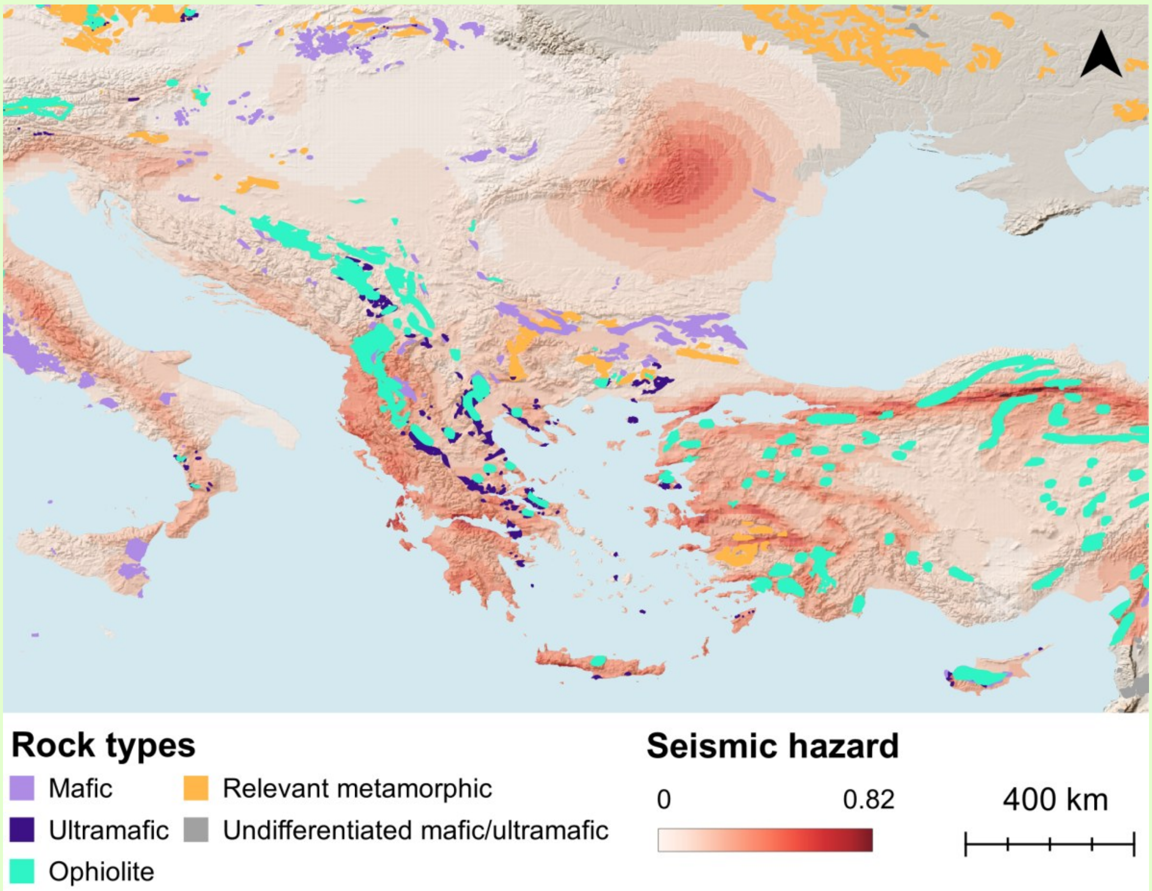
During the orogeny, oceanic crust and upper mantle were emplaced in what is now Southeastern Europe and Southwestern Asia. As a result, CO_2-reactive rocks can be found throughout the region at higher elevations or in mountainous terrain (Figure 8).

The Pindos ophiolite complex is found in northern Greece. Several mountains in the Pindos range, including Smolikas (2,632 m) and Vasilitsa (2,248 m) are part of that complex (Hughes et al., 2007). While these mountains may have the right rock type for mafic and ultramafic CO_2 storage, they are likely not accessible for CO_2 storage due to their terrain and because they are within an area of natural protection.

Development of potential resources in Southeastern Europe may also be affected by natural seismicity in the region. The region is the most seismically active in Europe owing to the continued subduction of the African plate beneath the Anatolia and Eurasia plates. This elevated seismic hazard of this region may also impact resource accessibility owing to concerns that fluid injection could trigger seismic events.

While it is premature to classify potential resources in Southeastern Europe and Southwestern Asis using the SRMS, it is probable that some will be undevelopable due to geographic considerations or because the risk of induced or tiggered seismicity cannot be derisked to an acceptable threshold. Resource assessment is needed to determine whether mafic and ultramafic CO_2 storage is possible in this region.

Figure 8. Potential resource distribution and seismic hazard in SE Europe and SW Asia



Notes: Seismic hazard is in peak ground acceleration (PGA). Elevation is displayed as relief.

Sources: Seismic hazard: Danciu et al. (2021). Rock distribution: Asch et al. (2022); Asch, K. (2003). Elevation: Danielson and Gesch (2011).

2.3. Mineral carbonation

As mentioned in Section 1.3, mineral trapping is one of four, potentially five, mechanisms that immobilize injected CO_2 in the subsurface. Mineral trapping, whereby CO_2 is trapped in carbonate minerals that precipitate from injected CO_2 and divalent metals present in the storage reservoir, can occur in both sedimentary and mafic or ultramafic CO_2 storage.

Mineral trapping is based on the carbonation reaction and is essentially a three-step process. First, CO_2 must dissolve into formation waters or be dissolved into an injectant such as water. Free-phase CO_2 can directly react with minerals, but typically reactions are between dissolved species – carbonic acid, carbonate ions, and bicarbonate ions – and minerals. Second, silicate minerals dissolve and release the metal cations needed for carbonate precipitation. This dissolution requires a low pH. Third, carbonate minerals precipitate in the reservoir following reaction between the CO_2-charged fluids and the released metal ions. This occurs at high pH. Silicate dissolution and carbonate precipitation buffer the pH of the system.

Mineral trapping is more relevant for mafic and ultramafic CO_2 storage than sedimentary storage due to the minerals that are found in the different rock types. Mafic and ultramafic rocks are composed of minerals that readily dissolve in acidic conditions and release divalent cations (Ca^{2+}, Mg^{2+}, and Fe^{2+}). Sedimentary reservoir rocks are typically made up of minerals, such as quartz or alkali feldspar, which are less reactive to CO_2. As a result, mineral trapping is unlikely to be a dominant trapping mechanism in sedimentary storage on short, medium, and even long timescales. [22]

2.3.1. CO_2 dissolution in water

When CO_2 is mixed with water, it will dissolve to form carbonic acid. The carbonic acid will in turn dissociate further, releasing bicarbonate and carbonate ions and protons. This reaction makes the water more acidic:

$$\mathrm{CO_2(aq) + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+} \qquad \textbf{Eq. 1}$$

In a pure water system, solubility typically increases with pressure and decreases with temperature (Figure 9). The pH of the resulting solution depends on the water-to-CO_2 ratio, the initial chemistry of the water, temperature, and pressure.

Geochemical modelling and laboratory experiments can be used to assess CO_2 dissolution in various types of water and whether dissolved species in the planned water type can have adverse interactions with either formation waters or reservoir rocks. The chemical composition of the injectant can impact silicate dissolution, mineralization rates, and the types of minerals that precipitate. Projects designed around aqueous injections will have variable water needs depending on the chemistry of the water they are using, and the temperature and pressure of the reservoir. Water ratios and water demands are discussed further in Section 3.2.2.

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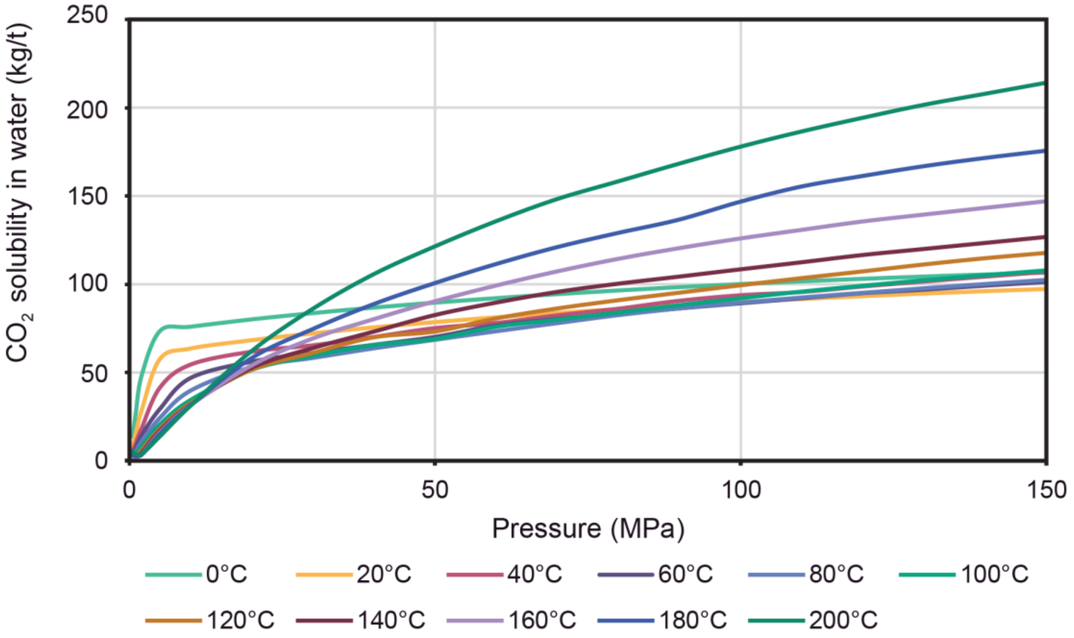
[22] Sedimentary rocks formed from mafic or ultramafic rocks, such as mafic sandstones, will also be CO_2-reactive. Mineral trapping may be a dominant trapping mechanism in such reservoirs.

Figure 9. Solubility of CO_2 in pure water



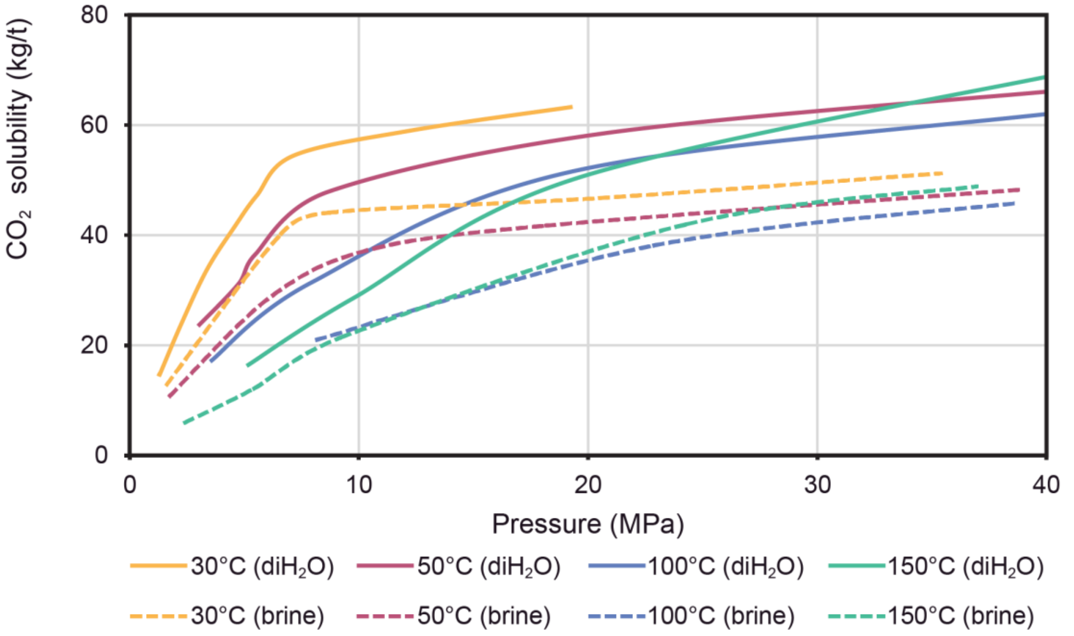
CarbStrat (2025). CC BY-SA.

Notes: MPa = megapascal. The 0°C and 20°C isotherms were calculated using equations from Spycher et al. (2003).

Source: Data excluding 0°C and 20°C from Wang et al. (2021).

In addition to pressure and temperature, water chemistry including salinity and total dissolved solids will also impact CO_2 solubility. Salinity can negatively impact CO_2 solubility across a range of temperatures and pressures (Figure 10).

Figure 10. Solubility of CO_2 in pure water and synthetic oilfield brine



Notes: diH_2O = deionized water. The synthetic brine used was composed of a mix of salts with a salinity of around 80,000 ppm (Ahmadi and Chapoy, 2018). Differences in CO_2 solubility between this figure and Figure 9 can be attributed to calculation or measuring methodologies.

Source: Data from Ahmadi and Chapoy (2018).

2.3.2. Silicate dissolution

When exposed to acidic fluids, silicate minerals in mafic and ultramafic rocks can dissolve and release the divalent cations needed for carbonate precipitation. Silicate mineral dissolution is widely considered to be the rate-limiting step in the carbonation process since silicate dissolution reaction kinetics typically are slower than carbonate precipitation kinetics (Gadikota et al., 2014; Kelemen et al., 2011; Snæbjörnsdóttir et al., 2020; Tutolo et al., 2021).

Dissolution kinetics, or the rate at which the minerals dissolve, are influenced by four main factors: pH, water activity in the system, temperature, and accessible rock surface area (Oelkers et al., 2018).[23] Individual mineral species and volcanic glass each have their own kinetics. Olivine dissolution rates typically are fastest between 150° and 200°C and at low pH (Hänchen et al., 2006; Oelkers et al., 2018). At high pH, olivine dissolves more slowly than other silicate minerals such as plagioclase, suggesting that an extremely low pH may not be required for rapid host rock dissolution in plagioclase-rich rocks like basalt (Gudbrandsson et al., 2011). These dissolution kinetics will also impact the type of mineral carbonates that will later precipitate since olivine, pyroxene, and plagioclase contain different concentrations of divalent metals. Olivine is rich in magnesium and iron and poor in calcium while the plagioclase minerals found in mafic and ultramafic rocks are typically calcium rich. Depending on the host rock, more magnesium and iron may be released in low pH systems where olivine dissolution is favoured, while more calcium may be released in higher pH systems where plagioclase dissolution is favoured (Gudbrandsson et al., 2011).

Reactive surface area likely plays an important role in dissolution rates, which can be impacted by surface passivation or mineral armouring. Amorphous silica layers and secondary minerals can coat reactive mineral surfaces, thereby isolating them from circulating fluids and reducing fluid–rock interactions. Biofilms grown by microorganisms can also create passivating layers, and microorganisms can exert localized control on the geochemistry of the system. This can change dissolution rates and the types of minerals that precipitate (Ménez et al., 2012).

Laboratory experiments on crushed or powdered rock, and rock plugs, along with studies of natural carbonation rates, inform our understanding of silicate dissolution kinetics and mineral carbonation. That being said, such laboratory experiments can exhibit faster dissolution rates than those observed in nature because of the increased mineral surface area that is available for reaction (Daval et al., 2011; Moore, 2018). In some cases, laboratory dissolution rates may align with those in nature (Kelemen et al., 2011).

2.3.3. Carbonate precipitation

As with silicate dissolution, carbonate precipitation kinetics are influenced by several chemical and physical factors including pH. At low pH dissolution of carbonate minerals is favoured, while precipitation of carbonate minerals accelerates at high pH (Pokrovsky and Schott, 2002). Carbonates are not the only minerals that can precipitate when carbonic acid interacts with mafic or ultramafic rocks. Naturally occurring alteration products, including

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[23] Water activity is the energy state of available water, which relates to how much water is available for chemical reactions.

zeolites, clays, carbonates, and iron oxides, offer clues to how CO_2 storage may influence secondary mineral formation.

Table 5 presents a simplified overview of carbonation reactions for key mineral species. The secondary minerals that form will depend on the temperature, pH, and geochemistry of the system. As with other rock-forming minerals, carbonate minerals form solid solutions. Calcite ($CaCO_3$), siderite ($FeCO_3$), and magnesite ($MgCO_3$) are only some of the carbonate mineral species that may be precipitated. For example, the Wallula Basalt Project observed that ankerite, $Ca(Fe,Mg,Mn)(CO_3)_2$, precipitated following their supercritical CO_2 injections (McGrail et al., 2017b). Additionally, hydrated minerals such as serpentine and hydroxylated minerals such as brucite can also form.

Table 5. Simplified carbonation reactions for key mineral species

Mineral species	Idealized carbonation reaction	
Olivine		
Fosterite	$Mg_2SiO_4 + 2CO_2 = 2MgCO_3 + 2SiO_2$	**Eq. 2**
Fayalite	$Fe_2SiO_4 + 2CO_2 = 2FeCO_3 + 2SiO_2$	**Eq. 3**
Plagioclase		
Anorthite	$CaAl_2Si_2O_8 + 2H_2O + CO_2 = CaCO_3 + Al_2Si_2O_5(OH)_4$	**Eq. 4**
Pyroxene		
Enstatite	$Mg_2Si_2O_6 + 2CO_2 = 2MgCO_3 + 2SiO_2$	**Eq. 5**
Ferrosilite	$Fe_2Si_2O_6 + 2CO_2 = 2FeCO_3 + 2SiO_2$	**Eq. 6**
Wollastonite	$Ca_2Si_2O_6 + 2CO_2 = 2CaCO_3 + 2SiO_2$	**Eq. 7**

Notes: Reactions are idealized. Wollastonite is not technically a pyroxene group mineral, but it is commonly used as an endmember of the pyroxene solid solution series.

Existing projects have observed or modelled the likely precipitation of zeolites and clays as a result of CO_2 injections (Oelkers et al., 2019; Pogge Von Strandmann et al., 2019). If rapid carbonation is desired, the geochemistry of the system will need to be carefully controlled. Geochemists can model and assess the carbonation process through reactive transport models; these are discussed in more detail in Section 4.1.2.

Close up of carbonate veins in a peridotite. CC BY-SA 2.5 Katie Pratt via Wikipedia.

Chapter 3. The technological basis of mafic and ultramafic CO_2 storage

Key takeaways

The technological basis of mafic and ultramafic storage borrows from sedimentary CO_2 storage, geothermal activities, nuclear waste disposal, oil and gas, environmental remediation, and hard rock mining. These activities contribute valuable knowledge that supports the development of this type of storage.

Due to geochemical constraints, it is likely that large-scale supercritical CO_2 sites in mafic and ultramafic resources will have mineralization rates in the order of centuries rather than the years that aqueous CO_2 sites may have. Regardless of injection style, mineralization will be faster in mafic or ultramafic rocks than in sedimentary resources.

Operating aqueous projects use a range of different water-to-CO_2 ratios, but the literature most commonly references 20-30 t water to 1 t CO_2. That is approximately one-third of the annual water consumption of a resident of France (France Stratégie, 2024). A site that aims to inject 1 Mt CO_2 per year would require ~20-30 Mt of water per year, or around 12-18% of the annual domestic water consumption of Paris (Apur, 2022). Water production may be required to mitigate increases in subsurface formation pressure. Produced formation water, seawater or wastewater can all be used to dissolve CO_2. Aqueous injections do not have to use potable water.

Modelling of water-alternating-gas (WAG) injections found that when compared to pure CO_2 injections (e.g. a supercritical injection), WAG with water-to-CO_2 ratios between 1:1 and 10:1 can moderately improve mineralization efficiency. At high water-to-CO_2 ratios (e.g. 27:1) WAG injections can be more efficient than aqueous injections. This injection style could offer a compromise between the water demand of aqueous injections and the slower predicted mineralization rates of supercritical injections.

While mafic and ultramafic rocks rarely have conventional caprocks like a shale or anhydrite, they can still have a structural trap. Localized CO_2 mineralization in fracture branches or along glassy rims can self-seal fluid migration paths. Mineralization is not a requirement for safe and secure CO_2 storage in mafic and ultramafic rocks, if CO_2 can be contained structurally.

From a technology readiness level (TRL) point of view, mafic and ultramafic CO_2 storage is approximately 30 years behind dedicated CO_2 storage in sedimentary resources. Today, no mafic or ultramafic site has exceeded around 14 ktpa of annual injection and in aggregate less than 120 kt of CO_2 has been injected globally into these resources.[24] Comparatively, more than half of the operating dedicated sedimentary CO_2 storage sites have nominal injection capacities above 1 or 2 Mtpa (Table 6). In 2026, Sleipner, the first dedicated CO_2 storage site, will reach 30 years of operation, and by the end of 2020 it had injected and stored more than 19 Mt of CO_2 (Equinor, n.d.). Additionally, CO_2 has been used as a working fluid for enhanced oil recovery (CO_2-EOR) in oil reservoirs since the 1970s.

Table 6. Operating dedicated sedimentary CO_2 storage sites

Site or project name	Location	Nominal injection capacity (Mtpa)	Start of operations	Resource type
Sleipner	Off Norway	1	1996	Saline aquifer
Snøhvit	Off Norway	0.7	2006	Saline aquifer
Quest	Canada	1.3	2015	Saline aquifer
Illinois Industrial	United States	1	2017	Saline aquifer
QatarEnergy LNG	Qatar	2.2	2019	Saline aquifer
Gorgon	Australia	4	2019	Saline aquifer
Richardton Ethanol	United States	0.18	2022	Saline aquifer
CNOOC Enping	China	0.3	2023	Saline aquifer
Blue Flint Ethanol	United States	0.2	2023	Saline aquifer
Moomba	Australia	1.7	2023	Depleted reservoirs

Note: Projects listed as in “Deep Saline Formation” in the GCCSI’s 2024 Global Status Report were excluded if they were operating in the United States via UIC Class II wells rather than Class VI wells, or if in their current phase they capture and store less than 100 ktpa.

Sources: GCCSI (2024a); IEA (2025).

To discuss the technological basis of mafic and ultramafic storage it is necessary to define a target size for future CO_2 storage sites. This work considers a site large-scale if it has a nominal CO_2 injection capacity of at least 100 ktpa and plans to inject for at least 15 years. This requires a CO_2 storage resource of at least 1.5 Mt. A 100 ktpa site injecting into a mafic or ultramafic resource will be able to accommodate small emitters or direct air capture plants. A large-scale site is more than double the largest permitted mafic or ultramafic CO_2 storage well and is about 1,000 times larger than sites operating outside Iceland. Such sites are likely to have a higher levelized cost of CO_2 storage than sedimentary storage sites since they do not capitalize on economies of scale. Nevertheless, they would provide valuable learning and help demonstrate the scalability of mafic and ultramafic CO_2 storage.

This does not mean that we need another 30 years of research and development before large-scale CO_2 storage operations can start in these rocks. There is an existing technological foundation developed from sedimentary CO_2 storage, geothermal activities, nuclear waste disposal, oil and gas, environmental remediation, and hard rock mining. Even though no large-scale mafic or ultramafic CO_2 storage sites are yet operating, this type of CO_2 storage has been piloted and demonstrated by several companies and research groups (Table 7). Some small-scale sites are also in commercial operation.

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[24] Estimated from injection reported National Inventory Documents and documentation outside Iceland from other known injection projects. For the period of 2012-2023, 94.5 kt of CO_2 had been injected in Iceland (Icelandic Environment and Energy Agency, 2025a; Environment Agency of Iceland, 2024); 120 kt CO_2 is likely to be an overestimation.

Table 7. Completed and operating mafic and ultramafic CO_2 storage projects

Project name	Developer	Location	Resource type	Date	Project status	Amount injected	Injection style
Palisades	Columbia University	New Jersey, USA	Diabase	2004	Completed	1.5 t CO_2	Aqueous
CarbFix1	CarbFix consortium	Hellisheiði, Iceland	Vesicular basalt	2012-2014	Completed	P1: 175 t CO_2 P2: 55 t CO_2, 18 t H_2S	P1: Aqueous (22:1) P2: mixed gas
CarbFix2	CarbFix consortium	Hellisheiði, Iceland	Vesicular basalt	2014-2017	Completed	23.2 kt CO_2 11.8 kt H_2S	Aqueous mixed gas
Seastone	Carbfix	Helguyik, Iceland	Vesicular basalt	2023	Unclear	1 kt CO_2	Aqueous (seawater)
Nesjavellir Geothermal Pilot	Carbfix	Nesjavellir, Iceland	Vesicular basalt	2023-ongoing	Ongoing with scale-up plans	Total unknown Announced: 3 ktpa CO_2, 1 ktpa H_2S	Aqueous
Hellisheiði site* (Hellisheiði 1)	Carbfix	Hellisheiði, Iceland	Vesicular basalt	Likely since the end of 2017	On injection	Total unknown Permitted rate: 47 ktpa CO_2, 11 ktpa H_2S	Aqueous (88:1) mixed gas
Unknown project name* (Jarðhitagarður 4)	Carbfix	Hellisheiði, Iceland	Vesicular basalt	Unknown	Permitted in 2025	Total unknown Permitted rate: 15 ktpa CO_2	Aqueous (26:1)
Mammoth DAC* (Jarðhitagarður 3)	Carbfix	Hellisheiði, Iceland	Vesicular basalt	2024-ongoing	On injection	Total unknown Permitted rate: 40 ktpa CO_2	Aqueous (61:1)
Orca DAC* (Þrengsli 2)	Carbfix	Hellisheiði, Iceland	Vesicular basalt	2021-ongoing	On injection	Total unknown Permitted rate: 4 ktpa CO_2	Aqueous (23:1)
Wallula Basalt Project	PNNL	WA, USA	Flood basalt	2013	Completed	977 t CO_2	Supercritical

Project name	Developer	Location	Resource type	Date	Project status	Amount injected	Injection style
Oman Pilot	44.01	Oman	Peridotite	2021-2023	Test completed, in scale-up	Unknown	Aqueous
Fujairah Demonstration	44.01	Fujairah, UAE	Peridotite	2023	Test completed, in scale-up	10 t CO_2	Aqueous
Jizan	Aramco	Jizan, KSA	Basalt	2023	Test completed, in scale-up	131 t CO_2	Aqueous

* Sites for which Carbfix received permits in 2025. Project documentation is taken from those permitting documents. Some injection infrastructure may have been reused from the pilot projects.

Notes: PNNL = Pacific Northwest National Laboratory; WA = Washington State; USA = United States; UAE = United Arab Emirates, KSA= Kingdom of Saudia Arabia. The ratios listed in the injection style column are the water-to-CO_2 ratios when known. They are defined based on the permitted maximum allowable injection rate of water and CO_2 (kg H_2O per second (/s): kg CO_2/s). Mixed gas refers to aqueous injections of both CO_2 and H_2S.

Sources: Press releases, discussions with project operators, Clark et al. (2020); Icelandic Environment and Energy Agency (2025b); Matter et al. (2007); McGrail et al. (2017b).

Table 8. Mafic and ultramafic CO_2 storage activities in development or companies with announced plans to develop projects

Project name	Developer or consortium lead	Location	Resource type	Project status	Indicative size	Injection style
Fujairah Demo	44.01	Fujairah, UAE	Peridotite	Scale-up in development	300 t	Aqueous (seawater)
Project Hajar	44.01	Oman	Peridotite	Scale-up in development	1,000 t	Aqueous (seawater)
Jizan	Aramco	Jizan, KSA	Basalt	Scale-up in development	Unknown	Aqueous (water type unknown)
Coda Terminal	Carbfix	Iceland	Basalt	In development	P1: 500 ktpa Scaled up: 3.1 Mtpa	Aqueous (freshwater)
SiMBa*	Carbon Solutions	Nebraska, USA	Basalt	In development	> 50 Mt resource capacity	Supercritical
Project Hummingbird	Cella	Kenya	Basalt	In development	1 ktpa	WAG
Project Jacaranda	Cella	Kenya	Basalt	In development	Unknown	WAG

Project name	Developer or consortium lead	Location	Resource type	Project status	Indicative size	Injection style
SAM site	CO$_2$Lock	British Columbia, Canada	Brucite rich sequences	In development	Unknown start size, scale up to 1 Mtpa	Aqueous
Leandra, Mpumalanga research site	Council for Geosciences	South Africa	Basalt	In development	Test-bed or pilot	Aqueous
Deep Sky One	Deep Sky	Quebec Canada	Ultramafic	In development	Unknown	Aqueous
CANstore*	EPRI	California, USA	Basalt	In development	> 50 Mt resource capacity	Supercritical
Carbozorb	Hardie Pacific	New South Wales, Australia	Ultramafic	In development	> 50 Mt resource capacity	Aqueous
Weora	Hardie Pacific	New Zealand	Ultramafic	In development	Unknown	Aqueous
Grays Harbor*	Projeo	Washington, USA	Basalt and basaltic sandstone	In development	> 50 Mt resource capacity	Supercritical
Tamarack Intrusive	Talon Metals Corp.	Minnesota, USA	Ultramafic	In development	Unknown	Unknown
Ankeron DAC Hub*	Rocky Mountain Institute	Washington, USA	Basalt	In development	> 50 Mt resource capacity	Unknown
CO$_2$HQ*	University of Arizona	Arizona, USA	Mafic lava flows as seals	In development	> 50 Mt resource capacity	Unknown
SICarbS*	University of Iowa	Iowa, USA	Basalt	In development	> 50 Mt resource capacity	Unknown
SHINE*	University of North Dakota EERC	Washington, USA	Basalt	In development	> 50 Mt resource capacity	Unknown
HERO*	University of Wyoming	Oregon, USA	Basalt	In development	> 50 Mt resource capacity	Unknown

* Indicates projects that are supported by the US Department of Energy's CarbonSAFE program; to qualify for CarbonSAFE support, the project must have confidence that the resource under assessment is able to store at least 50 Mt of CO$_2$.

Notes: PNNL = Pacific Northwest National Laboratory; WA = Washington State; USA = United States; UAE = United Arab Emirates, KSA= Kingdom of Saudia Arabia. P1 = Phase 1. This table aims to be comprehensive, but omissions may be present. It is unclear from press releases whether Cella has two projects or if they are the same project with a different name. This table includes any activities that were identified as potential pilots, site-specific resource assessment, and/or commercial project development. Not all listed projects may enter operations; some listed activities may be research oriented.

Sources: Publicly available information, peer-reviewed papers, press releases, conference proceedings, and discussions with individuals active in the mafic and ultramafic CO$_2$ storage space.

Mafic and ultramafic resources are still quite far from hosting sites that inject 100 ktpa or 1 Mtpa. Several companies and organizations are currently working to develop mafic or ultramafic CO_2 storage projects across a range of scales and geographies (Table 8).

While several activities in development are small-scale, others are looking at developing large scale sites. Carbfix has received EU Innovation Fund support for the development of the Coda Terminal in Iceland. According to project documentation, the Coda Terminal should start injecting around 500 ktpa of CO_2 in mid-2026 and scale up incrementally to 2031 when it aims to reach an injection capacity of around 3 Mtpa of CO_2 (Johannsson, 2023; Voigt and Galeczka, 2025). The initial capacity of the Coda Terminal is slightly larger than the Greensand Future storage site currently being constructed off Denmark and the Coda Terminal's expanded capacity would be around double the capacity of Northern Lights Phase 1 off Norway.

The US Department of Energy CarbonSAFE Program in the United States is supporting the assessment and characterization of several prospective mafic and ultramafic storage resources. The CarbonSAFE program supports CO_2 storage resource assessment and the development of CO_2 storage resources that can likely store at least 50 Mt over the lifetime of the storage site. The programme is resource type agnostic, and the most recent round of awards included several projects targeting mafic or ultramafic resources (NETL, n.d.).

3.1. Injection aim

Dedicated CO_2 storage is fundamentally a climate tool aimed at reducing the amount of CO_2 that is in the atmosphere by locking it away in a geological formation where it will remain for many thousands to millions of years. As discussed in Section 1.3, several different trapping mechanisms contribute to the safe and secure storage of CO_2 in geological reservoirs. The importance of these mechanisms and the timescales at which they become active varies between resource types. This is a key difference between sedimentary CO_2 storage resources and mafic and ultramafic CO_2 storage resources.

Mafic and ultramafic storage resources offer a pathway for accelerated mineral trapping, which locks CO_2 in the subsurface via geochemical rather than physical means (McGrail et al., 2006). For this reason, it is sometimes called in situ mineralization or mineral CO_2 storage. This type of CO_2 storage is less mature than CO_2 storage in sedimentary reservoirs, with the first research injection occurring in 2004 in the Palisades Sill in the United States.

Based on the modelled mineralization rates for large-scale injections and water demands, supercritical and aqueous CO_2 injections represent the two endmembers of CO_2 injection styles into mafic and ultramafic rocks. Rapid CO_2 mineralization was observed in both a supercritical injection pilot and aqueous injection pilots (Matter et al., 2016; McGrail et al., 2017b; White et al., 2020). At high injection rates, supercritical CO_2 injections are likely to result in lower carbonation efficiency due to lower alkalinity in the reservoir (Nelson et al., 2025; Postma et al., 2022a; Tutolo et al., 2021).

Aqueous and WAG injections may result in more rapid mineralization than supercritical injections, but they require large volumes of water to be co-injected with CO_2 (Table 9). Since water is a relatively incompressible fluid, additional fluid injection may accelerate pressure increases in the reservoir if water is not being produced for pressure relief or to be used as the injectant. As a result, aqueous and WAG injections may need to be smaller in scale and/or require more wells and infrastructure to reach similar nominal CO_2 injection rates when compared to supercritical CO_2 injections.

These injection styles may reduce total injectivity and may represent less efficient use of the CO_2 storage resource. However, aqueous and WAG injections do not require CO_2 to remain in supercritical form, so they do not need to occur at depths greater than 800 m. Therefore, these injection styles may make it feasible to have shallower injections. To protect groundwater resources and reduce the risk of accidental production of injected CO_2 in water wells, CO_2 should be injected deeper than the deepest potable water aquifer in the target region.

Given that large quantities of water may be required for rapid mineral trapping, as mafic and ultramafic CO_2 storage scales up, project developers will need to consider the trade-off between mineralization rates, water demands, and efficient use of resources. WAG and aqueous injections will normally have higher capital and operating costs than supercritical projects of a similar size due to the additional infrastructure and energy they require to pump water and dissolve CO_2. Infrastructure needs and cost components are discussed in more detail in Chapter 5.

It is necessary to evaluate whether CO_2 mineralization should be the primary goal of mafic and ultramafic storage and whether it is the most efficient use of these storage resources. It is becoming increasingly recognized that pressure, and in particular the safe threshold to which to increase subsurface pressure, can be more of a limiting factor than pore space within a resource (Bump and Hovorka, 2024). While this is understood for sedimentary resources, it is still untested in the field for mafic and ultramafic resources given the small scale of projects currently operating. Nevertheless, as with sedimentary storage, pressure is likely to be one of the most significant constraints on large-scale mafic and ultramafic storage.

Mineralization is not required for the safe and secure storage of CO_2 in mafic and ultramafic rocks if containment can be assured in other ways. Ultimately, some mafic and ultramafic projects may wish to rapidly mineralize their CO_2, while others may seek to maximize the amount of stored CO_2 and rely on physical trapping mechanisms. Certain resources may lend themselves more to one injection style or another. This suggests that globally referring to mafic and ultramafic CO_2 storage as CO_2 mineralization or CO_2 mineral storage could be misleading. Therefore, as first mentioned in Section 1.2, this report uses resource-focused terminology to describe this type of storage rather than trapping mechanism-focused terminology.

Fracture networks in mafic and ultramafic resources are likely to serve both as an important source of permeability and potential containment risks. Since mafic and ultramafic sequences often lack conventional caprocks, active monitoring may be required to de-risk vertical leakage. This active monitoring is likely to be required regardless of injection style to ensure that injected CO_2 does not interact with potable sources of groundwater or exit the targeted storage zone.

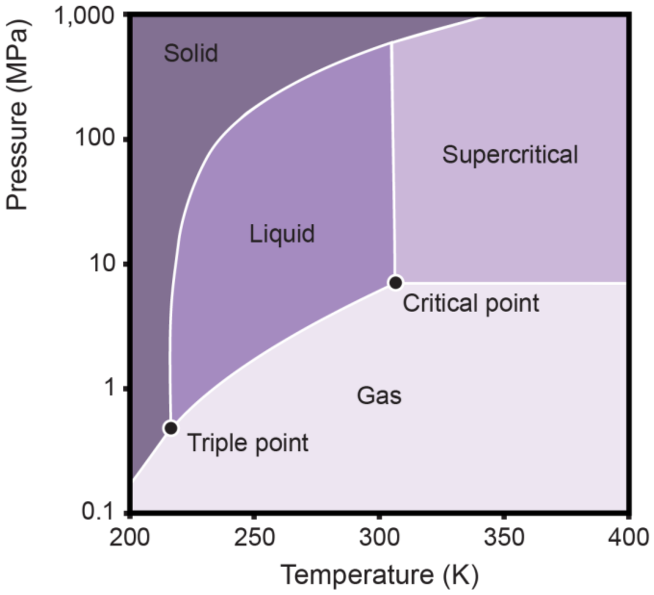
Flow interiors in flood basalts are not identical analogues to shale, mudstone, or anhydrite caprocks, but they may be able to serve as vertically confining features when paired with appropriate monitoring (McGrail et al., 2006; Millett et al., 2024). Flow interiors have much lower primary porosity and primary permeability than interflow zones due to their comprehensive nature, but they typically have columnar jointing, which could provide vertical pathways for fluid flow. Research suggests that supercritical CO_2 accumulates at the intersection of branching fractures, leading to localized mineralization, which could contribute to self-sealing (Pollyea and Benson, 2018). Additionally, many fractures may be closed due to the stress state of the rock (Millett et al., 2024). If CO_2 is injected into a deep interflow zone, a series of flow interiors can serve as vertically confining so long as the sequence is not crosscut with faults. The tortuosity of flow paths across a stack of flow interiors when paired with the reactivity of mafic minerals should restrict upward mobility of CO_2 (Gierzynski and Pollyea, 2017). As with sedimentary CO_2 storage resources, containment needs to be assessed on a site-by-site and resource-by-resource basis. The flow interiors of one flood basalt may provide sufficient vertical containment, while the flow interiors of another may be crosscut with faults or fractures that link directly to potable water sources. Peridotites and plutonic mafic rocks may have large fracture networks that propagate from depth to surface or vice versa, which could increase leakage risks.

The rapid mineralization potential that exists in mafic and ultramafic rocks may provide this type of storage with some advantages over sedimentary storage. However, further research, development, and demonstration are required to robustly evaluate this. If sites can demonstrate rapid mineralization of their injected CO_2, they may be able to have reduced post-closure monitoring requirements as compared to sedimentary CO_2 storage sites. This in turn could potentially reduce liability. This is speculative since there are no large-scale sites currently in operation. Today, mineral trapping is only demonstratable through geochemical analysis of rock and/or fluid samples paired with modelling. This is discussed further in Section 5.3.

3.2. Injection styles

Free-phase CO_2 can be injected in gas, liquid, or supercritical form (Figure 11). If CO_2 is first dissolved in a fluid such as water and then injected it is called an aqueous injection. An overview of injection styles is found in Table 9.

Figure 11. CO_2 phase diagram



CarbStrat (2025) CC BY-SA.

Notes: K = Kelvin; MPa = megapascal.

Source: After Witkowski et al. (2013).

In the subsurface, starting at around 800 m deep, reservoir pressure conditions are usually above the CO_2 condensation point. For free-phase injections, storage developers usually target an injection depth of 800 m or deeper to allow CO_2 to be stored in supercritical form.

Supercritical form is targeted because it allows for efficient use of resources. Sometimes sites that target supercritical CO_2 storage will inject CO_2 in gas phase initially to reduce the risk of near-wellbore damage caused by cold shock. When CO_2 enters the reservoir from an injection well it can experience evaporative or adiabatic cooling or the Joule-Thomson effect. These different processes can all cause a rapid decrease in temperature, which can lead to reservoir fracturing or damage to injection zone infrastructure. Injection of cold fluids can also sometimes lead to fracturing. When done intentionally to enhance permeability it is called reservoir stimulation.

Table 9. Comparison of mafic and ultramafic injection styles

Criteria	Supercritical	WAG	Aqueous
Water demands	**Very low** ▪ Strictly for surface operations	**Low to high** ▪ Depends on WAG injection parameters	**Very high** ▪ ~20-30 t H_2O to 1 t CO_2 ▪ Can use aquifer water ▪ Can use wastewater or seawater
Depth	**> 800 m** ▪ Potentially shallower depending on reservoir pressure	**Variable** ▪ Dictated by regulation and WAG injection parameters ▪ Likely deeper than aqueous	**Variable** ▪ Dictated by regulations related to groundwater and other subsurface activities
Vertically confining features	**Required**	**May be required** ▪ Monitoring fluid movement and mineralization could be a substitute	**May be required** ▪ Monitoring fluid movement and mineralization could be a substitute
Pressure considerations	▪ Resource and site engineering dependent ▪ Like sedimentary resource pressure management needs	▪ Will depend on WAG injection parameters ▪ May need water production for pressure management	▪ May need water production for pressure management (produced water could be used for CO_2 dissolution)

Notes: Aqueous injections may require additional permits related to water injection and/or water production. Using wastewater or seawater to dissolve and then inject CO_2 may not be legal in every jurisdiction. Wastewater and seawater chemistry may affect CO_2 solubility, silicate dissolution, and/or carbonate mineralization depending on the other chemical species present in the water.

3.2.1. Supercritical CO_2 injection

Supercritical CO_2 injections into mafic or ultramafic rocks will normally target a zone deeper than 800 m so that injected CO_2 remains in dense phase.[25] Shallower reservoirs can be

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[25] Dense phase refers to CO_2 that is above the critical pressure of CO_2 (73.5 bar or 7.35 MPa) and is not in solid form. At temperatures below the critical temperature of CO_2 (31.8°C), dense phase CO_2 will be a dense liquid. At temperatures higher than 31.8°C, dense phase CO_2 is supercritical (NIST, 2025).

targeted if they are above the critical pressure of CO_2. One of the biggest challenges for any supercritical CO_2 storage site is ensuring containment of CO_2; the second is ensuring sufficient injectivity.

A report on the opportunities to scale up CO_2 storage in the Columbia River Basalt Group investigated the maximum achievable injectivity based on pressure limitations. They found that a single well operating at 95% borehole breakout pressure could conceivably inject between 0.12 and 2 Mtpa of supercritical CO_2 for 20 years (Pollyea and Benson, 2018). This work was an initial look at field data-constrained modelling of multiphase flow and maximum injection rates in mafic rocks. While it provides a very large injection rate range, that study and a companion paper suggest that it will be possible to achieve Mt-scale mafic and ultramafic CO_2 storage sites with supercritical injections (Jayne et al., 2019). Given the limited operational experience with mafic or ultramafic CO_2 storage, it is advisable to incrementally scale up injection rather than moving directly to Mt-scale wells.

Example projects

Supercritical injection of CO_2 into basalt was piloted during the Wallula Basalt Project implemented by the Pacific Northwest National Laboratory (PNNL) in the United States. That project injected 977 t of CO_2 into the Columbia River Basalt Group over a three-week period in 2013 (McGrail et al., 2017b). The injection targeted two permeable interflow zones located around 830-890 m below surface. It is the main example of supercritical CO_2 storage in mafic or ultramafic rocks.

Two years after injection, sidewall cores retrieved from the injection zone were found to have carbonate nodules in vesicles and veins (McGrail et al., 2017a). Isotopic analysis of those carbonates found that they were composed of ankerite, a naturally occurring carbonate from the dolomite group, and that they were formed from injected CO_2. A later paper used comparative hydrologic test analysis to assess how much injected CO_2 mineralized. That work found that around 60% of the CO_2 injected at the Wallula site was mineralized within about two years (White et al., 2020).

3.2.2. Aqueous CO_2 injection

Aqueous CO_2 injections dissolve CO_2 in water prior to its injection into the target formation. CO_2 can be dissolved at surface and then the CO_2-charged water can be injected, or the water and CO_2 can be mixed down-well prior to injection. Initially, dissolution is a physical process, but CO_2 then reacts with water to form carbonic acid, which then dissociates further (see Section 2.3). Aqueous CO_2 injections do not require reservoirs with pressures and temperatures above the CO_2 critical point; however, the specific reservoir properties need to ensure that CO_2 cannot outgas from the solution.

In principle, aqueous CO_2 injections can be shallower than supercritical injections because the site does not need to have reservoir conditions above the critical point of CO_2. However, regulatory frameworks protecting groundwater resources are likely to place limits on how shallow aqueous injections can occur. Additionally, the shallower the injection, the smaller the volume of rock available to attenuate CO_2 if it were to exit the target injection zone. Shallower sites will also have lower pressure, which could impact the solubility of CO_2.

The amount of water required to dissolve 1 tonne of CO_2 varies with temperature, pressure, and water chemistry (see Figure 9 and Figure 10). In general, about 20 to 30 tonnes of water is needed to dissolve 1 tonne of CO_2 at pressures and temperatures relevant to most mafic and ultramafic CO_2 storage sites (Nelson et al., 2025; Snæbjörnsdóttir et al., 2020). Sites may choose to inject with a higher water-to-CO_2 ratio than is required for complete CO_2 dissolution if they also have to dispose of water from other activities.

According to the permits Carbfix received in May 2025, the company is using several different ratios of water to CO_2, including 88:1, 61:1, 26:1, and 23:1 (Icelandic Environment and Energy Agency, 2025b). The injection well permitted with the highest water-to-CO_2 ratio is for a mixed-gas injection dissolving 47 ktpa CO_2 and 11 ktpa hydrogen sulphide (H_2S) in water. The CO_2, H_2S, and water for that injection are sourced from the geothermal powerplant nearby. The high rate of water injection allowed for that well may be related to the disposal of geothermal effluent and not be strictly required for CO_2 dissolution.[26] It is unclear whether the well with a 61:1 water-to-CO_2 ratio is also being used to dispose of water sourced from the geothermal powerplant.

The pilot site at the Nesjavellir Geothermal Plant is also mixed gas, injecting around 3 ktpa CO_2 and 1 ktpa H_2S mixed with an unknown amount of water (Carbfix, 2023). The H_2S component of these injections can reduce the pH of the injectant even further than just CO_2, which can lead to additional host rock dissolution. It can also impact the geochemistry of the system, leading to increased precipitation of sulphides or sulphur-bearing mineral species. Iron sulphides from a mixed-gas injection in Iceland were identified as a source of near-wellbore clogging (Gislason et al., 2014). In addition to the geochemical impacts that a mixed-gas injection may have, including H_2S in the injectant may require a site to adapt its injection infrastructure. Depending on the amount of H_2S involved, the corrosion mechanism and associated risks may shift from sweet corrosion to sour corrosion.[27]

Example projects

Aqueous CO_2 injection for the purpose of storage has been piloted at several sites in Iceland and in Oman, the United Arab Emirates, and Saudi Arabia. Information is relatively limited about the activities that have taken place outside Iceland.

Carbfix's injection technology is currently the most tested and, given the recent permit the company has received, it is validated for injections up to around 50 ktpa of CO_2 in a single well. The company has tested and deployed both surface dissolution and downhole mixing for its injections and it appears to be using both dissolution strategies in the sites it is currently operating. The company has also tested aqueous injections in low- and high-temperature reservoirs.

In 2016, scientists from the CarbFix1 consortium announced that over 95% of the CO_2 injected during the CarbFix1 pilot mineralized in under two years (Matter et al., 2016). That injection targeted a low-temperature aquifer (20-35°C) found at 400-800 m below the surface. A later paper examining Ca isotopes at the same site found that, based on the isotopic composition of pre- and post-injection fluids, around 72% of the injected CO_2 precipitated as calcite, and the additional fraction of mineralized CO_2 calculated by Matter et

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[26] The high water to CO_2 ratio may also be linked to the temperature and depth of the target reservoir since a reservoir at 5 MPa pressure and 200°C would require over 70 tonnes of water to dissolve 1 tonne CO_2 (see Figure 9).

[27] While both H_2S and CO_2 are considered “sour gases”, they cause different types of corrosion. Sour corrosion refers to metal deterioration that occurs in the presence of H_2S. Sweet corrosion refers to metal deterioration that occurs in the presence of CO_2 or other non-H_2S corrosive substances. Sour corrosion can lead to stress cracking and embrittlement while sweet corrosion usually causes pitting or material loss (slb, n.d.-b, n.d.-c).

al. (2016) may be from early fractionation of iron-magnesium carbonate minerals (Pogge Von Strandmann et al., 2019).

The CarbFix2 injection was split into two phases, the first between June 2014 and June 2016 and the second between June 2016 and December 2017. That project injected a dissolved gas mixture of CO_2 and H_2S into a hydrothermally altered basalt at a depth of about 750 m and where reservoir temperature was > 250°C (Clark et al., 2020). Mass balance and mineralization calculations based on tracer tests and sampling campaigns found that during Phase 1 over 50% of the CO_2 and 76% of the injected H_2S mineralized in under nine months, and that amount increased to 60% of CO_2 and 85% of H_2S during Phase 2 (Clark et al., 2020).

3.2.3. Water-alternating-gas CO_2 injection

WAG injection is a technique that uses gas flooding to improve sweep efficiency in a reservoir. WAG alternates injecting free-phase CO_2 with injecting water. Injected CO_2 dissolves into formation fluids and then the pulse of the water injection sweeps the CO_2-charged formation waters away from the wellbore.

Deploying this style of injection for mafic and ultramafic CO_2 storage is still theoretical. Cella, a United States-based start-up, is one of the main pioneers. They are working on developing a pilot site in Kenya (see Box 5).

Modelling led by one of the founders of Cella found that over the lifetime of a WAG project the mass ratio of water to CO_2 is the main control on mineralization efficiency (Nelson et al., 2025). Across the three modelled sites, all WAG injection scenarios tested saw an improvement in 40-year mineralization efficiency when compared with supercritical injection scenarios. Most WAG scenarios had much lower efficiencies than the aqueous injection scenario. The authors found that a mass ratio of around 27:1 of water to CO_2 resulted in an identical or higher 40-year mineralization efficiency than aqueous injections that were performed at a ratio of around 30:1.

The 27:1 water-to-CO_2 ratio requires only a little less water than the aqueous injection that the study modelled, and the parameters of the WAG injection fall within the range of water-to-CO_2 ratios that many aqueous sites are discussing. This suggests that if a high mineralization efficiency is desired, either aqueous injections or WAG injections may be feasible. Moderate mineralization efficiency gains were made at lower water-to-CO_2 ratios, with improvements of 5-14% with a water-to-CO_2 ratio of 1:1 and 20-35% with a water-to-CO_2 ratio of 10:1 (Nelson et al., 2025). This suggests that WAG injections can be an intermediate approach between aqueous and supercritical injections, since they can potentially require less water than aqueous injections, but still have a higher mineralization efficiency than supercritical CO_2 injections. However, the work is still theoretical and based on modelling. Field-scale studies will help refine our understanding of the benefits or disadvantages WAG injections may offer.

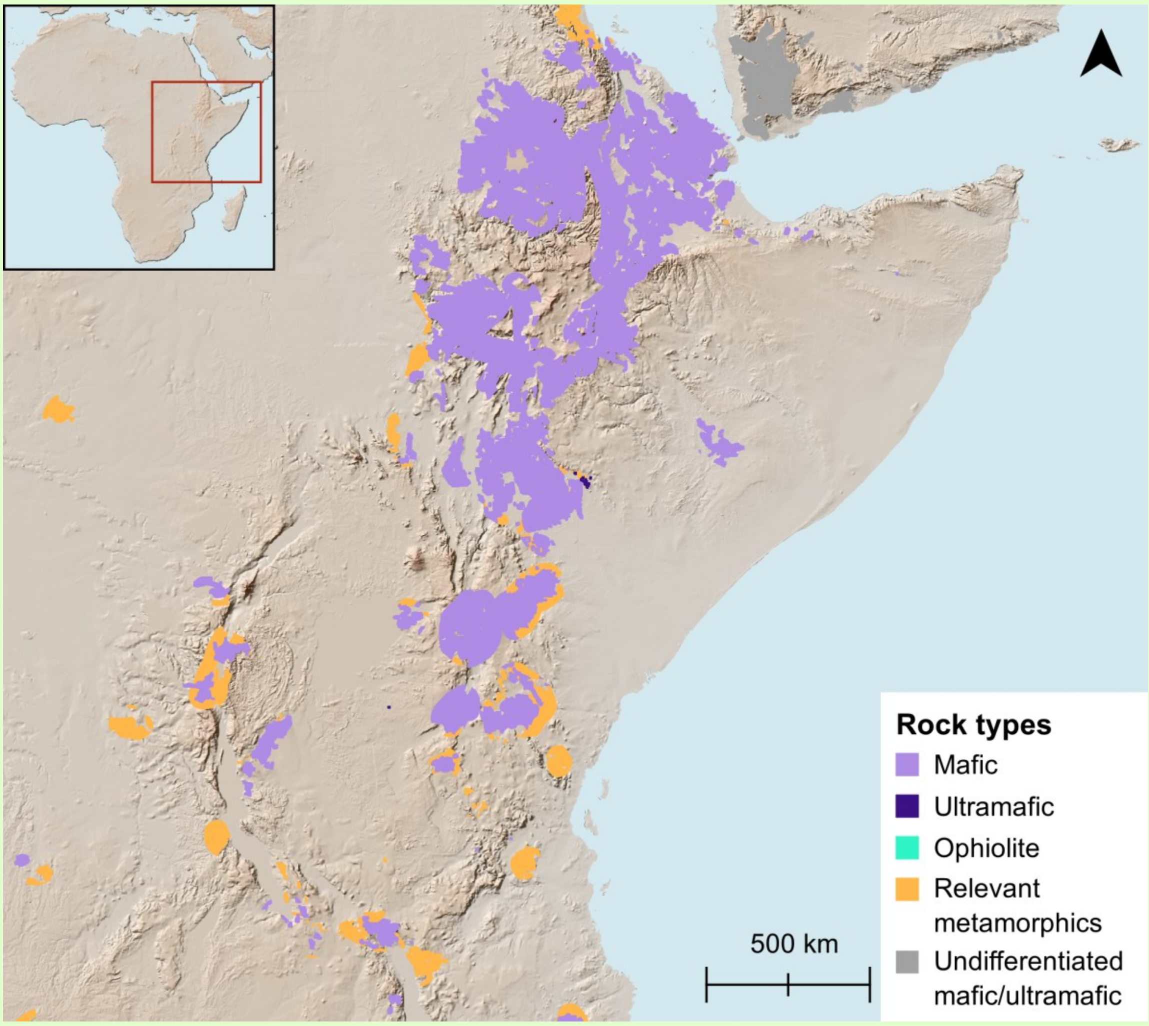
Box 5. CO_2 storage in Kenya’s Great Rift Valley

The Great Rift Valley is part of the East African Rift system and is characterized by extensive mafic and intermediate volcanic activity tied to ongoing continental rifting (Figure 12). It occupies a similar geographic footprint as the Afro-Arabian LIP, but it is geologically distinct (Rooney, 2020). The area has conditions favourable for geothermal energy generation with multiple relatively shallow hot springs (Jones, 2020).

Kenya is emerging as a potential direct air capture (DAC) hub due to the Great Rift Valley’s geothermal potential and its abundance of mafic rocks. Several DAC project developers are looking to deploy geothermal-powered DAC projects in the region (Trendafilova, 2024, 2023a; Sirona Technologies, 2025).

In 2025, Cella and Sirona Technologies launched Project Jacaranda. This project aims to capture CO_2 directly from the air using Sirona Technologies’ DAC machines and to store that CO_2 in the subsurface of the Great Rift Valley using WAG CO_2 injections. It is unclear when the project will enter operation (Sirona Technologies, 2025).

Figure 12. Potential resource distribution in the East African Rift region



Sources: Rock distribution: Chorlton (2007); Pollastro (1998); Regional Centre for Mapping of Resources for Development (RCMRD) et al. (2017). Elevation: Danielson and Gesch (2011).

Cooled lava. Image by Jeison Mattos via pexels.

Chapter 4. Assessment of mafic and ultramafic CO_2 storage resources

Key takeaways

Mafic, ultramafic, and sedimentary CO_2 storage resources have different reservoir properties related to their rock type and formation environment. The screening criteria used for sedimentary CO_2 storage resources will need to be adapted to the specific characteristics of mafic and ultramafic rocks. Adapting or defining screening criteria for these rock types can help advance regional and global efforts to assess uncharacterized mafic and ultramafic formations.

Significantly less data are available on mafic and ultramafic formations than sedimentary formations. This can complicate resource assessment. Additionally, most CO_2 storage features, events, and processes (FEP) databases are not designed for mafic and ultramafic resources, and therefore some critical FEPs may be omitted.

Alignment across the CO_2 storage industry on the terminology used to describe project and resource maturity can reduce confusion about the difference between theoretical storage potential and technically and commercially feasible storage capacity. The Storage Resource Management System (SRMS) is understood by many financial institutions. While the SRMS was written with sedimentary resources in mind, it is applicable to all CO_2 storage resource types and can be used to define a resource's capacity and to report a project's stored CO_2.

Researchers and companies have used several methods to estimate the storage potential of mafic and ultramafic resources globally, regionally, and sub-nationally. Resource potential estimates can vary by two orders of magnitude for the same resource depending on the methodology used. Methods based on geochemical aspects produce the highest estimations, while methods based on pore volume produce much lower estimates. Since pressure is a known constraint in all types of CO_2 storage, pore volume estimations may be more in line with what is potentially technically achievable. Significantly more research and data are required to refine storage potential methodologies and estimations before global or regional storage potential estimates can be made.

Sedimentary CO_2 storage resources can take three to ten years to assess and develop into operating storage sites (IEA, 2022a). The development timeline for large-scale (> 100 ktpa CO_2) mafic or ultramafic CO_2 storage sites is unknown. However, limitations on historic data and modelling complexities suggest that assessment and development of mafic and ultramafic resources will take longer than assessment and development of sedimentary CO_2 storage resources. For reference, Carbfix's activities around Hellisheiði received a permit to inject a total of 106 ktpa CO_2 across four wells in May 2025, while the first pilot injections at Hellisheiði took place in 2012.

The resource assessment process allows for risk-based evaluation of potential CO_2 storage resources. The same general workflow can be followed to assess and characterize both sedimentary and mafic or ultramafic resources. Regardless of the resource type targeted, project developers will initially screen potential resources to identify a subsection of prospects. Those prospects will then be screened further based on existing site-specific analysis to further whittle down prospects to a handful of sites that may be valuable targets. This risk-based evaluation allows project developers to exclude resources or sites that are not technically and commercially developable. Such resources are typically discarded early in the process.

Three main approaches – defined screening criteria, historical operating data from similar geological settings, and site- and project-specific FEPs – are employed to screen CO_2 storage sites for their suitability during the resource assessment and development process. Most sedimentary CO_2 storage sites take a hybrid approach.

Resource developers can define screening criteria according to their risk tolerance. Common screening criteria are outlined in Table 10. Potential storage resources can be evaluated against screening criteria and then they can either advance to more detailed assessment or be discarded. This process is used during regional and site screening to eliminate prospective storage resources that exceed a developer's risk threshold or do not appear to be technically or commercially developable.

Screening criteria are relatively well defined for sedimentary resources, though data availability can be a constraint, especially for sedimentary saline aquifers. Conversely, due in part to the immaturity of mafic and ultramafic CO_2 storage, there are no rules of thumb or consensus on screening criteria for these rock types. Additionally, data availability is a significant constraint due to significantly more limited subsurface exploration of these resources.

Historical operating data can inform model development and estimations of resource potential. These data provide analogues that can support resource assessment and are widely used during early resource estimation. Analogy is also one of the three analytical procedures that the SRMS proposes as a method for estimating storable quantities of CO_2.

There are more historical operating data for subsurface activities in sedimentary resources than in mafic or ultramafic resources. Even though oil and gas production is not analogous to CO_2 storage, it does provide data that can be highly informative to resource evaluation. While there have been limited relevant operations in mafic and ultramafic resources, data related to geothermal activities, wastewater disposal, or water production can support resource assessment. In some regions there also may be relevant data from mining or igneous-hosted petroleum resources.

Table 10. Common criteria used during regional or site screening to assess prospective storage resources

Criteria	Information used for evaluation	Considerations for sedimentary resources	Considerations for mafic or ultramafic resources
Depth	▪ Stratigraphic studies ▪ If available: seismic data if available	▪ > 800 m	▪ CO_2(sc): > 800 m ▪ CO_2 (aq): no clear depth restrictions, may be restricted by depth of potable water
Vertically confining features	▪ Stratigraphic studies ▪ If available: legacy well logs, core data, or seismic data	▪ Presence of caprock confirmed	▪ Limited subsurface data available to identify if there are vertically confining features ▪ Confining features may still have fractures or faulting that can serve as leakage pathways ▪ Vertically confining features may not be required depending on likelihood/expected rate of mineralization, injection style, and regulation
Porosity or permeability	▪ Historic production data ▪ If available: legacy well logs or core data	▪ Analogues used to estimate porosity if sufficient data not available	▪ Limited information at depth ▪ Rough estimations based on existing data from rocks of the same type and age
Existing penetrations	▪ Wellbore inventory	▪ Operator-defined risk threshold on existing penetrations	▪ Drilling has been more limited in these resources ▪ Water wells or mineral wells may enter the targeted depth horizon for shallow projects
Thickness of resource	▪ Stratigraphic studies ▪ If available: legacy well logs, core data, or seismic data	▪ Resource thickness can be extrapolated to basin scale from a limited number of penetrations	▪ Desired thickness will depend on injection strategy and permeability ▪ Limited data for most potential resources
Surface access constraints	▪ Surface geography data on population centres, areas of dense industrial activity, environmental protection zones, topography, etc.	▪ Resource type does not impact potential surface access constraints and information used to evaluate them	
Competing resource use	▪ Existing permits for exploitation or licences for exploration	▪ Competing resource uses can exist across all resource types, though they are potentially more common in sedimentary resources due to oil and gas extraction ▪ If a project is designed for CO_2(aq) injections, existing water extraction can be a competing or complimentary activity	

Note: See Section 6.1.5 for further discussion on competing resource use.

FEP analysis is one of the most common risk assessment approaches, even though it requires a company to devote substantial staff resources. CO_2 storage project developers can either work from the open-access Generic CO_2 Geological Storage FEP Database 2.0 developed by Quintessa, or develop their own (Maul et al., 2005; Quintessa, n.d.). FEP databases can be valuable tools for developers since they are often relatively exhaustive. Comparing a project's design and parameters to a standardized FEP database can reduce the likelihood that a material feature, event, or process is omitted (Tucker et al., 2013).

The Generic CO_2 Geological Storage FEP Database 2.0 is not designed for mafic or ultramafic resources. Due to its relatively exhaustive approach, many relevant features, events, or processes are included, but project developers should carefully review it to ensure that relevant FEPs are not omitted. FEP databases for multiple types of subsurface activities, such as geothermal, nuclear waste disposal, and wastewater disposal, can also be reviewed to identify FEPs relevant to CO_2 injection in mafic and ultramafic rocks.

4.1. Resource modelling

Modelling is a key part of the resource assessment process. Robust and mature modelling frameworks exist for sedimentary resources; they inform initial resource potential estimates all the way through to assigning a SRMS Capacity to a resource.

Modelling mafic and ultramafic resources is much less mature due to differences in fluid flow in these rocks and the need to couple reactive transport modelling with more conventional reservoir models.

4.1.1. Porosity and permeability

The porous media-based modelling frameworks that are commonly used to model sedimentary CO_2 storage reservoirs may not be appropriate for mafic and ultramafic rocks for a few reasons. In porous media, pore throat size is the primary control of permeability. In clastic sedimentary rocks such as sandstones, pore throat size is a function of particle size and sorting. In vesicular igneous rocks, pore throat size is controlled by inter-bubble aperture rather than particle size (Petford, 2003; Saar and Manga, 1999). At primary porosities above ~10%, the majority of vesicles within a vesicular igneous rock should be connected, allowing for fluid flow. Below ~10% primary porosity, the vesicles are unlikely to be fully connected and as a result the permeability of the rock is low to very low (Saar and Manga, 1999). If aperture spacing is one of the main mechanisms controlling permeability in mafic or ultramafic rocks, then aperture-based permeability models are needed.

In addition to the complexities associated with deploying aperture-based modelling to assess matrix flow through micro-scale permeability, crystalline rocks also exhibit significant heterogeneities across a variety of scales. Fluid flow occurs both within the rock matrix and through larger fracture networks. Fracture networks that serve as an important source of secondary permeability can have apertures ranging from less than a micrometre to more than several centimetres. Sedimentary rocks are more homogeneous than crystalline rocks and in the case of sandstones, they function like porous media.

Lab-based flow-through experiments typically have much higher flow rates than field-scale CO2 injections. These higher flow rates will limit the residence time of CO2 in a specific zone and as a result could limit carbonation. One set of laboratory experiments found that at high flow rates permeability increases and at low flow rates permeability decreases. The high flow rate experiments were dissolution dominated, and flow likely moved via existing preferential paths. The authors expect that ultimately, if time were provided for secondary mineralization, even the high flow rate experiments would have a net reduction in permeability due to secondary mineralization (Luhmann et al., 2017).

The experience from the referenced experiments highlights one of the key problems with modelling igneous rocks: defining what volume of rock is representative of the material as a whole, or what qualifies as a representative elementary volume (Moore, 2018).[28] Models generated from lab-scale flow experiments are unlikely to be representative of field-scale processes, including fracture-dominated fluid transport and/or fracture formation, because they are not performed on representative volumes of material. Field-scale fractures and near-wellbore fracture networks provide critical flow paths for CO_2 injected into mafic and ultramafic rocks, but since they cannot be reproduced, their impact on secondary permeability and CO_2 transport is more difficult to study and to model.

The complexities related to modelling the porosity and permeability of these systems, both at a lab and field scale, suggest that mafic and ultramafic resources may require more extensive field testing than sedimentary resources. Various hydrogeology testing techniques, including pumping, slug, and tracer tests, are likely to provide important data that can be used to refine field-scale models.

4.1.2. Reactive transport modelling

Reactive transport modelling is used to predict how geochemical systems evolve in response to fluid movement or changes in fluid chemistry. A variety of software is available to perform reactive transport modelling, and it can be done at different scales, from pore to field scale. Depending on the goal of the modelling exercise, the model can be run until it reaches chemical equilibrium or for a set period (e.g. from end of injection for 50 or 100 or 500+ years).

Reactive transport modelling requires an in-depth understanding of the (geo)chemical make-up of the system being modelled, and as with any model, it is only ever as good as the data upon which it is built. Thermodynamic databases are used to determine which reactions are favourable under the modelled conditions. These are coupled with kinetics databases so that the model can account for reaction rates and model the system through time.

In the case of mafic and ultramafic CO_2 storage, reactive transport modelling can be used to see how much CO_2 could be mineralized over a set amount of time. It can also be used to investigate how temperature, pressure, and mineral composition could affect the types of minerals that will precipitate. Several different databases for thermodynamics and kinetics include some of the minerals that are needed to model mafic and ultramafic rocks, but often databases are missing some secondary minerals and may even be missing key primary minerals or volcanic glass (Aradóttir et al., 2012; Voigt et al., 2018). In the case of kinetics, most studies that look at CO_2 storage in mafic and ultramafic rocks use kinetic data from Palandri and Kharaka (2004), who compiled kinetic rate constants for a variety of mineral

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[28] A representative elementary volume is the smallest volume of material that can be measured and still yield results that are representative of the whole material. In the case of fractured media such as mafic and ultramafic rocks, laboratory-scale experiments are not representative of field-scale processes, so while they may be a representative elementary volume from the perspective of rock composition, they may not be from a permeability point of view.

species at 25°C and near neutral pH. Scientists continue to work on improving kinetics databases (Heřmanská et al., 2023, 2022).

Reactive transport modelling, especially at a field scale, is often computationally demanding due to the number of reactions that need to be considered, the evolution of fluid properties, and the need to solve both mass transport and geochemical reactions (Postma et al., 2022b). While several reactive transport software packages are available, further research is still required to improve model frameworks. As with porosity and permeability modelling, data collected from field trials will be valuable since it can be used to test and evaluate reactive transport models.

4.2. The SRMS and mafic and ultramafic storage

The SRMS is designed to classify the maturity and commerciality of a specific CO_2 storage resource or project (Society of Petroleum Engineers, 2025). It was first released in 2017, with an updated edition published in 2025. The framework is modelled after the widely used Petroleum Resource Management System (PRMS). This suggests that financial institutions and investors familiar with the PRMS should be able to understand the SRMS methods and the approach it uses to define the maturity and commerciality of a resource.

There are many differences between mafic or ultramafic and sedimentary CO_2 storage, but there is value in using a standard maturity and commerciality classification framework across all resource types. Even though the SRMS was not written with mafic or ultramafic CO_2 storage in mind, it can be expanded to accommodate them. The SRMS is relatively agnostic towards the exact methodology used for resource assessment. The framework focuses on classifying a resource's maturity based on the probability that it will achieve the defined storable quantities. It is a project-based framework, but notional projects can be used to assess the potential of prospective storage resources. The framework's sections on "Classification and Categorization Guidelines" and "Evaluation and Reporting Guidelines" can be applied to all resource types.

Only the "Estimating Storage Quantities" section may require minor updates to account for mafic and ultramafic resources. That section outlines three broad categories of analytical procedures to estimate storable quantities: analogy, volumetric estimates, and performance-based estimates. There is currently insufficient deployment of mafic or ultramafic CO_2 storage to allow the definition of appropriate analogues or make performance-based estimations. Nevertheless, volumetric estimations are possible.

The SRMS provides examples of how reference volumes can be defined for saline aquifers, depleted fields, and for CO_2-enhanced oil recovery (EOR) operations. These examples can guide how a reference volume for mafic or ultramafic rocks could be defined. One possible definition could be:

> *For regional CO_2 storage assessment within flood basalts, large igneous provinces, or peridotites, the reference volume may be the effective pore volume within the defined area or alternatively the volume of rock that can be viably mineralized within the operating lifetime of the project.*

Volumetric methods can be based on the amount of pore space present in the rock or on geochemical parameters that dictate how much CO_2 can be mineralized by a set volume of rock. Therefore, the SRMS's treatment of volumetric estimates is not a barrier to mafic or ultramafic resources.

Volumetric estimates also require a storage efficiency that should be defined for the resource and should reflect a project's development concept. That storage efficiency should be "established from analog stores or by flow modeling representative of the storage type and storage mechanism" (Society of Petroleum Engineers, 2025). This definition of storage efficiency poses no problem for CO_2 storage in mafic or ultramafic resources. However, there are currently no large-scale analogues in place to allow for the establishment of storage efficiency, so modelling (flow, geomechanics, geochemistry) is required to reflect CO_2 storage resources from a specific injection style into a specific site. The same section goes on to discuss containment and modelling. Both subsections are sufficiently broad to apply to all potential resource types.

4.3. Estimating mafic and ultramafic CO_2 storage resource potential

Global and regional maps of undiscovered storage resources, such as the ones that appear further in this chapter, are useful for identifying the location of potential resources. The estimations of undiscovered storage resources that typically accompany them should be evaluated qualitatively rather than quantitatively due to the uncertainties and assumptions that accompany such work.

Initial resource potential estimates in sedimentary resources often use some variation of an equation focused on injecting CO_2 into a porous rock following Bachu (2015) and Bachu et al. (2007):

$$M_{CO2} = A \times H \times \phi \times \rho CO_2 \times E \qquad \textbf{Eq. 8}$$

where M_{CO2} is equal to the mass of CO_2 stored, A is equal to the formation area, H is equal to the formation thickness, ϕ is equal to formation porosity, ρCO_2 is equal to the density of CO_2 at depth, and E is a storage efficiency factor.

A storage efficiency factor is included to account for subsurface fluid dynamics, reservoir response to injection, and injection properties (De Silva and Ranjith, 2012). Depending on how the storage efficiency factor is defined, it can account for factors such as sweep efficiency, pressure response, and how much pore space can be effectively filled. In sedimentary resources, pressure is one of the biggest limitations on injection and injectivity. This is also likely to be the case for mafic and ultramafic resources unless substantial water production is used to relieve reservoir pressure, given the potentially more limited porosity and permeability of many mafic and ultramafic rocks.

From sedimentary CO_2 storage resource assessments, we know that there can be significant variations between global, regional, and sub-national estimations of undiscovered storage resources. One such study estimated global (onshore and offshore) sedimentary resource potential to be between 8,000 and 55,000 Gt (Kearns et al., 2017). Mafic and ultramafic CO_2 storage resource estimates also produce large ranges, for instance a study of mafic and ultramafic CO_2 storage potential just for the ocean crust found storage potential ranging from 4,300 Gt to 196,000 Gt (Norton et al., 2024).

4.3.1. Methodologies used to estimate resource potential

A variety of studies look at the CO_2 storage potential offered by mafic and ultramafic rocks in a specific region, formation, or sequence. However, the methodologies behind estimating storage potential in mafic and ultramafic rocks are not well defined (Raza et al., 2022). As discussed previously, insufficient analogues are available to use analogous comparison to evaluate storage potential, and uncertainty about porosity, permeability, resource thickness, and containment is very high.

Mafic and ultramafic resource potential estimations have been made using methods such as volumetric estimations, natural analogue, pore-filling, and complete mineralization (Cao et al., 2024). However, none of the CO_2 storage potential estimation methods reviewed for this study accounted for pressure of injection or reservoir pressure. Some studies accounted for how much rock the injected CO_2 could interact with by including an accessibility term; others produced different estimations for aqueous versus supercritical injections; and others still assessed how much pore volume would be available to be filled by different minerals. Methodologies focused on geochemical potential are often favoured over methodologies focused on pore volume, though some studies use a hybrid of the two. In most cases geochemical methodologies use either laboratory-derived mineralization rates or natural analogues.

Natural analogue methods look at the amount and spatial distribution of carbonate minerals found within a specific host rock to estimate the volume of CO_2 that can be stored per fixed unit of rock. They are used by several different researchers to estimate storage potential around the world, including onshore and off Iceland, and in the Jizan region of Saudi Arabia (Oelkers et al., 2022; Snæbjörnsdóttir et al., 2014; Snæbjörnsdóttir and Gislason, 2016). Some researchers choose to include a depth threshold when they estimate storage potential with the natural analogue method, but others do not. Snæbjörnsdóttir et al. (2014) established a depth threshold of 500 m and then estimated the storage potential of a 1,000 m interval. Snæbjörnsdóttir and Gislason (2016) consider the first 1,500 m of seabed to be viable for CO_2 storage while Oelkers et al. (2022) consider the full 1,000 m thickness of the Jizan basalt. In both cases, which would potentially mean that injected CO_2 could be in contact with ocean bottom waters or surface waters/soils respectively.

Eq. 8 can be applied to mafic and ultramafic CO_2 storage when supercritical injection strategies are employed. If aqueous injections are employed, the density of CO_2 will need to be replaced with the density of water, and the water-to-CO_2 ratio will need to be added. This general principle forms the basis of the pore-filling method used by some researchers. That method looks at the volume of pores available to be filled with CO_2. It has been used to estimate the storage potential of the Juan de Fuca Ridge in the Pacific, the Columbia River Basalt Group in the United States, and in Iceland, India, Finland, and Ireland (Andrews, 2023; Anthonsen et al., 2013; Bakshi et al., 2023; Cao et al., 2023; Goldberg et al., 2008; McGrail et al. 2006). However, researchers do not usually include a storage efficiency factor. As a result, they consider that the entire volume of porosity is available to be filled with CO_2.

Complete mineralization estimations assume that it will be possible to liberate all divalent cations present in the rock for use in carbonation (P. C. Li et al., 2023). This would imply extensive dissolution and remineralization. This methodology has been used to estimate resource potential in China.

Given the state of understanding of mafic and ultramafic rocks and their ability to serve as storage resources, all estimates of storage potential must be evaluated critically. Initially this study set out to estimate global mafic and ultramafic CO_2 storage potential. However, considering the low level of data available about these resources and the fact that there is no clear consensus on how storage potential should be calculated, instead we have taken several storage potential estimations from peer-reviewed literature and used some of the methods described above to calculate potential as a basis of comparison. The two following tables describe what we have done.

Table 11 provides an overview of the methodologies used by various authors to assess mafic and ultramafic storage potential. For reference purposes, it includes the sedimentary methodology discussed previously as expressed by Eq. 8. None of the authors used Eq. 8 in its entirety in their work. Note that Eq. 8 and Eq. 9 are pore-filling methodologies, while Eq. 10 and Eq. 11 are natural analogue methodologies.

Table 12 summarizes some of the mafic and ultramafic storage potential estimates made by selected authors in scientific literature (bold underlined numbers). To present how different calculation methodologies and assumptions can affect storage potential estimates, we used the same methodologies, and the sedimentary methodology, to estimate the potential of other resources. The numbers presented in that table should not be considered storage potential estimations. The table is included to demonstrate the enormous range of outcomes and exemplify how much additional work is needed to improve our understanding of these potential storage resources.

Table 11. Methodologies and assumptions used to assess storage potential

Equations	Reference	
Sedimentary storage, static pore volume $M_{CO2} = A \times H \times \phi \times \rho CO_2 \times E$	Derived from Bachu (2015); Bachu et al. (2007)	**Eq. 8**
Basalt storage, static pore volume CO_2(aq) $M_{CO2} = A \times H \times \phi \times \rho CO_2$	After Andrews (2023)	**Eq. 9**
Basalt storage, natural analogue $M_{CO2} = A \times H \times C$ Where C is a mineralization efficiency	After Snæbjörnsdóttir et al. (2014)	**Eq. 10**
Basalt storage, natural analogue with accessibility factor $M_{CO2} = A \times H \times C \times d$ Where d is a surface accessibility factor	After Oelkers et al. (2022)	**Eq. 11**
Assumptions	**Reference**	
Mineralization efficiency (kg CO_2/m^3): $C_{Low} = 10; C_{Mid} = 55;\ C_{High} = 90$ $C_{Low} = 18.8;\ C_{Mid} = 43.8;\ C_{High} = 48.7$	 Oelkers et al. (2022) Snæbjörnsdóttir et al. (2014)	
Accessibility factor (%): $d_{Low} = 10; d_{Mid} = 40;\ d_{High} = 90$	 Oelkers et al. (2022)	
Porosity (%): $\phi_{Low} = 3;\ \phi_{Mid} = 22;\ \phi_{High} = 32$	 Andrews (2023)	
Storage efficiency factor: $E_{Low} = 0.0009\ ;\ E_{Mid} = 0.029;\ E_{High} = 0.2$	 De Silva and Ranjith (2012)	
Density of supercritical CO_2 (kg CO_2/m^3): $\rho CO_2 = 650$	 Cao et al. (2023)	

Notes: Eq. 8 is commonly used to estimate the potential of sedimentary storage resources. The majority of mafic and ultramafic CO_2 storage potential studies reviewed during this work did not include a storage efficiency factor (E). The storage efficiency factors applied were defined for sedimentary CO_2 storage resources.

Table 12. Comparison of storage potential estimations (Gt CO_2) made by applying the methodologies and assumptions listed in Table 11

	Region	**Antrim Lava E**	**Antrim Lava W**	**Jizan**	**Antrim Lava N**	**Icelandic Rift**	**Columbia River Basalt Group**	**Deccan Traps**
	Area (km^2)	131	179	180	189	34,000	164,000	500,000
	Sequence thickness (km)	0.78	0.24	1	0.77	1.5	3	2
Eq. 8 CO_2(sc), calculation excludes first 800 m	Low			0.001		0.42	6.33	10.53
	Mid			0.15		98.70	1,496	2,488
	High			1.50		990.08	15,009	24,960
Eq. 9 CO_2(aq), calculation excludes first 500 m of formation	Low	**0.002**	**0.001**	0.01	**0.003**	2.03	24.48	44.78
	Mid	**0.016**	**0.006**	0.04	**0.022**	14.89	179.50	328.35
	High	**0.023**	**0.009**	0.06	**0.032**	21.65	261.09	477.60
Eq. 10 CO_2(aq), calculation excludes first 500 m of formation	Low	0.69	0.27	1.69	0.96	**639.20**	7,708	14,100
	Mid	1.61	0.63	3.94	2.24	**1,489**	17,958	32,850
	High	1.79	0.70	4.38	2.49	**1,656**	19,967	36,525
Eq. 11 CO_2(aq), calculation does not exclude any depth	Low	0.10	0.04	**0.18**	0.15	51.00	492.00	1,000
	Mid	2.25	0.95	**3.96**	3.20	1,122	10,824	22,000
	High	8.28	3.48	**14.58**	11.79	4,131	39,852	81,000
	After McGrail et al. (2006)						**100**	**305**
	Original study	Andrews (2023)	Andrews (2023)[*]	Oelkers et al. (2022)[†]	Andrews (2023)	Snæbjörnsdóttir et al. (2014)[‡]	McGrail et al. (2006)[§]	Bakshi et al. (2023)[‖]

[*] The author defined a usable thickness of 80 m, that value was used for Eq. 9 and 10. Eq. 11 used the full thickness.

[†] The authors estimated storage potential using Monte Carlo simulations and presented a range of values. The calculated values in the table align with that range.

[‡] The authors provide two sets of values for how much CO_2 can be fixed: the amount of CO_2 fixed in the upper 1,500 m per unit surface area (t CO_2/m^2 rock) and the amount of CO_2 fixed in the uppermost 1,500 m (kg CO_2/m^3 rock). They stated that their estimations were for a 1,000 m thick segment from 500-1500 m depth, however their estimates (953-2,470 Gt CO_2) could only be replicated using the CO_2 fixed per unit surface area or by using a thickness of 1,500m. The table above uses a thickness of 1,000 m.

[§] Authors calculated potential based on a usable thickness of 100 m, split across 10 interflow zones of 10 m each, a porosity of 15% and they used a correction factor of 0.0406.

[‖] Authors followed the assumptions and methodologies laid out in McGrail et al. (2006).

Notes: This table is designed to show how calculation methodology and assumptions result in very large differences in storage potential estimations. Refer to Table 11 for the equations and assumptions. Bold underlined numbers are those from the original study. None of the original studies used Eq. 8 to estimate mafic and ultramafic CO_2 storage resource potential but since it is often used to estimate sedimentary CO_2 storage potential it has been included for comparison purposes where the resource is thicker than 800 m. Where calculated storage potential is above 1,000 Gt, decimal points have been removed.

4.3.2. A framework to assess storage potential

As shown in Table 12, depending on the evaluation methodology and the underlying assumptions used, resource potential estimates can vary by several orders of magnitude for the same resources. This mirrors the findings of Steinthorsdottir et al. (2024). In that study authors observed that, when assessing three formations in Canada, storage potential estimates based on pore filling were one to two orders of magnitude below those based on geochemical methods that used either natural analogues or mineralization efficiencies from experimental studies. From the methods reviewed, it appears that storage potential calculations that use mineral conversion factors or results from reactivity experiments yield significantly higher estimations than those based on pore filling, except when Eq. 8 is used with a high porosity (35%) and a high storage efficiency factor (0.2).

Volumetric estimations may be more representative of technically feasible storage potential than estimations based on dissolution and precipitation rates. However, large-scale demonstrations are needed to truly assess what contributes to the storage potential of these rocks.

It currently appears that we know too little about these resources to estimate their regional or global CO_2 storage potential with any confidence. However, a few guidelines can be suggested:

- **A depth threshold should be used.** If aqueous CO_2 injections are targeted, 500 m may be appropriate. However, the minimum depth should be below potable groundwater resources in the relevant regions, or below cold-water recharge zones in the ocean crust. If supercritical CO_2 injections are targeted, a minimum depth of 800 m is likely to be appropriate.
- **Storage efficiency factors should be used to account for reservoir response.** Storage efficiency factors are not the same as mineralization capacity, as sometimes used in geochemical methodologies. A mineralization capacity factor can also not replace a storage efficiency factor in pore-filling methodologies because it does not account for injection rates, pressure response, and/or sweep efficiency.
- **Geochemical approaches should consider the accessibility that CO_2 will have to mineral surfaces.** As used in Oelkers et al. (2022), an accessibility factor can be used to account for how much CO_2 is in contact with reactive mineral surfaces. This can reduce the overall efficiency of the predicted mineralization rate and result in a lower storage potential.

4.4. Global distribution of uncharacterized mafic and ultramafic formations

To understand how mafic and ultramafic CO_2 storage may support climate goals and where it could be deployed in the future, this work used publicly available geographic information system (GIS) data to identify where mafic, ultramafic, and relevant metamorphic rocks are found globally. As previously discussed, mafic, ultramafic, and relevant metamorphic rocks have been less of a target for subsurface activities, including exploration, than sedimentary rocks. They are also typically more diverse over small areas and can require more in-depth petrographic analysis to determine rock type than is often done for regional mapping exercises. As a result, at a global level these rock types are less well mapped than most sedimentary resources.

Lithological descriptions, and by extension geological mapping, include subjectivity. While there are field conventions, unlike geological ages, lithological descriptions are not completely standardized. Even within a single geological survey, maps can use different classification schemes. This lack of standardization and harmonization means that significant data processing is required to create a global map of mafic, ultramafic, and relevant metamorphic resources for a wide range of sources.

Data availability also poses a problem when attempting to map the global distribution of these rock types. Geological maps do not need to include country or regional borders and therefore do not need to directly comment on the limits of a sovereign territory. However, surface (or subsurface) lithologic information directly relates to natural resource distribution. Furthermore, even though sedimentary rocks can host a wide variety of natural resources, in many cases lithological descriptions are not sufficient to immediately link a sedimentary rock or sequence to a mineral deposit or natural resource.[29] Detailed lithological descriptions of igneous and metamorphic rocks very often can be used to identify mineral prospects, especially if linked with information on formation environment. Due to sensitivities around resource security and resource sovereignty, many countries either choose not to make high-resolution maps of their surface lithologies readily available, restrict the use of shared data, or only use high-level descriptions such as “low-grade metamorphic”.

More information on data sources and mapping methods can be found in Appendix 1.

4.4.1. Mapping resource distribution

Similar to sedimentary rocks, mafic, ultramafic, and relevant metamorphic rocks have uneven global distribution (Figure 13). Onshore, they can sometimes be found in sedimentary basins, but other times they may be the primary rock type in a region, as with the Siberian and Deccan Traps (Figure 14). Mafic and ultramafic CO_2 storage can broaden the geographic distribution of CO_2 storage activities since these rocks can be found in regions with limited or no sedimentary resources. Expanding CO_2 storage activities to regions without sedimentary resources could reduce the distance CO_2 needs to be transported, potentially reducing transportation costs. However, there is much we do not know about these rocks, so significant work is required to improve the mapping of them and to conduct pre-competitive resource assessment.

Onshore, mafic rocks have the widest distribution of relevant resource types. When working at a global level, large igneous provinces and ophiolites have some of the best lithological data available. On a national or sub-national level, rock formations that have been targeted for mining will usually also have peer-reviewed studies on their composition. As discussed in Section 2.2.2, ophiolites are geological complexes commonly composed of sedimentary, mafic, ultramafic, and metamorphic rocks. Due to the fact that ophiolites are of scientific and economic interest and that they contain several rock types in a small geographic area, many regional geological maps will specifically identify ophiolites. This report’s work on mapping follows this convention and considers ophiolites to be a “rock type” for simplicity.

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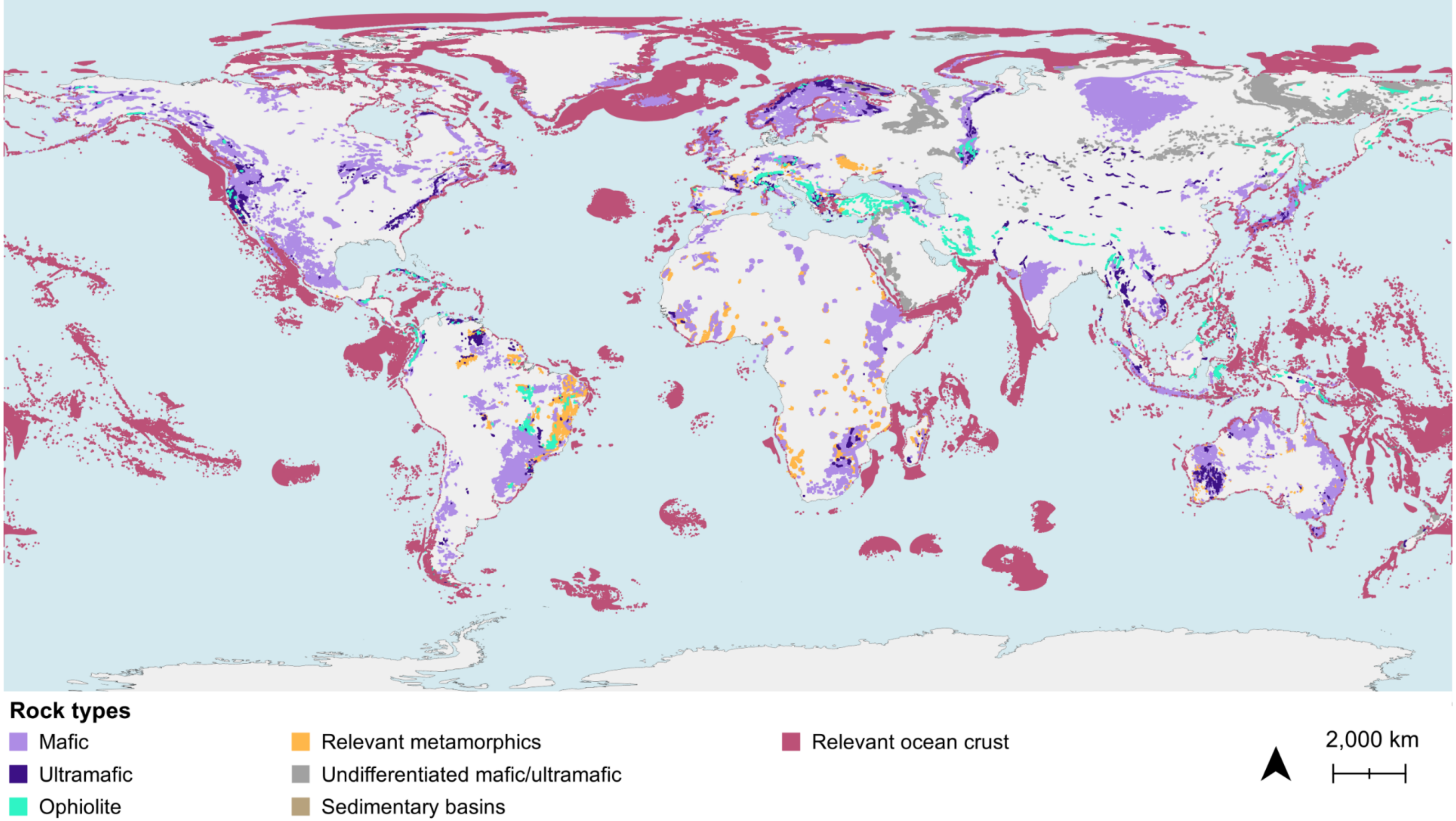
[29] There are some exceptions to this, for instance bauxite, phosphorites, and banded iron formation.

Moving offshore, mafic and ultramafic rocks are the principal component of the ocean crust. This suggests that the ocean crust could serve as a vast resource for this type of CO_2 storage. However, there are a few practical considerations that will limit its availability. This study considers ocean crust as a potential resource only if:

- **It is located within an exclusive economic zone (EEZ).** Countries have jurisdiction over a territorial sea of up to 12 nautical miles, an EEZ of up to 200 nautical miles, and the continental shelf (United Nations, 1982). Regions of the ocean outside of national jurisdiction are called the high seas. The International Seabed Authority (ISA) manages seabed resources in the high seas. As of today, it has not sanctioned any mining projects in the seabed it manages (International Seabed Authority, 2022). This suggests that it is unlikely that ocean crust resources in the high seas will be exploited for storage in the near or medium term.
- **Water depth is 3,000 m or less.** Deep water oil and gas production is technically demanding, and related infrastructure has a significant price premium. Since offshore CO_2 storage requires similar infrastructure as offshore oil or gas production, a 3,000 m depth cut-off is deeper than the deepest operating floating oil platform, which is situated in around 2,450 m of water (Offshore Technology, 2023).
- **Ocean sediment is 2,000 m or less in thickness.** Ocean sediment is a precursor to sedimentary rocks. In areas of thick sediment, sedimentary storage is more likely than mafic or ultramafic CO_2 storage. Depending on the level of compaction and the sediment type, 2,000 m of sediment may be sufficient for sedimentary CO_2 storage.

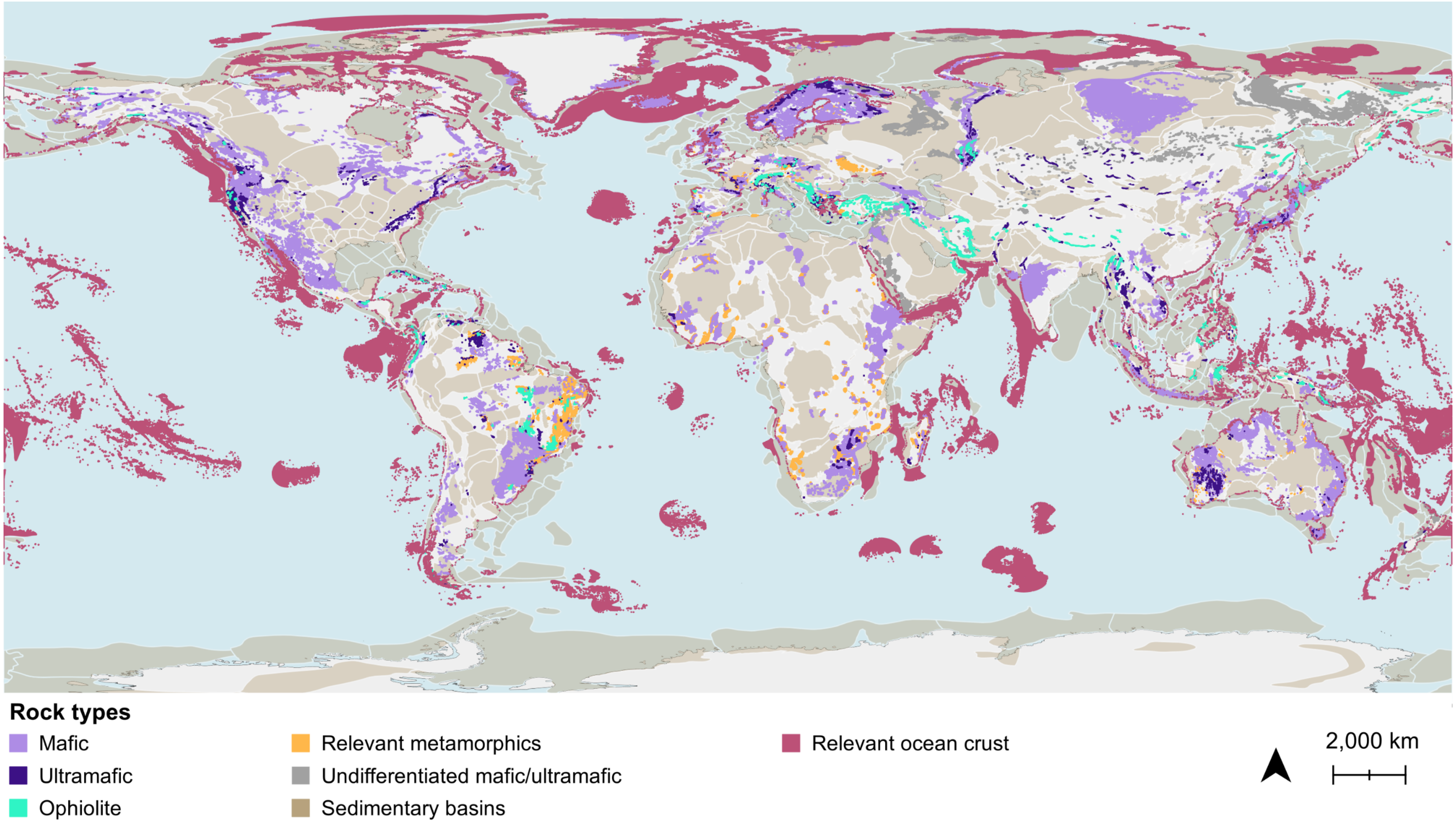
Since continental shelves are extensions of continental landmasses, they are typically not mafic or ultramafic rock. However, they sometimes can be relevant rock depending on the geological history of the region. The GIS data available on continental shelves did not include any lithological descriptions that allowed for classification by rock type. The “Relevant ocean crust” displayed in Figure 13 and Figure 14 excludes continental shelves and as a result it may not include some relevant areas. Versions of both maps including continental shelves can be found in the Appendix 1.

Figure 13. Global distribution of potential mafic and ultramafic resources



Notes: Relevant ocean crust is defined as ocean crust outside continental shelves, within exclusive economic zones (EEZs), at less than 3,000 m water depth, and with less than 2,000 m of sediment cover. Undifferentiated mafic/ultramafic corresponds to data that were identified as “mafic and ultramafic” or “basic and ultrabasic”. See Appendix 1 for underlying data sources.

Figure 14. Global distribution of potential mafic and ultramafic resources compared to sedimentary basins



Notes: Relevant ocean crust is defined as ocean crust outside continental shelves, within exclusive economic zones (EEZs), at less than 3,000 m water depth, and with less than 2,000 m of sediment cover. Undifferentiated mafic/ultramafic corresponds to data that were identified as “mafic and ultramafic” or “basic and ultrabasic”. See Appendix 1 for underlying data sources.

Close up of a columnar basalt. Image by falco via pixabay.

Chapter 5. Site design and cost components

Key takeaways

Site design for mafic and ultramafic CO_2 storage sites will depend on the targeted resource and injection style. These resources can be used for storage both on and offshore; however, due to the increased costs associated with offshore operations and the current maturity level of this type of storage, this report focuses on onshore storage site design.

Mafic and ultramafic CO_2 storage sites can potentially be shallower than sedimentary storage sites. Today many project developers are targeting aqueous injections that do not need to be at depths where the temperature and pressure are above the CO_2 critical point. Additionally, mafic and ultramafic rocks are slower to drill than sedimentary rocks, so there may be economic incentives to go for shallower sites.

Aqueous CO_2 storage sites will require significantly more wells than supercritical sites due to per-well fluid injection rate constraints and the fact that aqueous CO_2 storage sites typically inject between 20 and 30 tonnes of water per tonne of CO_2. In addition to an increased number of injectors, aqueous CO_2 storage sites are likely also to have water production wells, further increasing well count. Wells can be shallower, but injection should still be deeper than the deepest lens of potable water.

As with sedimentary CO_2 storage, monitoring is absolutely critical, but many of the geophysical techniques currently used for CO_2 storage monitoring will need to be adapted or refined if they are going to be deployed on mafic or ultramafic sites. Mafic and ultramafic sites are likely to rely more heavily on geochemical monitoring than sedimentary sites. Geochemical techniques can be used to estimate the mineralized fraction of injected CO_2, but they do not provide as much information about plume location and spread as geophysical monitoring techniques do with sedimentary resources. Additionally, while some monitoring technologies may be able to visualize mineralization fronts, they have not been tested broadly for carbonate mineralization. Direct monitoring of CO_2 mineralization is not currently possible.

As interest in mafic and ultramafic CO_2 storage has increased, so has the range of companies working on it and the number of projects (see Table 7 and Table 8 in Chapter 3). Projects range in size from scale-up of very small existing sites to resource assessments for sites that will be able to store at least 50 Mt of CO_2 over their lifetime.

One key part of developing a storage site is resource assessment; another is site design. As discussed in Chapter 4, the assessment process for mafic and ultramafic resources can follow the same generalized workflow as the assessment and development process for sedimentary resources. However, there will be some differences due to the different rock types and injection styles.

5.1. Site design

The technically and commercially exploitable capacity of a resource is determined by its geologic properties and site engineering. Plot size, surface or subsurface access constraints, well design, target injection rate and depth, regulatory requirements, and other factors contribute to the design of a CO_2 storage site of any resource type. Mafic and ultramafic storage site design will also be strongly influenced by injection style.

Due to the heterogeneous nature of geological systems, no two CO_2 storage sites will have the exact same site design. Nevertheless, sites are more similar than they are different. Each site, regardless of resource type, will have at least one CO_2 injection well, a variety of monitoring equipment, and infrastructure to deliver CO_2 to the wellhead. Aqueous CO_2 storage sites will have a larger physical footprint than supercritical sites due to the need for more injection infrastructure to achieve the same mass of CO_2 injected. They are also likely to have water production infrastructure and/or water pipelines.

Mafic and ultramafic CO_2 storage can occur both on and offshore, with most project developers targeting onshore storage. This work has focused on site design for onshore sites, although many of the principles apply to offshore storage as well.

Table 13. Comparison of site design parameters by resource type

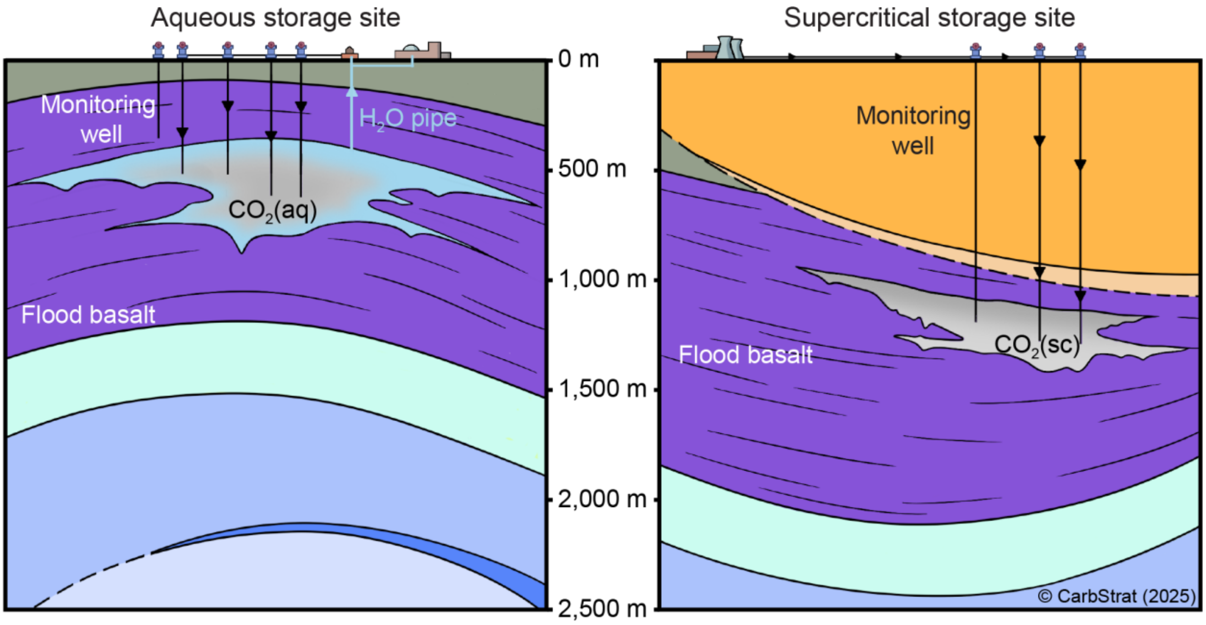
		Mafic and ultramafic	
Design parameters	**Sedimentary**	**Supercritical**	**Aqueous**
Injection depth	> 800 m	> 800 m	Variable Below the deepest lens of potable water
Single well fluid injection capacity (Mtpa CO_2)	1-2	0.12-2	0.016-0.14*
No. of injectors for 1 Mtpa CO_2	1	1-2	7-62*
Injection equipment	▪ Compressors, heating facilities if needed, and other standard equipment		▪ Dissolved CO_2 injection equipment or CO_2 injection and water injection equipment
Water requirements	▪ Water production may be required for pressure relief		▪ 20-30 t H_2O needed to dissolve 1 t CO_2 for the aqueous injection

Design parameters	Sedimentary	Mafic and ultramafic	
		Supercritical	Aqueous
			▪ Water production may be required for pressure relief ▪ Reservoir can be a source of water for injection
Non-injection infrastructure	▪ CO_2 transport lines ▪ CO_2 injection equipment	▪ CO_2 transport lines ▪ CO_2 injection equipment	▪ CO_2 transport lines ▪ Water connection or water production infrastructure ▪ CO_2 dissolution equipment
Monitoring needs	▪ Portfolio of monitoring technologies based on site's risks	▪ Portfolio of monitoring technologies based on site risks ▪ Likely a greater focus on geochemical monitoring than geophysical monitoring, but to be determined with scale-up ▪ Monitoring technology improvements likely needed to improve monitoring of dissolved and/or mineralized CO_2	

* This assumption is based on a minimum water-to-CO_2 ratio of 20:1 and a maximum of 30:1 and wells that can support between 0.5 and 3 Mtpa fluid injection (1,370 to 8,200 m^3/day).

Notes: CO_2 injection equipment includes compressors, heating facilities if required, and various other standard equipment used for injection. Pumps are required for water or dissolved CO_2 injections.

Figure 15. Idealized site design for aqueous (left) and supercritical (right) CO_2 storage sites in a flood basalt



Notes: CO_2(aq) = aqueous carbon dioxide; CO_2(sc) = supercritical carbon dioxide. The CO_2 plumes should not be interpreted as having dissolved the host rock. Injected CO_2 will move away from the injection point via fractures and high permeability layers within the flood basalt structure. Aqueous CO_2 storage sites will likely require more wells to reach a similar injection volume. In the schematic of the aqueous site, water is being produced from the target reservoir to be used as an injectant.

5.1.1. Injection depth

The targeted depth of injection depends on the resource type, injection style, and economic parameters.

Differences between resource types

Due to drilling-related costs, mafic and ultramafic CO_2 storage sites will likely need to target shallower resources than sedimentary storage sites if they aim to achieve a similar levelized cost of CO_2 storage. Based on discussions with project developers and examples from operating projects, most mafic and ultramafic CO_2 storage sites target resources between 500 and 1,000 m below surface.

Differences between injection styles

Aqueous CO_2 storage sites are less depth-restricted than supercritical CO_2 storage sites since they do not aim to store CO_2 above its condensation pressure. Regulatory frameworks of the jurisdiction where the site is located may place depth limitations on subsurface activities. In the absence of explicit depth limitations, operators will need to balance the depth of injection against the risk injection poses to potable groundwater resources. To prevent contamination of potable groundwater resources, at a minimum injection should target aquifer formations that are deeper than the total depth of public or private wells in the same region. Injection depth may also be influenced by the depth of permeable horizons, the temperature and pressure of the target reservoir, and the presence of confining features.

5.1.2. Injectivity and well requirements

The number of injection wells required by a CO_2 storage site depends on resource injectivity, targeted site capacity, and site design.

Differences between resource types

Research suggests that a single well injecting into an interflow zone in the Columbia River Basalt Group could support annual injection of between 0.12 and 2 Mt of supercritical CO_2 for 20 years while remaining at 95% of borehole breakout pressure (Pollyea and Benson, 2018). The Columbia River Basalt Group is a relatively young flood basalt, so this may not be representative of all basalts. The 0.12-2 Mtpa range and other data on fluid injection into crystalline rocks provides the means to estimate a potential per-well maximum.

The recent permit issued by the Icelandic Environment and Energy Agency suggests that mafic rocks and single wells can support large-scale fluid injections. Based on the listed water-to-CO_2 ratios in that document, Carbfix plans to inject over 4 Mtpa of water in the Húsmúli 1 well and nearly 3 Mtpa of water in the Geopark 3 well (Icelandic Environment and Energy Agency, 2025b).[30] Wastewater injections into crystalline basement also demonstrate the feasibility of large-scale fluid injections into mafic and ultramafic rocks.

Based on fluid injection rates in basalts and crystalline rock, and modelling information, mafic and ultramafic resources may be able to achieve similar per-well supercritical CO_2

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[30] The permitting document provides the maximum permitted injection rates for CO_2 and water in kg/s. Húsmúli 1 well has a permitted rate of 132 kg H_2O/s and Geopark 3 has a permitted rate of 92 kg H_2O/s. This comes to a daily injection rate of ~11.5 and 8 kt H_2O respectively. To reduce the risk of introducing errors, injected water amounts are discussed in terms of mass rather than volume.

injection rates as sedimentary resources. Additional piloting and demonstration is needed before per-well injection volumes can be estimated with any level of certainty.

Potential mafic, ultramafic, or metamorphic storage resources that are plutonic, or are located in cratons, or do not have a confining unit below their potential reservoir are likely to be at higher risk of induced seismicity.[31] High injection rates into crystalline rocks or into sedimentary rocks in hydraulic communication with the crystalline basement can result in induced seismicity. Wastewater disposal operations that injected near to crystalline basement in Oklahoma and Texas, United States, have been linked to thousands of instances of induced seismicity (≥ 3 magnitude [*M*]) (Langenbruch and Zoback, 2016; Zhang et al., 2013; Zoback and Hennings, 2025).[32] Induced seismicity risk is discussed further in Section 6.1.4.

In addition to uncertainty around the injectivity of mafic and ultramafic resources, injection rate decline in these resources is also less understood when compared to sedimentary resources. In sedimentary resources, injection rate decline is primarily related to rising pressure within the reservoir. In mafic and ultramafic resources, pressure will likely contribute to injection rate decline, but it may also be impacted by mineralization. If injected CO_2 rapidly mineralizes near the wellbore it could result in injectivity decline due to clogging of near-wellbore porosity. Rapid mineralization has been documented at the Wallula Basalt Project and CarbFix1. During the CarbFix1 pilot, well transmissivity dropped during July of 2012 due to near-wellbore clogging from iron sulphide precipitation and a bacterial bloom (Trias et al., 2017). During CarbFix2, well injectivity did not appear to be affected by the mineralization occurring in the reservoir (Clark et al., 2020).

Differences between injection styles

Aqueous CO_2 storage sites are likely to need more wells to reach an equivalent annual CO_2 injection capacity. Based on the fluid injection constraints discussed above, aqueous CO_2 storage sites are likely to need 1-6 wells and 7-62 wells to achieve nominal CO_2 injection capacity of 100 ktpa and 1 Mtpa respectively.[33] That number of wells can introduce well management and design concerns due to pressure, fluid communication, and risks related to well interference. It also can significantly increase site costs (see Section 5.2).

Box 6. Coda Terminal injection infrastructure

Carbfix is currently developing a large-scale storage project in Icelandic basalts. The Coda Terminal project has received support from the EU Innovation Fund. It aims to enter operations in 2026 with an initial injection capacity of 500 ktpa CO_2.

Limited information is available on the site design and per-well injection rates. A 2023 presentation included a plan for 5-10 injectors for the first phase with an annual CO_2 injection capacity of 500 ktpa, 16-32 wells for the 1 Mtpa phase (starting in 2028), and 50-100 wells for the 3 Mtpa phase (starting in 2031). This suggests that they expect to be able to inject between 30 and 100 kt CO_2 per well per year (Johannsson, 2023).

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[31] A craton is a relatively immobile block of the Earth's crust that acts as a nucleus to a continent or oceanic basin. They are composed of crystalline basement rock and are typically Precambrian in age.

[32] The referenced papers use different magnitude scales. The data in Langenbruch and Zoback (2016) comes from the USGS, and the original dataset does not specify which magnitude scale was used. Zhang et al. (2013) states that the seismic events ranged in magnitude from 3.8-5.5 M_b.

[33] Based on an annual fluid injection maximum per well of 0.5, 1, and 3, and a water-to-CO_2 ratio of 20:1, 25:1, and 30:1.

5.1.3. Water requirements

All CO_2 storage sites may have minor water demands over their lifetime, but aqueous or water-alternating-gas (WAG) injections will have significant water demands due to the inclusion of water during their injection process.

Differences between injection styles

As discussed in Section 3.2, aqueous and WAG injections require water. WAG projects may require less water than aqueous projects, but WAG for CO_2 storage in mafic and ultramafic rocks has not yet been piloted. For aqueous sites, assuming a water-to-CO_2 ratio of between 20:1 and 30:1, a site injecting 100 ktpa of CO_2 will have a daily injection rate of ~5.5-8.5 kt (~5,800-8,600 m^3) of water and require 2-3 Mt (2-3 million m^3) of water annually. This water does not need to be potable but must have a chemical composition that will not adversely impact site operations.

Water for aqueous injections can come from a variety of sources, including the target reservoir. If water is being produced from the target reservoir, operators will need to ensure that wells are spaced in a way that injected CO_2 does not break through into the producer wells. Water production can provide some pressure relief. Water can also come from other sources, including seawater, geothermal operations, and wastewater disposal operations. Different water sources and qualities may have an impact on CO_2 solubility and mineral carbonation kinetics (see Section 2.3). Water quality, type, and demands may also impact the permitting process for a site.

5.1.4. Surface footprint and non-injection infrastructure

Compared to other energy transition technologies, such as solar panel arrays and wind turbines, the physical footprint of an onshore CO_2 storage site is typically small. It is usually limited to one or several well pad(s) and CO_2 pipelines. If a site needs buffer storage tanks or is receiving CO_2 by ship, train, or truck, it may require additional infrastructure and site facilities and therefore have a larger physical footprint.

Beyond transport connections and injection infrastructure, storage sites have monitoring infrastructure, potentially including monitoring wells. Monitoring is designed to observe the behaviour of injected CO_2 and the reservoir. It is designed to increase confidence in storage operations and allow for early detection of irregularities in operation or plume behaviour. Monitoring is discussed in more detail in Section 5.3.

Differences between resource types

Due to differences in geochemical, geophysical, and geomechanical properties, monitoring strategies will vary between resource types. Compared to sedimentary resources, mafic and ultramafic sites may need more monitoring wells since they are likely to rely on geochemical measurements for primary monitoring. Monitoring these sites may also be more complex due to difficulties in modelling fracture flow and monitoring aqueous CO_2.

Vesicular basalts and other volcanics may have sufficient primary and secondary permeability to allow for injection without inducing fracturing. Peridotites and plutonic rocks, with their significantly lower primary permeabilities, may need to be fractured to allow for injection. Induced fracturing requires additional equipment during site development. The carbonation reaction itself can induce fracturing in the system since carbonate minerals have a larger volume than most primary minerals. This does not necessarily result in increased permeability since secondary mineral products can fill pore space (Kelemen et al., 2011).

Differences between injection styles

In addition to requiring more injection wells, aqueous CO_2 storage sites will need either water production wells and associated water transport infrastructure or a connection to a water source. This will increase the physical footprint of the site. Project developers will need to ensure that any water produced from the reservoir does not contain CO_2 that was injected or that any reproduced CO_2 is appropriately accounted for. They will also need facilities to dissolve CO_2 in water; dissolution can occur at the surface or at depth.

5.2. Drilling and wells

Many aspects contribute to well costs, including type of rig used, regional rig availability, remoteness of the drilling site, cost of labour, well depth, rate of penetration (ROP), current pricing of steel for tubulars, the type of cement and steel used, the type of equipment installed down-well, and the type and amount of drilling mud used. Since drilling costs are very regional and well design is site-specific, this study provides a framework for drilling-related technoeconomic analysis, but it does not produce any specific cost estimates.

Differences between resource types

One study postulated that the “term hard rock was perhaps originally coined by drillers to indicate poor drillability of these rocks” (Singhal, 2008). The minerals and mining sector has significantly more experience drilling mafic, ultramafic, and metamorphic rocks than the petroleum sector does, but globally there is still less experience drilling and exploiting hard rocks than sedimentary resources. Beyond the comparative lack of experience, drilling through hard rock is less efficient and often more complex (X. Li et al., 2023; Millett et al., 2016; Weili and Kai, 2017; Zha et al., 2017). As we move to scale up this type of storage, hard rock drilling techniques from the mining and minerals sector will need to be combined with well design, reservoir management, and fluid flow expertise from the petroleum and geothermal sectors.

Beyond their hardness, there are several challenges associated with drilling mafic and ultramafic rocks, including the following:

- There are typically a limited number of existing penetrations in an area that can inform the development of a drilling plan.
- Clay minerals are a leading cause of drilling problems and cost overruns (Aplin et al., 1999). Mafic and ultramafic rocks can contain a high percentage of clay minerals and may of the clays they contain have high swelling potential.[34] When exposed to drilling or formation fluids, they can swell and reduce wellbore diameter in uncased holes (Millett et al., 2016). Clay build-up around a drill bit can negatively impact ROP.
- The fractured nature of mafic and ultramafic rocks can make them prone to washout and/or lead to material falling into the hole, and against the bit or the drill string (Millett et al., 2016). This can damage equipment and lead to difficulties with wireline logging or casing.
- Mud loss into fracture zones can increase drilling costs and drilling complexity.

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[34] Clay minerals are a common product of low temperature alteration, especially of hyaloclastite.

To address some of the challenges associated with drilling hard rocks and exploratory wells, the Wallula Basalt Project followed a drill-and-test approach rather than focusing on drilling directly to total depth. The drill-and-test approach, which pauses drilling at key intervals or milestones, allowed the Wallula project team to incrementally collect hydrogeologic information and adjust their drilling strategy as required. Several projects in development today are planning to use a drill-and-test approach for their initial appraisal wells. While this approach increases the time the drill rig is on site, and associated cost, it can improve data collection. In addition to the drill-and-test strategy, the Wallula Basalt project used reverse circulation drilling to improve well control, reduce the risk of near-bore clogging due to mud infiltration, and improve fluid sampling (McGrail et al., 2009b).

Many companies involved in subsurface operations will have negotiated rates for drilling and/or will maintain internal databases on region-specific drilling costs based on rig type. These negotiated rates and internal databases may not account for the bits used in hard rock drilling, the increased bit wear, and slower rate of penetration. The information presented in Table 14 can help companies generate high-level cost estimates based on their standard drilling costs.

Table 14. Factors that can influence the cost of drilling

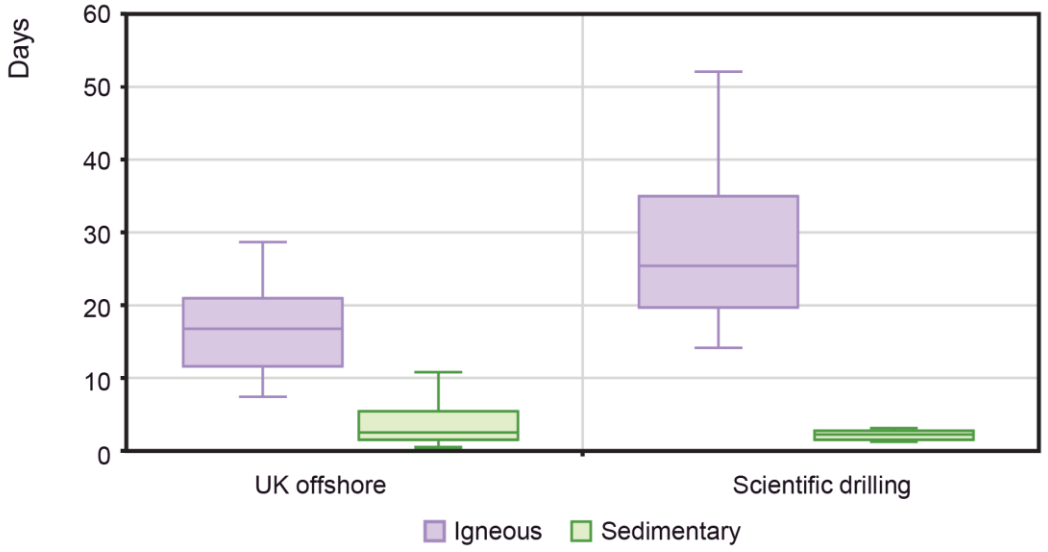
Aspect	Sedimentary resources			Mafic or ultramafic resources		
Rig type	Pressure-control drill rigs			Depth and resource dependent, but pressure-control drill rigs likely required for all but the shallowest wells		
ROP (m/hr)		**UK offshore**	**Sci. drilling**		**UK offshore**	**Sci. drilling**
	Average	15.8	20	Average	2.6	1.6
	Median	16.5	18.7	Median	2.5	1.6
	Fastest	90.1	33.7	Fastest	5.6	2.9
	Slowest	3.4	13.3	Slowest	1.5	0.8
Bit life (m)		**UK offshore**	**Sci. drilling**		**UK offshore**	**Sci. drilling**
	Average	261.9	896.8	Average	78.6	49.6
	Median	255.7	879.8	Median	88.4	50.5
	Highest	4012.4	987.0	Highest	339.2	106.0
	Lowest	21.9	815.0	Lowest	3.0	22.8

Notes: ROP = Rate of penetration; Sci. = Scientific. Scientific drilling data are derived from Ocean Drilling Program/Integrated Ocean Drilling Program wells 504B, 1256D, 397A, 391C, 361, 222, and 439. UK offshore data sourced from wells 21/3B-3, 217-15-1Z, 204/19-BC, 30/7Z-P11, 22/23a-3. ROP (metre/hour) does not differentiate between coring and drilling. Bit life (metres drilled) was defined based on the bit logs and includes all bit changes, not only those related to wear and/or damage.

Sources: Chevron (2010); Exlog North Sea (1990); Halliburton Energy Services (1994); X. Li et al. (2023); Occidental Petroleum (Caledonia) Ltd. and 7th Round Joint Venture (1981); Sperry-Sun Drilling Services (1996).

As shown in Figure 16, drilling igneous rocks requires around six times more active drilling time than drilling the equivalent number of metres in sedimentary rocks. The data are separated into scientific drilling and commercial drilling, both offshore, because the two different types of drilling have different aims and purposes. Both are included in Figure 16 due to the limited amount of publicly available ROP data for hard rock drilling.

Figure 16. Active drilling time required to drill 1,000 m



CarbStrat (2025). CC BY-SA.

Notes: Scientific drilling data are derived from Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP)/Integrated Ocean Drilling Program (IODP) wells 504B, 1256D, 397A, 391C, 361, 222, and 439. UK offshore data sourced from wells 21/3B3, 217-15-1Z,204/19-BC, 30/7Z-P11, 22/23a-3. ROP (m/hr) does not differentiate between coring and drilling.

Sources: Chevron (2010); Exlog North Sea (1990); Halliburton Energy Services (1994); X. Li et al. (2023); Occidental Petroleum (Caledonia) Ltd. and 7th Round Joint Venture (1981); Sperry-Sun Drilling Services (1996).

Differences between injection styles

Aqueous CO_2 storage sites may target depths sufficiently shallow that they may not need a pressure-control drill rig and may instead be able to use drill rigs that have lower day rates and mobilization fees. This can, in turn, result in cost savings. Since aqueous sites are likely to need significantly more wells, drilling costs have the potential to rise quickly regardless of rig type.

All CO_2 storage sites can face corrosion risk, but the risk is likely to be higher in aqueous injections due to the acidity of the injectant. Depending on the impurities present in the CO_2, the water (if used), and formation fluids, highly corrosion resistant stainless-steel tubulars may be required in certain zones. Casing thickness can also be adjusted to provide a buffer to reduce the risk of failure if corrosion occurs. This can have a significant ramification on cost. It may not be necessary to deploy corrosion-resistant steel tubulars for the entire depth of the well, but that will need to be evaluated on a per-well basis.

Unreactive cements may also need to be deployed depending on the composition of the injected fluids. Research around the cement used for CO_2 storage wells is conflicting, Portland cement can alter when exposed to acidic fluids. This can lead to cracking or delamination, but it can also lead to carbonate precipitation which can self-seal the cement and/or form passivating layers (Wolterbeek et al., 2019; Guthrie et al., 2018; Teodoriu and Bello, 2020). Specialized cements can be more difficult to deploy than Portland cement depending on the region, product availability, and the cement blending facility. They may improve long-term well integrity, but equally they lack the ability to self-seal and therefore may be less secure than reactive Portland-based cements (Azwar et al., 2024, 2023).

5.3. Measurement, monitoring, and verification

Measurement, monitoring, and verification (MMV) is a component of all CO_2 storage projects regardless of resource type. The goal of MMV is to verify that injected CO_2 is contained, to demonstrate that the behaviour of the CO_2 plume (or CO_2-charged water) conforms with expectations and models, and to provide regulators and project stakeholders with confidence that the site is operating as planned. Containment, conformance, and confidence are sometimes referred to as the "three Cs" of MMV (Dean and O'Brien, 2024).

In line with the three Cs, MMV programmes are designed to de-risk site operations and reduce critical risks to an acceptable threshold. Risk-based MMV programmes are dynamic. Detection of an abnormality or occurrence of a risk event will trigger the site operator to take predefined actions aimed at identifying the source of the abnormality and mitigating it as required. Mitigation procedures will depend on the triggering abnormality or risk events. Some abnormalities may trigger additional measurement and monitoring, but otherwise not affect operations. The occurrence of critical abnormalities or risk events, such as induced seismicity above a certain magnitude or leakage via a wellbore, may result in regulators requiring a site to cease injection operations.

The selection of monitoring technologies and techniques is site-specific and dictated by the MMV needs of the site, regulatory requirements, and overall cost. The technologies used will also evolve with the operations conducted at the site. For example, certain measurements, such as soil (or sediment if offshore) gas sampling and CO_2 land surface flux, may be relevant to collect during site design to establish baselines. If the risk of leakage is low and CO_2 should not be able to enter groundwater resources or soil layers, further measurements may not need to be collected unless triggered by a risk event or abnormality.

Monitoring of sedimentary CO_2 storage has been the focus of decades of research and technology development. Some of those lessons and techniques can be adapted to monitoring of mafic and ultramafic CO_2 storage sites, but these sites also present new monitoring challenges.

5.3.1. Monitoring techniques and technologies

As with resource assessment and site design, MMV plans are designed to be risk-based and will be site-specific. Table 15 outlines common monitoring techniques. Since there are no large-scale mafic or ultramafic CO_2 storage sites operating today, it is difficult to identify the importance of individual techniques for monitoring CO_2 storage these resources.

Differences between resource types

Due to their heterogeneous nature, mafic and ultramafic rocks can be difficult to resolve with seismic imaging. Interflow zones in flood basalts, sedimentary interbeds, and serpentine minerals can increase seismic attenuation (Payne, 2007). This can decrease data quality and potentially introduce shadows or artifacts. The high density of intrusive mafic and ultramafic rocks means that they have high impedance, therefore increasing the amount of reflection, especially at boundaries. Additionally, the individual grain boundaries of mineral crystals can cause scattering, further reducing data quality.

Table 15. Comparison of monitoring techniques by resource type

Measurement technique	Example applications	Importance by resource type Sedimentary	Mafic or ultramafic CO_2(sc)	Mafic or ultramafic CO_2(aq)	Mafic or ultramafic considerations
Tracers	▪ Trace subsurface CO_2 movement ▪ Quantify solubility trapping	Low to medium	High	Very high	▪ Critical to define transport time between injection well and monitoring well(s) ▪ Likely used in combination with water composition to estimate dissolution and mineralization rates
Water composition	▪ Quantify mineral and solubility trapping ▪ Detect out-of-zone CO_2 or formation fluid migration	Low	High to very high	Very high	▪ Critical to identifying residence time of CO_2 and potentially quantifying mineralization ▪ Water composition combined with tracers may be one of the only reliable ways to monitor a plume of aqueous CO_2
Subsurface pressure	▪ Control formation pressure below fracture gradient ▪ Monitor the condition of well tubulars	Very high	Low to medium (small scale) High to very high (large scale)	Medium (small scale) Very high (large scale)	▪ Small-scale injections may be less pressure-limited and may not approach fracture pressure of the reservoir ▪ Large-scale injection is likely to be at least as pressure constrained as sedimentary storage ▪ Aqueous injections will likely have more pressure constraints than supercritical injections due to the additional water volumes
Well logs	▪ Monitor formation temperature ▪ Track CO_2 movement in and above the formation ▪ Provide data for seismic survey calibration	Very high	Very high	Very high	▪ Nuclear magnetic resonance (NMR) logging can be used to estimate permeability ▪ Pulsed neutron logging (PNL) may be used to monitor CO_2 plume migration ▪ Resistivity logs can be used to identify rock dissolution ▪ Temperature logging can help identify if reservoir temperatures increase, which could be caused by the exothermic carbonation reaction

		Importance by resource type			
Measurement technique	**Example applications**	**Sedimentary**	**Mafic or ultramafic CO_2(sc)**	**Mafic or ultramafic CO_2(aq)**	**Mafic or ultramafic considerations**
Seismic imaging (2D, 3D, 4D)	▪ Visualize reservoir structure and injected CO_2 ▪ Track CO_2 movement ▪ Identify fractures and faults	Very high (resource assessment) Medium to high (operations)	Very high (resource assessment) Unknown (operations)	Very high (resource assessment) Unknown to low (operations)	▪ Heterogeneity in hard rocks can introduce artifacts ▪ Aqueous CO_2 cannot typically be differentiated from formation fluids with seismic imaging techniques because of an insufficient density contrast. Seismic imaging for plume monitoring may not be relevant at aqueous sites. ▪ If there are large primary wave (P-wave) velocity contrasts with over- or underlying material, shadows can be produced, and image quality will decrease ▪ Fracturing, porosity, and secondary mineralization can increase attenuation and result in decreased image quality ▪ Sediment interbedding, serpentinization, and dykes or intrusions can all decrease data quality and increase data processing complexity
Passive seismic monitoring	▪ Conduct baseline monitoring of seismic activity ▪ Monitor the development of microfractures ▪ Identify fractures and faults ▪ Can be used to support deployment of a traffic light system for managing seismic risk	High	Unknown to high	Unknown to high	▪ Required to manage induced seismicity risk ▪ Could be used to track fracture evolution ▪ Can aid in the location of seismic events depending on the velocity model

		Importance by resource type			
Measurement technique	**Example applications**	**Sedimentary**	**Mafic or ultramafic CO_2(sc)**	**Mafic or ultramafic CO_2(aq)**	**Mafic or ultramafic considerations**
Time-lapse gravity measurements	▪ Identify density changes caused by fluid displacement ▪ Potentially identify mineralization fronts	Medium	Unknown, but potentially high to very high	Unknown, but potentially high to very high	▪ Magnetic and gravity data can be used to constrain mineralization fronts; however, they do not appear to have been tested for mafic or ultramafic CO_2 storage
Remote sensing	▪ Identify tilting, or vertical or horizontal displacements	Medium	Unknown	Unknown to high	▪ May be more important for aqueous injections due to the volumes of fluids involved ▪ May be more important for shallow injection sites
CO_2 land surface flux	▪ Identify CO_2 fluxes between the land surface and the atmosphere	Medium	Unknown	Unknown to very high	▪ Used to monitor shallow systems to see if CO_2 may be leaking ▪ May be more important for shallower sites
Soil gas sampling	▪ Conduct isotopic analysis of soil gas composition ▪ Take measurements to establish natural baseline and variability	Low	Unknown	Unknown to high	▪ May be more important for shallower sites

Note: Importance by resource type was decided following consultation with CO_2 storage experts across resource types. The above list is not exhaustive and is based on the categories defined in Table 5.4 of the 2005 IPCC Special Report on CCS.

Sources: Techniques and example applications adapted from IPCC (2005); Raza et al. (2022).

In addition to difficulties associated with the quality of data produced from seismic surveys of mafic or ultramafic rocks, it may also be more difficult to image the plume of injected CO_2. Seismic imaging of an injected CO_2 plume relies on the density contract between supercritical CO_2 and formation fluids. Given the strong density difference between mafic or ultramafic rocks and formation fluids, the more subtle density contrast between formation fluids and supercritical CO_2 may not be resolvable. Additionally, if CO_2 is injected in aqueous form, there will be even lower density contrast.

Since many mafic and ultramafic CO_2 storage sites focus on mineralizing injected CO_2, geochemical monitoring techniques are of high importance to this type of storage. Project developers suggest that due to the rapid mineralization observed in laboratory studies, pilots, and small-scale sites operating today, mafic and ultramafic sites may not require extended periods of post closure monitoring.

The Carbfix developed, and DNV validated, methodology for greenhouse gas reporting suggests that geochemical monitoring techniques and mass balance calculations – such as those used by Clark et al. (2020), Matter et al. (2016), Pogge Von Strandmann et al. (2019), Ratouis et al. (2022), and Snæbjörnsdóttir et al. (2017) – are sufficient to demonstrate mineralization (Carbfix, 2022; Carbon Capture Journal, 2022). The methodology states that "if the project proponent(s) demonstrate at least 95% mineralization of the injected CO_2 during the post closure period, then post closure period monitoring can be terminated before the 10 years period and transfer of liability process launched" (Carbfix, 2022).

Geochemical monitoring techniques use conservative tracers to track fluid flow between injection wells and monitoring wells. Periodic water composition measurements are used to track dissolved inorganic carbon and key chemical species like calcium, iron, and magnesium. Clumped isotope measurements, for example carbon and oxygen, can be used to reconstruct the temperature and CO_2 source of mineralized carbonates (Holdsworth et al., 2024). These techniques are mainly based on mass balance calculations and have been used with great success at pilot sites to estimate the amount of mineralized CO_2 (Matter et al., 2016; White et al., 2020).

Unlike the subsurface imaging techniques often used to monitor sedimentary CO_2 storage sites, geochemical monitoring cannot be used to visualize the full extent of a plume. In addition, injected CO_2 can be immobilized in the subsurface by multiple mechanisms beyond carbonate mineralization (Daval, 2018). Further field-scale testing and independent review of collected data are likely needed to evaluate whether these techniques alone are sufficient to demonstrate mineralization. Currently, it is unclear whether geochemical techniques and mass balance calculations are sufficient to demonstrate to regulators that the CO_2 is securely trapped in the reservoir and that the plume is behaving as expected.

5.3.2. Containment

Containment refers to the ability of a CO_2 storage site to trap CO_2 in a defined zone or area for geological timescales. The resource assessment and site development process is designed to ensure that sites are only developed in resources where containment can be assured. Engineered pathways such as wells are likely to pose the highest risk of containment breach.

Several techniques can be used to monitor injected CO_2 to assure containment, including tracer tests, pressure monitoring, seismic imaging and passive seismic techniques, and gravity measurements. These techniques and others are discussed further in Table 15. Containment, containment failure, and related risks are discussed further in Section 6.1.3.

5.3.3. Conformance

Monitoring data are an integral component of storage site modelling. History-matching reservoir and flow models can improve forward-looking models. Today, many storage sites perform injection tests and/or slowly ramp up or phase injection operations to collect data to improve reservoir modelling prior to full-scale injections.

Conformance refers to the alignment between reservoir and CO_2 plume models and observed or measured reservoir and CO_2 plume behaviour. Conformance monitoring is a key part of CO_2 storage operations. In jurisdictions that allow it, transfer of site liability to a competent authority is usually contingent on the operator demonstrating that the site is in conformance during its period of post-closure monitoring.

Conformance can be demonstrated by comparing monitoring data with history-matched forward models (Bourne et al., 2014; Dean et al., 2019; Furre et al., 2020; Jiang and Durlofsky, 2024; Rowe et al., 2024). Given geological uncertainty, small deviations are not usually cause for alarm, but they may trigger additional monitoring. Typically, significant deviations will immediately result in a site engaging in remediation efforts or mitigation activities.

Differences between resource types

While conformance modelling is relatively well understood for sedimentary CO_2 storage, the limited number of mafic and ultramafic CO_2 storage sites mean that limited data are available to evaluate conformance and history matching of models. As with sedimentary CO_2 storage sites, a range of different techniques are likely to be needed to demonstrate conformance.

Carbfix’s operations, while small scale, have been sufficiently continuous that they may already be engaging in history-matched forward modelling. A publication on their second injection site outlines their approach to reservoir and fluid flow modelling. They do not appear to aim for conformance between the measured and modelled concentrations of dissolved inorganic carbon, calcium, and other species. Instead, they use the difference in species concentration to estimate the amount of injected CO_2 that has mineralized between the injection and monitoring wells (Ratouis et al., 2022).

Passive seismic data acquisition on the same site was able to produce subsurface structures that correspond to the geological model of the injection area. The technique may have been sensitive enough to identify some of the injected CO_2, but there were no other monitoring seismic surveys available to compare the data with (Hassing et al., 2024).

It is unclear from the available information how Carbfix plans to monitor for conformance, and no other mafic or ultramafic project has released information on its plans for conformance monitoring. While geochemical tracers and water composition measurements can be used to model flow pathways and residence time, they are unlikely to be sufficient to demonstrate conformance as it is currently defined for CO_2 storage sites.

Reactive transport modelling combined with field-scale flow models could potentially provide a pathway to model the amount of CO_2 immobilized between the point of injection and monitoring wells. Conformance could potentially be demonstrated by alignment between the modelled and measured concentrations of dissolved inorganic carbon, calcium, and other chemical species. However, multiple mechanisms beyond carbonate mineralization can restrict the migration of CO_2 between the point of injection and monitoring wells. While mass balance approaches can be used to calculate how much injected CO_2 is potentially fixed, they cannot conclusively be used to demonstrate carbonate mineralization. Conformance monitoring based on geochemical techniques could require an extensive array of monitoring wells since fluids will need to be sampled at a range of depths and locations to ensure that injected CO_2 remains in the target storage complex and is not migrating out of zone.

5.3.4. Confidence

One key aim of monitoring is to demonstrate to regulators, local communities, and other stakeholders that the site is behaving as expected. This is called confidence monitoring. MMV is typically a legally mandated component of CO_2 storage site operations. In many jurisdictions, regulators review a site's MMV plan during permitting and at key intervals during site operations and post-closure. The timing of periodic reviews varies between jurisdictions.

While MMV activities directly contribute to confidence, it will also be influenced by external pressures including public perception of other CO_2 storage sites. Since CO_2 storage in all resources has yet to reach full commercial maturity, it is important for the industry to work together to ensure that the industry develops a reputation of safe and transparent operations.

Differences between resource types

Research suggests that large-scale supercritical CO_2 injections into mafic and ultramafic resources will have much slower mineralization rates than observed in the Wallula site due to the geochemical constraints on alkalinity. If messaging continues to focus on rapid mineralization and large-scale sites are unable to achieve similar rates and/or are unable to conclusively demonstrate mineralization, confidence in mafic and ultramafic storage may decrease.

Differences between injection styles

Local communities and regulators are rightly very protective of groundwater resources. Mafic and ultramafic CO_2 storage projects that are targeting shallower injections and are therefore injecting aqueous CO_2 may need more extensive deployment of groundwater and soil gas monitoring to ensure that they are able to demonstrate that the site is not adversely affecting groundwater resources or soils. Transparency about water sources and the effect that injection or any associated water production may have on the local community can improve confidence.

5.4. Cost components

One of the difficulties associated with developing CO_2 storage projects is the front loading of costs, with a significant portion of expenditure occurring prior to final investment decision (FID). Today, there is not sufficient information available to perform a detailed techno-economic assessment of mafic and ultramafic CO_2 storage and its different injection styles. Cost components and their distribution across the project lifetime can still be discussed.

- **Development and design expenditure** refers to all costs associated with resource assessment and appraisal. This cost component is exposed to exploration risk (see

Section 6.2.3). A significant portion of these costs will be staff time, but they include all aspects of resource assessment and appraisal such as licensing fees, drilling of exploration wells, reservoir testing, purchasing historic data, and engineering studies.

- **Capital expenditure (CAPEX)** includes the capital costs associated with site facilities, wells, and other fixed assets. Depending on many factors, including resource type and location, the site's injection style, regional labour costs, and the cost of capital, either CAPEX or operational expenditure (OPEX) can be the most significant cost component for a storage project. Since CAPEX is required up front prior to revenue generation, project developers that cannot afford to self-fund development may need to seek loans or other financing options. The CAPEX of small-scale mafic and ultramafic CO_2 storage projects storing CO_2 from direct air capture (DAC) or bioenergy with capture may be low enough that the project developer can finance construction with funding from advance market commitments for carbon dioxide removal (CDR) credits or via equity raises. Large-scale mafic or ultramafic CO_2 storage sites that require the developer to raise debt may be more difficult for small startups to develop if they do not also have access to public support such as grants or government-backed loans.
- **Operational expenditure (OPEX)** is related to facility operations over the lifetime of the project. Either OPEX or CAPEX can be the highest overall cost component of a project, but in the case of OPEX, costs are spread over its operating lifetime. OPEX will include insurance for the site. While many of the activities of a CO_2 storage site can be insured with existing insurance projects, insurance coverage for some aspects of subsurface risk are still being developed.
- **Abandonment expenditure (ABEX)** is the CAPEX and OPEX related to the closure of a site. This includes plugging and abandoning wells, site remediation, etc.
- **Post-closure costs** are costs tied to post-closure MMV and preparing the site for turnover to a competent authority or regulator, if allowed in the specific jurisdiction.

In addition to those cost categories, depending on the jurisdiction, CO_2 storage projects in all resource types may be required to put up a financial guarantee as a condition of receiving a permit. They may also be required to pay royalties or place funds in a stewardship fund.

Differences between resource types

Table 16 compares the considerations that impact CO_2 storage cost components in different resources. Based on available data, mafic and ultramafic CO_2 storage projects are likely to have higher levelized costs of CO_2 storage than sedimentary resources of a similar size and in a similar region, since drilling is expected to be more expensive due to a slower ROP. If mafic and ultramafic resources can be drilled using smaller drill rigs or drill rigs without pressure control, drilling costs may be substantially reduced since such rigs usually have a lower day rate and mobilization fee compared to rigs used for drilling sedimentary CO_2 storage wells.

In the near term and on an absolute basis, costs for mafic and ultramafic CO_2 storage sites are likely to be lower than those of sedimentary sites due to the differences in target site size. Most developers of sedimentary CO_2 storage sites are focused on larger resources which may be more costly, in absolute terms, to assess and develop. On a levelized basis, per tonne of CO_2 injected, smaller mafic and ultramafic CO_2 storage sites are expected to be more costly than larger sedimentary CO_2 storage sites because they are unable to capitalize on economies of scale.

Table 16. Comparison of CO_2 storage cost components in different resource types

Cost component	Share of cost	Sedimentary resources	Mafic and ultramafic resources all injection styles	Mafic and ultramafic resources $CO_2(aq)$
Design and development expenditure	Low to medium	▪ Depending on resource type, more geological data may be available on regional or local seals ▪ Access to the resource may be limited if there is ongoing oil or gas production in the same formation ▪ Legacy wells in targeted resource need to be assessed for risk	▪ May require more exploration wells to characterize resource ▪ Lower risk of legacy wells if not in active mining region ▪ Exploration risk is very high ▪ Data purchasing is likely lower than sedimentary resources due to limited data availability ▪ Drill-and-test approaches may be required for initial wells into a resource due to lack of information at depth. This can increase costs.	▪ Inventories of legacy wells at shallow depths may be incomplete since they may not account for all private water wells ▪ May need to characterization of a water source ▪ May need to apply for water-related exploration or production licences ▪ May need more extensive field testing understand the resource's hydrogeology and potential flow paths for aqueous CO_2
Capital expenditure (CAPEX)	High to highest	▪ If the resource has already been exploited for oil or gas production, there may be opportunities to repurpose or reuse infrastructure ▪ Higher number of legacy wells that could penetrate the caprock or into the reservoir, potentially increasing costs if they need to be re-abandoned	▪ Likely more expensive to drill (if using the same rig types) due to slower ROP ▪ Shallower sites may be able to use less expensive/smaller drill rigs ▪ Near-wellbore mineralization may lead to clogging of the injection zone; therefore, new wells may need to be drilled periodically	▪ Infrastructure costs potentially higher due to water facilities ▪ Likely shallower wells needed which can reduce total drilling time ▪ Likely more injectors needed to achieve the same annual injection rate as a $CO_2(sc)$ site due to additional fluid volumes ▪ May need to use corrosion resistant steel alloys from surface to injection zone due to corrosion risk from the dissolved CO_2

Cost component	Share of cost	Sedimentary resources	Mafic and ultramafic resources all injection styles	Mafic and ultramafic resources $CO_2(aq)$
Operational expenditure (OPEX)	High to highest	▪ Likely lower well count than mafic or ultramafic projects ▪ Well workovers may be more expensive since wells are likely to be deeper ▪ Monitoring costs can be high since many sites rely on time lapse seismic surveys for plume tracking	▪ Potentially requires active pressure management more often than in sedimentary resources ▪ Likely to have a higher well count, which could increase routine maintenance needs ▪ Monitoring costs may be higher since periodic geochemical analysis may be needed	▪ Increased energy needs due to water pumping and CO_2 dissolution ▪ Potential fees for water extraction ▪ Potentially higher maintenance needs due to corrosion ▪ Potentially more frequent geochemical sampling required to track the plume of injected $CO_2(aq)$ ▪ Likely fewer repeat seismic acquisitions needed since seismic techniques may not be able to resolve the plume of CO_2
Abandonment expenditure (ABEX)	Medium	▪ Well count is likely to be lower than mafic or ultramafic projects	▪ Likely to have more wells due to lower permeability of most mafic and ultramafic resources ▪ May have more monitoring wells to plug and abandon	▪ Water production wells (if used) will need to be plugged and abandoned ▪ Likely will have a higher well count to plug and abandon
Post-closure	Low to medium	▪ Potentially requires a larger area of monitoring due to plume extent	▪ Potentially shorter monitoring period, or more limited monitoring required if CO_2 mineralization can be demonstrated ▪ Due to constraints on imaging, more wells may need to be left open to allow for fluid sampling ▪ No clear understanding of what will be used to define conformance at present which can impact the timeline to handover liability (when applicable)	▪ Mineral trapping may increase confidence in containment of CO_2 which could lead to a shortened post-closure monitoring period ▪ It may be challenging to demonstrate that water flow from the storage site will not lead to CO_2 migration outside of the storage complex and/or to CO_2 outgassing

Note: Share of cost varies across different resource types and whether deployment is onshore or off.

Mineralization may lead to clogging of the near-wellbore zone which could require new wells to be drilled periodically. The increased well count could also increase related OPEX and ABEX since more wells will require routine maintenance and ultimately decommissioning.

Differences between injection styles

The cost components of supercritical CO_2 storage sites across all resource types are expected to be similar, with main differences coming from exploration costs due to data availability and drilling costs.

Aqueous injections require the addition of water-related infrastructure, which will lead to increased costs across all cost components. If the aqueous injection is associated with existing water disposal or geothermal reinjection projects, as is the case with some of Carbfix's activities, then CO_2 dissolution equipment may represent an incremental cost. However, if the site is greenfield, the facilities associated with the sourcing, transporting, and injecting of water will require significant capital investment. Water infrastructure will increase costs across the lifetime of the project given higher energy demands, increased maintenance requirements, and the need to decommission additional infrastructure when the site is closed.

For the shallower CarbFix1 injection, estimated transport and storage costs were USD 17/t CO_2; this rose to USD 49/t CO_2 for the deeper project (Selma-Penna Utonih and Vhelma Viviana León R., n.d.). It is unclear what contributed to the change in cost. Injection and monitoring costs published for the CarbFix2 site amount to USD 2.2/t CO_2 if the cost of drilling an injection well is excluded and USD 5/t CO_2 if the cost of drilling an injection well is included (Gunnarsson et al., 2018). That study does not appear to include costs related to wells for water production. According to Carbfix's website, CO_2 storage using their technology is estimated to cost EUR 9-16/t CO_2 (Carbfix, 2021). The variability in costs can be explained by the differences in currency, base year, transport costs, and well depth. However, that cost range seems on the low end when comparing them with a study about the levelized cost of storage in the United States, drilling costs in general, the infrastructure Carbfix has discussed for the Coda Terminal, and the required water infrastructure (Ma et al., 2024).

The potential differences in post-closure costs between resource types and injection styles are not well understood at this time because of uncertainty around how conformance for these sites will be demonstrated. It appears that aqueous projects are looking to leverage the expected high rate of mineralization to reduce their post-closure monitoring period. This could result in some cost savings, although post-closure monitoring is typically a relatively small cost compared to the total cost of the project. However, if mineralization can be conclusively demonstrated, then project operators may have significantly lower exposure to long-term liability related to the CO_2 that has been injected. At this time, it is unclear what methodologies can be used to demonstrate mineralization to regulators.

Close up of weathered basalt. Image by Alfo Medeiros via pexels.

Chapter 6. Risk assessment and management

Key takeaways

Scaled-up piloting and large-scale demonstration are needed to better assess the risks related to CO_2 storage operations in mafic and ultramafic rocks. Small-scale projects can demonstrate proof of concept, but data from large-scale projects are needed to develop, test, and refine field-scale reservoir modelling methodologies. Small-scale injections have not been sufficient to test the upper limits of the CO_2 buffering capacity of mafic and ultramafic rocks, and these rocks have rarely been the target of large-scale fluid injection campaigns to test their geophysical and geomechanical responses. As a result, it is difficult to determine technically achievable injection rates and the risks that large-scale mafic and ultramafic CO_2 storage sites may be exposed to.

Geothermal projects and wastewater disposal activities into crystalline rocks can provide some analogues for induced seismicity risk. These activities, along with deep mining, can also provide some experience with using geophysical techniques to characterize a reservoir or monitor subsurface activities. None of these activities are perfect analogues, however, since they do not require as much focus on containment.

Compared to sedimentary CO_2 storage, mafic and ultramafic storage is likely to present a higher risk to groundwater resources because of difficulties related to modelling fractures, a poorer understanding of containment in these resources, and the fact that shallower injections may be targeted. Large-scale aqueous CO_2 storage operations may represent a less efficient use of the reservoir since a significant portion of injectivity will be consumed by water. Additionally, aqueous CO_2 storage sites may face increased induced seismicity risk due to the higher volumes of fluid injected.

All CO_2 storage sites should follow industry good or best practice for risk management regardless of resource type. Risk management processes should be directly integrated into the project development and operations framework.

Risk is project-specific due to the unique nature of each subsurface resource, the local community that surrounds it, and the risk tolerance of individual operators and regulators. Risk exposure and impact also vary across the lifetime of the project. Therefore, risk management programmes should be dynamic and evolve as the project does. Our current understanding of CO_2 storage risks is weighed toward activities that inject CO_2 into sedimentary resources. This chapter outlines how mafic and ultramafic CO_2 storage risks may differ from sedimentary CO_2 storage risks. It differentiates between socio-economic and technical risks, though they are strongly interrelated.

6.1. Technical risk assessment and management

CO_2 storage projects face five categories of technical risk: site performance; health, safety and environmental; containment; induced seismicity; and resource interaction (IEA, 2022a). The risk categories presented in Table 17 were evaluated following an in-depth literature review and discussions with individuals involved in a range of subsurface operations, including mafic and ultramafic storage, sedimentary storage, geothermal, mining, wastewater disposal, and oil and gas. Due to the limited global experience of storing CO_2 in mafic and ultramafic resources, probability estimations were not made.

6.1.1. Site performance

Site performance is a critical risk for all CO_2 storage sites. It lays the technical framework for a storage site to meet its contractual obligations and is the combination of three main factors: a resource's injectivity, its capacity, and the site's conformance. As discussed in Section 4.2, this report adheres to the SRMS definition of "Capacity", meaning the commercially and technically viable portion of a Contingent Storage Resource that is attached to a commercial project.

Rock type, age, formation environment, and geological history influence reservoir characteristics and ultimately its performance. Currently, most sedimentary CO_2 storage developers target resources that can support injection of 1-2 Mtpa for at least 15-20 years. Comparatively, no mafic or ultramafic CO_2 storage site has exceeded 10 to 15 ktpa CO_2 injection.[35] Scaling from tens of thousands of tonnes a year to hundreds of thousands or millions would mean exploiting mafic and ultramafic rocks in a way that has never been done before.

Differences between resource types

Resource performance is likely to be linked to age and rock type. Peridotites generally have lower porosity than basalts, but they have a higher proportion of reactive minerals. This suggests that they have higher mineralization potential, but they may be more technically complex to exploit. Natural carbonation of peridotites and scientific research suggest that CO_2 can rapidly mineralize (Kelemen et al., 2019).

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[35] This estimate is based on reporting Iceland made to the UNFCCC in their 2024 and 2025 National Inventory Documents (NID) (Icelandic Environment and Energy Agency, 2025a; Environment Agency of Iceland, 2024). The highest reported annual injection is 13.3 ktpa in 2021. It is unclear if the injected CO_2 reported in the NIDs was injected via a single well in a single site, or multiple wells across multiple sites.

Table 17. Technical risk categories and considerations for mafic and ultramafic resources

Risk category	Description	Potential top event	Defined mitigation	Considerations for mafic and ultramafic resources	Considerations by injection style
Site performance	Risks primarily relating to resource injectivity and capacity or to non-conformance	Site unable to realize contracted storage obligations	▪ Detailed site assessment and optimized site design ▪ Pressure management ▪ Progressive or incremental build out of the resource	▪ Limited analogues available to support resource evaluation ▪ Risk of near-wellbore clogging of permeability due to mineralization ▪ Risk of non-conformance with modelled behaviour potentially higher due to complexities related to modelling fluid flow in mafic and ultramafic rocks and identifying fracture systems ▪ The potential of injection rate decline poorly understood ▪ Improving modelling frameworks can help de-risk	▪ Injectivity and capacity will be strongly influenced by injection style since aqueous injections include large volumes of water that can result in pressure increases in the reservoir
Health, safety, and environment (HSE)	Unsafe exposure to CO_2 because of CO_2 storage activities	Large leak into a confined area resulting in risk to human health	▪ Appropriate site operations and management ▪ Measurement, monitoring, and verification (MMV) programmes to detect any leaks	▪ Developers are targeting shallower injection horizons, which could increase risk of CO_2 interacting with soils or ocean sediments if vertical containment breaches occur	▪ Aqueous injections increase the complexity of surface facilities and can add more points of failure ▪ Aqueous CO_2 is less hazardous to human health than CO_2 in free-phase and the main hazard is CO_2 release due to outgassing ▪ Aqueous injections are likely to have a larger surface footprint since more wells are needed to reach the same injection rates as supercritical injections

Risk category	**Description**	**Potential top event**	**Defined mitigation**	**Considerations for mafic and ultramafic resources**	**Considerations by injection style**
Containment failure	Leakage of CO_2 or brine from the storage reservoir due to a failure of containment features	Leakage of CO_2 from defined storage zone	▪ Thorough assessment of the natural seals in the selected reservoir ▪ Robust site management ▪ Thorough assessment of any legacy wells	▪ Most resources do not have a traditional caprock or vertical seal ▪ Detecting faults and fractures can be more difficult ▪ Mineralization can decrease the risk of leakage	▪ Mineralization is likely to be faster in aqueous injections ▪ Aqueous injection projects may target shallower injection horizons meaning there is less overburden to attenuate CO_2 if it exits the target injection zone ▪ Containment of injected fluids may also need to be considered to reduce risks to potable drinking water if shallower injection horizons are targeted
Induced seismicity	Injected fluids can activate known or unknown faults and cause seismic events	Felt induced seismicity	▪ Integrated monitoring to detect subsurface and surface pressure changes ▪ Micro-seismic and distributed acoustic sensing (DAS) monitoring for site and reservoir integrity monitoring and monitoring of micro-seismic events	▪ Hydraulic fracturing may be a design component for certain sites ▪ Fluid injection activities into or near to crystalline rocks are a known source of induced seismicity ▪ Fracture networks can propagate pressure downward into crystalline basement if there is not vertical isolation between the basement and injection zone	▪ Aqueous injections may have increased induced seismicity risk due to the relatively incompressible nature of water and higher volume of fluids that need to be injected
Resource interaction	CO_2 can have positive, neutral, or negative interactions with other subsurface resources	Degradation of a critical resource e.g. potable groundwater	▪ Regulation of development ▪ Prioritization of natural resource development based on interaction risks and resource importance	▪ Shallower injections may increase risk of interaction with potable groundwater or sea water ▪ Rock dissolution can lead to release of metals allowing for them to be mined	▪ Aqueous injections may place stress on groundwater resources if freshwater is used. ▪ If wastewater, seawater, or other non-potable water sources are used as the water source for aqueous injections, they may place potable water sources at risk

Notes: Risk categories, description, and defined mitigation were adapted from IEA (2022a), which focused on CO_2 storage in sedimentary resources. The use of the term capacity aligns with its definition under the Society of Petroleum Engineers Storage Resource Management System (SPE SRMS).

Analogues are usually used during the resource assessment process to evaluate potential performance. Analogues for sedimentary CO_2 storage are more widely available due to the historic use of CO_2-enhanced oil recovery (EOR) and several long-term operating sedimentary CO_2 storage projects. No analogues are currently available to assess or benchmark mafic or ultramafic resource performance for scaled-up sites. The closest potential analogue is wastewater disposal in crystalline rock, but it is imperfect due to differences in fluid compressibility and geochemical considerations.

Mafic and ultramafic CO_2 storage pilots and small-scale commercial projects have all been very small scale and have not approached the geomechanical, geochemical, or geophysical limitations of the individual resources that they targeted. As a result, they may not be appropriate benchmarks for performance. Due to this, it is not possible to accurately compare potential site performance across resource types. Large-scale piloting and demonstration is needed before the performance of mafic and ultramafic CO_2 storage can be compared to sedimentary storage.

Enhanced geothermal systems (EGS) research shows that hydraulic conductivity and economically viable flow rates can be a challenge in deep crystalline rocks (Kukkonen et al., 2023). To store CO_2 at scale, plutonic rocks such as sheeted dyke complexes in ophiolites or peridotites may need to be hydraulically or thermally fractured to increase permeability. Peridotites and sheeted dykes are characterized as having low hydraulic conductivity that is mainly controlled by weathered fractures (Jeanpert et al., 2019). Samples from the sheeted dykes in the Troodos Ophiolite exhibited permeabilities of 6.5×10^{-3} and 2.5×10^{-4} mD (Coelho et al., 2015), while samples from several different peridotites had permeabilities of between 3 and 20×10^{-7} mD (Farough et al., 2016). The permeabilities for sheeted dykes and peridotites were measured on laboratory samples and therefore would not accurately represent field-scale permeability or hydraulic connectivity because of the absence of significant fractures.

Differences between injection styles

Aqueous CO_2 injections can potentially increase the rate of CO_2 mineralization, but they may also decrease the total volume of CO_2 that can be stored. For several years, scientists and CO_2 storage experts have been discussing how pressure space rather than porosity is the resource (Bump and Hovorka, 2024; Lane et al., 2021). Aqueous injections increase the total volume of injected fluids, which in turn can lead to significantly higher pressure. However, aqueous injections can be paired with water production from the same aquifer (Thibeau and Adler, 2023). In that case, pressure may still be a limiting factor, but there will be a lower impact from the co-injected volumes of water.

Water production wells introduce several site performance challenges of their own since they need to be placed far enough away from the injector to prevent CO_2 breakthrough but also need to be in hydraulic communication with the injection zone. These challenges are well known from oilfield operations and sedimentary CO_2 storage projects. However, they are less well understood for mafic and ultramafic resources. Since Carbfix's initial sites are coupled with geothermal powerplants, they are already linked to water production operations.

Modelling based on injections and tracer tests in Iceland suggest that faults can be a preferential pathway for injected fluids, transporting them and the CO_2 they are charged with away from the injection zone (Ratouis et al., 2022). Several of the wells in the study have dual use – for water production and monitoring. The breakthrough time for tracers in the production/monitoring wells is well below the time required for near-complete mineralization and the authors' report slightly elevated dissolved inorganic carbon and partial pressure of CO_2 (pCO_2) compared to background in the monitoring/production wells (Clark et al., 2020; Ratouis et al., 2022). This suggests they may be co-producing injected CO_2. It is unclear how the company is handling this in its MMV programme. In addition to the complexities related to water production and pressure, aqueous injections will also have an impact on project economics due to increased energy demands, a higher well count, a higher risk of corrosion, and elevated induced seismicity risk.

Mineralization has the potential to clog pore space with secondary minerals, but some studies have found that it can also result in increased porosity and/or permeability (Hövelmann et al., 2012; Luhmann et al., 2017; Neuhoff et al., 1999). Near-wellbore mineralization could lead to clogging and decreases in injectivity; however, the actual risk this poses is not well understood. Carbfix has reported that the permeability of their reservoir has not substantially degraded over the injection period of the CarbFix2 project (Clark et al., 2020). Supercritical CO_2 injections into slow-moving basalt- or peridotite-hosted aquifers are likely to have lower rates of mineralization than aqueous injections into the same resource and/or supercritical injections into reservoirs with fast-moving aquifers due to constraints related to alkalinity and water activity (Kelemen et al., 2011; Oelkers et al., 2018). Clogging is likely to be less of an issue for projects with limited or slower mineralization than for projects with rapid mineralization.

Mitigation methods

Site performance risks can be mitigated during resource assessment and during site operations. In sites with many wells, pressure and fluid communication between wells could lead to interference and a decrease in injectivity. As with sedimentary CO_2 storage sites, fluid extraction can be used to improve the sustainability of long-term injection by relieving reservoir pressure. Aqueous injections can recycle reservoir fluids for use as a co-injectant, although the operator will need to manage the risk of CO_2 breakthrough and other complexities related to water production infrastructure.

The resource assessment process is a key mitigation measure for site performance risks since it allows project developers to eliminate resources that may not meet performance needs. One of the most important ways to mitigate future site performance risks for mafic and ultramafic CO_2 storage is to improve the modelling tools available to assess hard-rock reservoirs. CO_2 storage resource performance is assessed using static and dynamic models that are developed from historic operating data if available, well data, and standard modelling methodologies if applicable. Experience from hydrocarbon production in fractured reservoirs shows how difficult modelling fracture flow behaviour can be. This suggests that mafic and ultramafic CO_2 reservoir models will be more complex than sedimentary reservoir models due to the influence of secondary porosity and fracture flow.

Work is ongoing to improve modelling frameworks, but significantly more subsurface and injection data are required to properly test them. It is likely that we are several years away from achieving the level of modelling standardization that we have today for sedimentary reservoir systems. Since mafic and ultramafic CO_2 storage has passed proof of concept, pilots and demonstration projects should consider aiming to inject at a suitable scale to test resource performance and more robustly identify the physical and chemical parameters that can limit scale-up.

6.1.2. Health, safety, and environment

At high concentrations, CO_2 is a recognized workplace hazard. Since it is denser than air, CO_2 can pool in confined spaces or natural depressions in the landscape. A top event with health, safety, and environment (HSE) implications would be a sudden release of CO_2 into a confined area like a warehouse or natural depression like a small valley.

The ecosystem impacts caused by elevated CO_2 concentrations depend on the environment and the severity of the CO_2 leak or release. Localized CO_2 leakage can lead to localized harm to plant and animal life onshore. Most marine life has higher tolerances to CO_2 variability and water movement, and diffusion can cause underwater leaks to disperse more quickly.

In addition to surface release of CO_2, storage sites present other known HSE risks or considerations, including water use (discussed in the resource interaction section below) and degradation of the surface environment. Surface infrastructure at onshore operating sites is limited to one or a few well pads, suggesting a smaller surface footprint than most other energy transition technologies. Surface impact will increase with the number of required wells and if temporary CO_2 storage tanks are required.

Adding other substances to the CO_2 stream, such as H_2S, can significantly alter the risk profile of a site.

Differences between resource types

The risk associated with a surface CO_2 release is less dependent on resource type than it is on site size. The greater the amount of CO_2 at a site, the higher the potential impact a surface release may have. Currently, mafic and ultramafic storage sites have a significantly lower annual mass flux than sites injecting into sedimentary resources. As a result, these sites have less CO_2 available to release if a surface installation fails, thereby lowering the potential impact of a surface release.

Mafic and ultramafic resources typically have lower permeability than sedimentary CO_2 storage resources. To achieve the same annual mass flux, more wells may be required. This could increase the number or size of well pads and the surface footprint of a site, potentially leading to additional environmental damage.

CO_2 mineralization rates are faster in mafic and ultramafic resources than sedimentary resources. Mineralization reduces the amount of free-phase CO_2 in a reservoir and can therefore reduce the risk of CO_2 backflow if a pressure barrier were to fail. While mafic and ultramafic CO_2 storage sites may consider shallower injections if they are not relying on CO_2 being over its critical point, they may still need pressure control drill rigs if they are targeting higher-temperature reservoirs. Commonly discussed in the context of oil and gas operations, documented well blowouts have occurred in geothermal operations and can result in a sudden influx of hot fluids or steam potentially scalding nearby personnel or causing washouts in the surrounding area (Bolton et al., 2009; Kruszewski and Wittig, 2018). Limited information is available to estimate the probability of a well blowout in mafic and ultramafic resources, so site developers should assess risks based on their targeted depth, the geothermal gradient, and their specific drilling plan. There are several good and best practices related to maintaining well control during drilling and operation that can be practised to reduce risk of well blowout.

Differences between injection styles

Aqueous CO_2 sites will have a different surface release risk profile than free-phase (gaseous, liquid, or supercritical) CO_2 storage sites. On site, aqueous projects will typically have three types of pipelines: those moving free-phase CO_2 from a capture installation, distribution line, or temporary storage; those moving water for the CO_2 to be dissolved in; and those moving aqueous CO_2 (if mixing occurs at surface). The risks associated with pipelines moving free-phase CO_2 will depend on the pipeline design specifications and rating; these risks are injection style and resource type agnostic.

The risks associated with pipelines moving water will depend on their design, the amount of water they move, the type of water they move, and their operating environment. Onshore, leakage from or rupturing of a pipeline moving freshwater will pose a lower risk to the surrounding environment than a leak from or rupture of a pipeline moving seawater or wastewater. That said, a leak or rupture of any water pipeline could lead to surface flooding, landslides, erosion, and soil degradation.

Due to the addition of CO_2 dissolution, aqueous CO_2 storage sites will have more infrastructure than free-phase CO_2 storage sites of the same size. This can introduce more points of failure and thereby increase the probability of a risk arising.

Aqueous CO_2 is less of a hazard than free-phase CO_2. A large-scale surface release of CO_2-charged water would likely lead to outgassing, depending on the temperature and pressure that was used to dissolve the CO_2 in water. However, CO_2 is typically dissolved in water at a ratio of 20-30 t water to 1 t CO_2 (Snæbjörnsdóttir et al., 2020). Therefore, a leak from or failure of a pipe moving aqueous CO_2 would need to be significantly larger to achieve the same CO_2 flux as if the same pipe were to fail moving free-phase CO_2. If CO_2-charged water were to leak into surface waters, it could lead to acidification and/or water degradation.

Mitigation methods

Mitigation methods will largely be resource type agnostic. As with other technical risks, industry good and best practice can contribute to HSE risk mitigation.

CO_2 storage sites in mafic and ultramafic rocks may target resources with steeper geothermal gradients since a rock temperature of 185°C can optimize carbonation in peridotites (Kelemen and Matter, 2008). Well development in areas with steep geothermal gradients will need to maintain strict pressure control to reduce the risk of steam blowout. Sharing of industry good and best practice between the geothermal industry and CO_2 storage industry should be encouraged as a key mitigation measure.

6.1.3. Containment

Containment is a critical aspect of all CO_2 storage sites. It ensures that injected CO_2 remains within the planned boundaries of a CO_2 storage site and within the targeted storage zone. Containment is a function of a site’s geology and its engineering.

The geological component of containment relates to the integrity of the reservoir and its structural morphology. Sedimentary CO_2 storage sites are usually vertically confined by a caprock, or an impermeable rock layer like a shale, which sits above the porous reservoir rock. Even though containment and containment failure for CO_2 storage are both extensively researched, they remain poorly understood for mafic and ultramafic resources. Table 18 outlines containment failure risks for mafic and ultramafic rocks.

Differences between resource types

Due to how they form, mafic and ultramafic rocks often do not have clearly identifiable impermeable caprocks. Therefore, it is necessary to consider confining features and containment in a slightly different way. In flood basalts, dense flow interiors have the potential to act as containing features if they are not crosscut with open faults or fractures and if reservoir pressures remain below fracture dilation pressure. Additionally, the fracture networks in flow interiors should be sufficiently tortuous so that CO_2 can pool in branches and self-seal the reservoir (Gierzynski and Pollyea, 2017; Jayne et al., 2019; Pollyea and Benson, 2018). Containment in peridotites will be more complex due to the extensive fracturing that these rocks exhibit. However, the reactivity of peridotites may allow for enhanced mineralization rates, thereby reducing the risk of a containment breach.

Mafic and ultramafic rocks may not require features that can vertically confine CO_2 if the site's rate of carbonation is in the order of years. In that case, if the site can demonstrate that CO_2 remains in the target zone prior to mineralization and that all CO_2 is mineralized at the time of site closure, the site may be able to rely on active vertical barriers, in the form of monitoring, rather than a passive barrier like an impermeable rock layer. Demonstrating mineralization remains an open question and is discussed further in Section 5.3.

While rapid mineralization is likely in small-scale sites, as mafic and ultramafic CO_2 storage scales up, mineralization may become more restricted by the total alkalinity in the reservoir zone. This suggests that some form of passive or active vertical confinement may be required for all mafic and ultramafic sites at least until more field data are collected from several large-scale sites.

Due to the often low primary porosity of mafic and ultramafic rocks, CO_2 storage sites may need to use hydraulic fracturing to expose fresh surfaces and increase permeability. This has been proposed by several scientists (Bažant et al., 2023; Kelemen and Matter, 2015, 2008). If hydraulic fracturing is deployed to enhance permeability and expose new reactive surfaces, it will be important to understand the propagation direction of the induced fractures and whether they may intersect with any existing fractures that could allow CO_2 to flow out of the targeted zone. Additionally, carbonation of basalts or peridotites can lead to reaction-induced fracturing since the carbonate minerals occupy a larger volume than silicate minerals and the reaction is exothermic (Monasterio-Guillot et al., 2021; Rudge et al., 2010; Zhu et al., 2016). Therefore, project developers will need to assess whether hydraulic or reaction-induced fracturing can result in a containment breach. Research suggests that supercritical CO_2 pools at fracture branches can promote mineralization, but fractures that exit the targeted storage zone represent leakage pathways (Pollyea and Benson, 2018).

Differences between injection styles

Aqueous or water-alternating-gas (WAG) injections are predicted to have faster mineralization rates than supercritical injections, even on a large scale. This suggests that vertically confining features may be less important for aqueous or WAG injections. However, due to the volumes of water injected in aqueous injections, the risk of reactivating faults or fractures may be higher (Zhang et al., 2013). If injection fluids or formation fluids were to migrate upwards into other zones, it could put critical groundwater resources at risk. This is especially true if the project developer has targeted a shallower zone for injection or may have fractures and faults in their storage complex that can connect the injection zone to groundwater resources.

Table 18. Containment failure risks in mafic and ultramafic rocks and their mitigation

Leakage pathway	Description	Mitigated probability	Severity	Mitigation
Lateral migration	Migration of the CO_2 plume (aqueous or supercritical) or formation fluids beyond the defined boundaries of the storage zone or complex.	CO_2(sc): Low to very low CO_2(aq): Low to medium	Low to high	▪ Robust characterization and monitoring of the targeted zone ▪ Integrating safeguards against lateral migration in site design ▪ Site design informed by reactive transport modelling and expected mineralization rates ▪ Push-pull and tracer tests to map fracture network and preferential flow pathways
Absence or inadequacy of a vertically confined feature	Mafic and ultramafic CO_2 storage sites rarely have conventional cap rocks to serve as vertical seals. In flood basalts, dense flow interiors can serve as vertically confining features. Alternatively, highly reactive zones may self-seal with mineralization and can also support confinement.	Unknown	Medium to high	▪ Assessment of the presence of vertically confining features or highly reactive surfaces that can self-seal ▪ Properly managed site operations ▪ Pressure management ▪ Monitoring of drilling conditions to reduce risk of damage to the formation
Embrittlement of reservoir due to cooling	Excessive cooling in the injection zone can lead to embrittlement and/or fracturing of the reservoir and/or confining features.	CO_2(sc): Unknown CO_2(aq): Low	Medium	▪ Managing the temperature and pressure of CO_2(sc) and fluid injections
Faults and fractures	CO_2 or formation fluids can migrate along pathways created by faults, fault zones, or fracture systems. Injection-related pressure changes can cause existing faults to reactivate and/or new fractures to form. Existing faults can also act as valves that release pressure and then close. High-pressure injection can also induce shear failure in existing fractures. Sites can employ hydraulic fracturing to increase permeability. Reaction-driven fracturing of the rock due to the increased volume of secondary minerals can also create new leakage pathways.	Low to unknown	Low to very high	▪ Site-specific assessment of the risks posed by faults and fractures ▪ Maximizing distance from the injection point to existing faults ▪ Pressure management ▪ Micro-seismic and flow monitoring for early detection of potential fracture or fault reactivation and changes in fluid flow regimes ▪ Robust risk assessment if hydraulic fracturing is deployed to enhance resource permeability ▪ If the vertically confining barrier is fractured, sites may need to restrict operations to be below the pressure of sealing fracture dilation ▪ Reaction driven fracturing from mineralization of injected CO_2 could introduce further complexities to mitigating this risk

Leakage pathway	Description	Mitigated probability	Severity	Mitigation
Purpose-built CO_2 wells	CO_2 wells can provide a pathway for leakage if they are not properly constructed, operated, and decommissioned. Additionally, improperly selected casing may corrode and lead to out-of-zone migration.	Negligible	Low	▪ Regulation regarding well construction and operations ▪ Monitoring for well integrity throughout site lifetime ▪ Following up-to-date best practice guidelines and regulation for well construction, operations, and abandonment ▪ Plugging and abandoning wells after injection ceases ▪ Water producers, if they are producing fluids from the same aquifer, could end up producing injected CO_2 if its breaks through
Legacy wells	Mafic and ultramafic resources have significantly fewer penetrations at depth; however, $CO_2(aq)$ injections may target zones shallow enough to have private wellbores entering them.	Very low to medium depending on depth of injection	Low to medium	▪ Reservoir and caprock studies and pumping tests can aid in identification ▪ Site-specific assessment of legacy wells and their leakage risk ▪ Targeting shallower formations may introduce the potential for unidentified private water wells ▪ Abandonment of mineral exploration wells may not focus on isolating specific reservoir sequences and therefore they may provide a pathway to the surface

Note: Probability and severity are site-specific and should be evaluated during risk assessment.

Source: Adapted from IEA (2022a). The original version was defined for sedimentary storage resources.

Mitigation methods

Mitigation of containment risk in mafic and ultramafic resources broadly aligns with the mitigation methods used by sedimentary CO_2 storage sites. Storage resources should only be developed if containment-related uncertainties are low and the probability of a leakage event is low.

Resource assessment and site operations are two of the main ways to mitigate containment-related risks. The better the resource is understood and monitored, the more likely critical containment pathways can be identified and mitigated. Since mafic and ultramafic rocks rarely have conventional caprocks, passive vertical containment barriers may need to be replaced with monitoring to verify the security of injected CO_2.

6.1.4. Induced seismicity

Induced seismicity occurs when human activity increases the stress and strain on rocks in the subsurface. A wide variety of activities can do this, including oil and gas production, wastewater disposal, dam construction, geothermal and enhanced geothermal systems, mining, and CO_2 storage (Wilson et al., 2017; Zoback and Gorelick, 2012). All CO_2 storage sites have the possibility of inducing seismicity, although project developers and operators do their best to prevent induced seismicity at felt magnitudes.

Differences between resource types

Rock type, injection rate, formation pressure, regional pressure regimes, proximity and connectivity to crystalline basement, nearby subsurface activity, and other factors can contribute to induced seismicity risk. The extent of induced seismicity risk for mafic and ultramafic CO_2 storage resources cannot be directly identified from current projects in operation today due to their small size. However, geothermal and wastewater disposal operations provide an analogue to assess induced seismicity risks by resource type.

The Human-Induced Earthquake Database tracks induced seismicity. The 5 January 2025 edition of the database includes 1,320 entries; it records 164 induced seismicity events related to non-mining subsurface activities, with 52 of those occurring in crystalline rocks (Foulger et al., 2018; HiQuake, n.d.). Most of the events in crystalline rock related to enhanced geothermal system projects, although some related to drilling and water injection for geothermal or wastewater disposal projects. The sedimentary-hosted subsurface activities that induced seismicity related to oil and gas production, geothermal, wastewater disposal, research, and groundwater extraction. The number of tracked induced seismic events relating to activities in sedimentary rocks is higher, but that may be biased by the fact that more subsurface activity is in sedimentary rocks. Nevertheless, the HiQuake Database confirms that fluid injection into crystalline rocks can cause induced seismicity.[36]

Stress accumulates more in crystalline rocks than sedimentary rocks due to their stiffness; this stress can propagate to the crystalline basement (Vilarrasa and Carrera, 2015). While the stress regime of the crystalline basement is not identical to that of non-basement crystalline rocks, such as those found in large igneous provinces or ophiolites, the stiffness of mafic and ultramafic rocks will result in the accumulation of more stress than sedimentary rocks. Additionally, in crystalline rocks, hydraulic fracturing from high-pressure fluid injection can cause shearing along existing fractures (Dutler et al., 2019; Preisig et al., 2012). Based

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[36] The HiQuake website appeared to be offline in June 2025; however, archived versions are available using web.archive.org.

on analogues from granitic geothermal reservoirs, high-pressure fluid injection can lead to a broader damage zone since fluids can travel through existing and new fracture networks (Zang et al., 2014). In sedimentary rocks, hydraulic fracturing is dominated by pore collapse and tensile cracks, which lead to more localized damage (Zang et al., 2014).

Injection activities into sedimentary resources that were hydraulically connected to the crystalline basement have led to significant induced seismicity. That seismicity was likely caused by brittle failure of crystalline basement rock several hundred metres below the injection zone (Zhang et al., 2013). Vertical faulting and fractures can allow pressure to propagate outside the injection zone. The change in pressure due to injection could lead to induced seismicity if there is a significant permeability difference between the target zone and basement rock and if the two are hydraulically connected. Given the relatively low permeabilities of certain mafic and ultramafic rocks, their fractured nature, and the fact they are often emplaced on crystalline basement (or in the case of ophiolites can include basement units), it will be important to robustly assess induced seismicity risk and to monitor for warning signs of induced seismicity throughout injection operations. For potential resources in seismically active zones, injection rates may need to be lowered to reduce risk.

Differences between injection styles

Fluid injection into crystalline rocks can cause induced seismicity as demonstrated by induced seismicity related to geothermal water reinjection into basalts in Iceland, enhanced geothermal systems in igneous rocks around the world, and several other water injection projects. There is insufficient direct research to say whether there will be a significant difference in probability based on injection style. However, it is likely that, on a per tonne of CO_2 injected basis, the risk will be higher with aqueous injections since the total fluid injection is at least 20 to 30 times greater for the same mass of CO_2 compared to supercritical injections (see Sections 3.2 and 5.1.3 for additional information about water needs).

If aqueous CO_2 storage sites are not using water produced from the same formation as the injection, the site may become pressure-constrained quite quickly. Carbfix’s largest operating site produces water from the same aquifer that it injects into. Water production operations are downstream from the injection site, and the water passes through the geothermal powerplant before it is used to dissolve and inject CO_2 (Ratouis et al., 2022). Induced seismicity at the Hellisheiði geothermal field, where Carbfix has its main operating injection site, tends to occur at faults that cut across fluid re-injection wells (Cao et al., 2022). Thermo-hydro-mechanical modelling of reservoir behaviour by Cao et al. (2022) found that the potential for induced seismicity in response to geothermal fluid reinjection increases when contraction of the reservoir rock due to cooling is considered. Modelling of ten years of fluid re-injection found that the enhanced potential for induced seismicity can extend more than 2 km from the re-injection wells following the direction of faulting (Cao et al., 2022).

Mitigation methods

It is typically not possible to assess the risk of induced seismicity prior to injection unless there are pre-existing injection projects or micro-seismic monitoring in the area. Some of the key parameters for the prediction of induced seismicity, such as seismogenic index and magnitude, are not available prior to injection. Additionally, prior to injection it is unlikely that many faults or fractures, especially smaller ones, will be identified. Micro-seismic data collected during injection aid in the identification of faults and fracture networks. Proper monitoring and a robust response plan if abnormalities are detected are keyways that induced seismicity risk can be mitigated.

6.1.5. Resource interaction

The importance of subsurface resource management and the risks associated with adverse resource interaction are becoming increasingly recognized (Volchko et al., 2020). Subsurface activities in overlapping geographic areas or subsurface reservoirs can complement one another, be neutral, or result in adverse effects (Table 19). Resource interaction needs to be assessed on a site-by-site basis. In cases where there may be adverse interactions between resources or where CO_2 storage activities can result in degradation of other resources, the benefits and consequences need to be evaluated.

While resource interaction is a technical risk, the legal and regulatory environment in specific countries may magnify or reduce the risk it poses to CO_2 storage project developers. Many countries have either national or subnational regulations protecting groundwater and/or all waterbodies (e.g. the US EPA Underground Injection Control [UIC] Program, the EU Water Framework Directive, Saudi Arabia's Water Law 2020, the Brazilian National Water Resources Policy, the Canada Water Act). Some countries have regulations in place protecting and/or prioritizing other resources, such as oil and gas fields, which can limit access to subsurface resources for CO_2 storage.

Differences between resource types

Table 19 summarizes resource interactions across all CO_2 storage resource types. Most resource interaction risks apply to both sedimentary and mafic or ultramafic resources, but some are more relevant to one resource type or another. Synergies that may exist between mafic or ultramafic CO_2 storage and geothermal, mineral resources, enhanced hydrogen production, and other subsurface resources and/or energy activities are briefly summarized below and discussed further in Section 7.2.

Both sedimentary basins and mafic and ultramafic rocks can serve as important groundwater aquifers (Millett et al., 2024). Since sedimentary CO_2 storage is typically supercritical, it usually starts at a minimum depth of 800 m. This can reduce the risk of negative interactions with important groundwater resources, except in cases of deep groundwater extraction. Conversely, mafic and ultramafic CO_2 storage, especially projects that focus on aqueous injection, typically target shallower injections since they rely more on mineral than structural trapping. This may put them in high conflict with groundwater resources or increase the risk of contamination. In addition to the difference in targeted injection depth, mafic and ultramafic rocks typically have less well-defined vertical confining features. Depending on the formation environment, they also may include significant vertical fracturing or faulting. Such fractures or faults could serve as upward leakage pathways for CO_2 and mobilized metals. This could also potentially lead to contamination of shallower groundwater resources.

Igneous petroleum systems are atypical oil and gas reservoirs. Compared to sedimentary oil and gas reservoirs, they are more variable in quality. Since mafic and ultramafic rocks more rarely hold oil and gas, they will have a lower risk of resource interaction with oil and gas activities than sedimentary resources will. However, there is active production in several igneous petroleum systems, including the Songliao Basin in China and the Campos and Santos Basins in Brazil. If mafic and ultramafic CO_2 storage developers look to develop activities in igneous petroleum systems, their storage site may have negative or positive interactions with the oil or gas resources that are also present in the system.

Coal and coal bed gas production can have positive and negative interactions with CO_2 storage. Potential interactions are highest with sedimentary CO_2 storage resources since coal is a sedimentary rock type. However, coal and coal-like material does have geographic overlap with the distribution of mafic and ultramafic rocks, in areas such as the Siberian Traps in Russia, New South Wales in Australia, and the Songliao Basin in China. Coal mining often results in significant water production, which could serve as a source of non-potable water for aqueous injections. CO_2 can serve as a working fluid for coal bed methane production. Additionally, CO_2 can be used to quench subsurface coal seam fires. Such fires are a significant safety and climate concern, so this may present synergies worth exploring.

Geothermal projects can be developed in both sedimentary sequences and mafic or ultramafic rocks. In both cases there can be positive and negative resource interactions. CO_2 can also be used as a working fluid for geothermal projects. If projects inject CO_2 directly into the subsurface (called open loop) rather than circulating it through a closed pipe, this can result in incidental storage of CO_2 because some will be retained in the reservoir via various trapping mechanisms. Open loop geothermal projects in mafic and ultramafic rocks may, depending on the amount of water present in the reservoir, result in CO_2 mineralization that could reduce the porosity of the system and potentially impact geothermal production.

Economic minerals can be found in all resource types and CO_2 storage can adversely affect access to mineral deposits. However, there are also potentials for synergies if minerals and CO_2 storage projects work together. Typically, there are differences in the types of economic minerals present in the different resources. Economic mineral recovery from oilfield wastewater is being explored; currently this mainly targets lithium, beryllium, strontium, and rare earth elements (Gerardo and Song, 2025; Schaller et al., 2014). If CO_2 storage sites in sedimentary resources produce formation fluids to reduce reservoir pressure, they may consider whether economic minerals can be recovered. Mafic and ultramafic resources can host rare earth elements and other economic minerals such as nickel, copper, and cobalt; they can similarly consider producing formation fluids to manage pressure. The Tamarack Nickel Project in Minnesota, United States, has received US Department of Energy funding to investigate whether aqueous CO_2 can be used as a working fluid to support both mineral extraction and CO_2 storage in a peridotite (Rio Tinto, 2022). Combining mining and CO_2 storage is also being investigated by several research projects (see Table 21 in Chapter 7).

Some work is being done on the use of CO_2 as a cushion gas for natural gas or hydrogen storage (Zhang et al., 2021). However, these are typically considered to be incompatible activities since CO_2 mixing with either stored natural gas or stored hydrogen could result in contamination of the resource.

Differences between injection styles

Supercritical CO_2 storage across all resource types is likely to be incompatible with wastewater storage in the same reservoir due to pressure that simultaneous wastewater and supercritical CO_2 injections would place on the reservoir. However, wastewater injection could support aqueous CO_2 injection across all resource types.

As discussed in Section 3.1, aqueous CO_2 injections have very high water demands. Typically, project developers consider a water-to-CO_2 ratio of between 20-30 t of water to 1 t of CO_2 (Icelandic Environment and Energy Agency, 2025b; Nelson et al., 2025;

Snæbjörnsdóttir et al., 2020). However, the ratio can depend on the depth and temperature of injection, the type of water used, and other factors. If the project is using fresh water, its use will need to be weighed against current and future drinking water, ecological, and irrigation demands. If extraction exceeds the rate of recharge, the project could contribute to current or future water stress. Aqueous CO_2 storage projects in mafic and ultramafic rocks are able to target shallower injection zones because they are not restricted by the need for the reservoir to be above the critical pressure and temperature of CO_2. Since shallower aquifers are usually earmarked for drinking water and/or irrigation water, aqueous injections could lead to contamination of freshwater resources. The contamination can come from the injected CO_2, from the metals that are released by dissolution of the host rock, or by biofouling. If aqueous CO_2 storage projects are dissolving CO_2 into wastewater, brine, or seawater, the contaminants present in those waters can also lead to degradation of freshwater resources.

Activities that produce substantial volumes of water from the subsurface could potentially serve as a source of water for aqueous CO_2 storage operations. If the activities are already injecting wastewater back into the subsurface for its disposal, they can consider whether dissolving CO_2 into the reinjected water to also provide CO_2 storage is an option for the project. Such injections might require new permits since CO_2 storage is usually regulated under a separate framework from wastewater disposal.

Many open-loop geothermal energy projects reinject extracted water into the geothermal aquifer to maintain reservoir pressure and aquifer stability. This operation can have positive and negative effects on the aquifer’s injectivity and productivity (Luo et al., 2023). Geothermal energy projects can serve as a source of water and potentially a source of CO_2 for aqueous CO_2 storage. However, using the same aquifer for aqueous CO_2 storage and geothermal activities can potentially impact productivity and heat flux. Carbfix has pioneered combining aqueous CO_2 storage and geothermal energy production; some of their operating projects reinject CO_2 and H_2S that was produced as part of geothermal operations.

Synergies between aqueous injections and subsurface hydrogen production are discussed in Section 7.2.3.

Mitigation methods

Mitigating resource interaction is relatively area- or site-specific. Regulators and governments should weigh the risk of adverse interactions when they are issuing exploration licences and project permits. Resource coordination agreements and access prioritization can help regulators manage competing uses and aims.

In the case of mafic and ultramafic storage, regulators and project developers will need to weigh the potential for rapid mineralization offered by aqueous injections against the potential stress they can place on groundwater resources.

Table 19. Potential positive and negative resource interactions between CO_2 storage projects and other subsurface activities

Subsurface resource	Positive	Negative	Specifics for aqueous injections
Groundwater	▪ Re-pressurization of low-productivity aquifers ▪ If project includes water management, produced water may be suitable for irrigation or industrial use	▪ Pressure interference causing a change in aquifer water level (hydraulic head) ▪ Changes in groundwater chemistry including pH and metal mobilization ▪ Displacement of formation fluids	▪ Could reduce amount of groundwater available for other activities, potentially leading to water stress ▪ Wastewater or seawater could lead to groundwater contamination
Oil and gas	▪ Possible enhanced hydrocarbon recovery (if not a dedicated storage site) ▪ Mitigation of existing depressurization ▪ Reversal of subsistence	▪ CO_2 contamination of hydrocarbons ▪ Potential pressure interference ▪ Potential infrastructure conflict ▪ Oil and gas wells provide leakage pathways	▪ Wastewater from oil and gas activity or other sources could be used to dissolve CO_2 ▪ Wastewater disposal wells may be suitable for aqueous injection
Coal and coal seam gas	▪ Could support coal bed methane production ▪ Can be used to quench coal bed fires	▪ Potential displacement of methane leading to its release ▪ CO_2 contamination of coal bed	Produced coal bed water could be used to dissolve CO_2
Geothermal resources	▪ Exploration synergies ▪ CO_2 can be used as a working fluid	▪ Could result in a cooling effect that could reduce efficiency of geothermal fluids	▪ CO_2 can be dissolved in water planned for re-injection
Mineral resources	▪ Potential displacement of dissolved minerals leading to enhanced extraction	▪ CO_2 could react with dissolved minerals and plug pore space	▪ Dissolution can release target elements ▪ Enhanced mineralization can lead to pore space clogging
Wastewater disposal	▪ Incompatible with supercritical injections	▪ Can lead to pressure interference ▪ Increased risk of induced seismicity	▪ Water source for aqueous injections ▪ CO_2 storage as a side benefit
Natural gas or hydrogen storage	▪ Potential for CO_2 to serve as a cushion gas	▪ Potential pressure interference ▪ Potential contamination of stored gas	▪ Typically considered incompatible
Enhanced hydrogen production	▪ Chemical reactions between CO_2 and mafic minerals can produce hydrogen (applies to mafic and ultramafic rocks)	▪ Could adversely affect natural serpentinization processes that produce natural hydrogen	▪ Enhanced dissolution of mafic minerals ▪ Reaction rates will be faster than if CO_2 is injected in supercritical form

Note: Aqueous injections here refer to aqueous CO_2 injections into any resource type and not specifically mafic or ultramafic resources.

Source: Adapted from IEAGHG (2013)

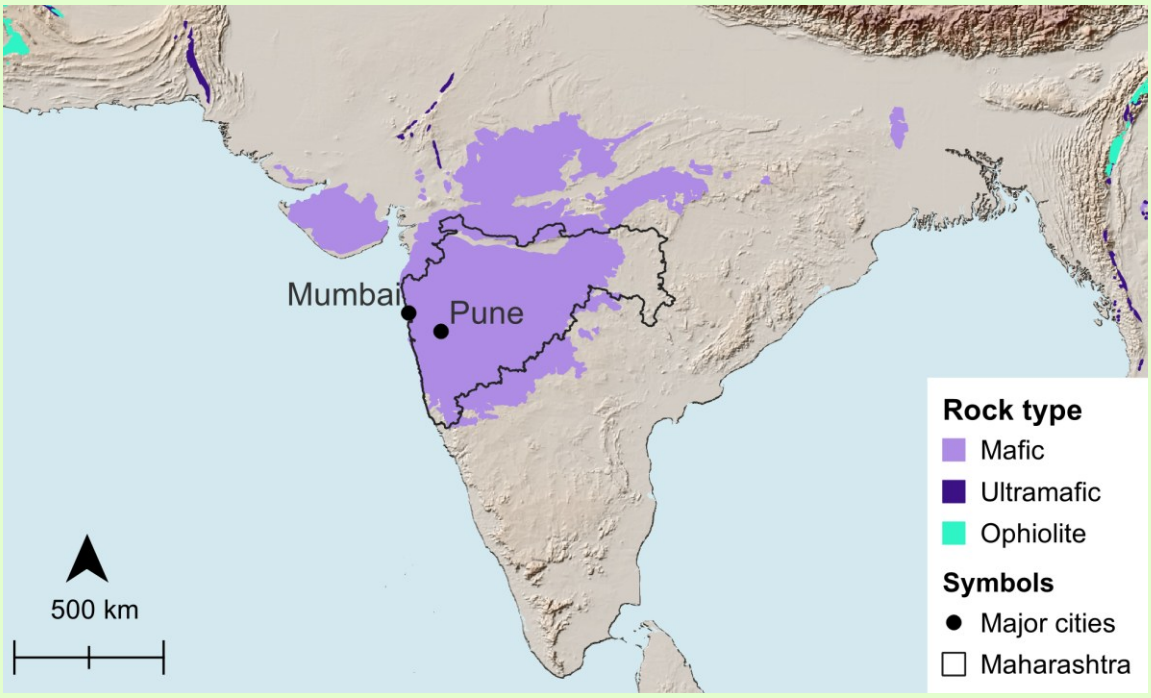
Box 7. Groundwater resources in the Deccan Traps, India

The Deccan Traps are a large igneous province located in India. Onshore, the province covers around 500,000 km^2 of western-central India. The trap system ranges in thickness from around 2 km in the west to less than 500 m in the east (Harinarayana et al., 2007; Krishnan, 1963). The traps are found in multiple states, including Maharashtra where they are the prevailing bedrock. Maharashtra is India's second most populated state and hosts two of India's top ten most populated cities, Mumbai and Pune (Government of India, 2011).

Researchers have investigated the possibility of aqueous CO_2 storage in the Deccan Traps (Banks et al., 2024; Kumar and Shrivastava, 2019; Liu et al., 2022; Nayak et al., 2024; Punnam et al., 2022). Work suggests there may be high potential for aqueous CO_2 storage in the Deccan Traps. Mafic and ultramafic CO_2 storage may be an attractive to India given the country's annual emissions and limited sedimentary CO_2 storage resources, but project developers will need to carefully consider the trade-off between predicted high mineralization rates for aqueous injections and water demand.

India accounts for nearly one-quarter of global groundwater extraction, and pumping often exceeds recharge (Biswas and Tortajada, 2024). According to the Indian government, the majority of Maharashtra is either under water stress or experiencing scarcity, with certain areas of the state receiving less than 750 mm of annual precipitation (Lamsoge et al., 2022; Niti Aayog, n.d.). Given the existing water stress in the country, if India wishes to pursue mafic or ultramafic CO_2 storage it may need to consider supercritical rather than aqueous injections. Supercritical injections may not result in rapid mineralization, but they have significantly lower water demands.

Figure 17. The Deccan Traps and Maharashtra state



Sources: Rock distribution: Wandrey (1998). State boundary and city locations: simplemaps.com (n.d.). Elevation: Danielson and Gesch (2011).

6.2. Socio-economic risks

CO_2 storage in mafic and ultramafic rocks and CO_2 storage in sedimentary rocks have similar socio-economic risks. These risks mainly relate to public perception, market risks, exploration risk, and legal and regulatory frameworks (Table 20).

6.2.1. Public perception

There is a large body of work suggesting that CO_2 storage projects, like other large-scale infrastructure projects, should engage with communities early and often, and that communities appreciate transparency about a project's impacts and risks (Bloxsome et al., 2017; Buah et al., 2021; Roberts et al., 2024). However, there is very little work specifically on CO_2 storage in mafic and ultramafic rocks.

A study, currently available only as a pre-print and specifically focused on a mafic CO_2 storage project in Iceland, demonstrates how the public engagement process can influence perception of a technology or project. Study authors found some interviewees were concerned about the planned scale of the Coda Terminal project since it is much larger than previous smaller projects. Participants in the study were also interested in receiving more information on the risks the project posed to local water systems and nature (von Rothkirch et al., 2024). The study also found that some citizens felt that the characterization of aqueous CO_2 injections as sparkling water downplayed leakage risks and that there was not sufficient information or transparency on the impact that large water extractions could have on the ecosystem.

Differences between resource types

Technology start-ups and/or academic organizations are the pioneering force behind most active mafic or ultramafic CO_2 storage projects. Additionally, several active projects are linked to carbon dioxide removal (CDR) projects. As a result, CO_2 storage in mafic and ultramafic resources is regularly associated with CDR rather than emissions reduction. This may contribute to positive media attention.

Anecdotally, CO_2 storage in mafic and ultramafic rocks appears to have greater acceptance or at least more visibility than CO_2 storage in sedimentary rocks. Headlines or articles that focus on sedimentary CO_2 storage are often more negative and sometimes frame it as a distraction (Abreu, 2023; Radtke and Jones, 2023; Sario, 2024; Stallard, 2025), while mafic and ultramafic CO_2 storage has featured on the cover of magazines and appeared in major newspapers around the world.

There are numerous positive headlines associated with CO_2 storage in mafic and ultramafic resources including:

- "Turn[s] carbon dioxide into rock-forever" (Perasso, V., 2018)
- "Experiment 'turns waste CO_2 to stone'" (Amos, J., 2016)
- "Icelandic company is turning CO_2 into stone" (CNN, 2022)
- "This Oman-based startup turns carbon into solid rock—and does it super fast" (Dutt D'Cunha, S., 2023)
- "Turning carbon dioxide into rock and burying it" (Fountain, 2015).

Table 20. Socio-economic risk categories and key differences between resource types

Risk category	Description	Sedimentary resources	Mafic and ultramafic resources
Public perception	Risks associated with perception of CO_2 storage, willingness of civil society to support development, and recognition of CO_2 storage as a climate mitigation tool	▪ Low awareness of CO_2 storage in civil society; however, some negative perception that sedimentary CO_2 storage extends business-as-usual emissions ▪ Some civil society organizations promote CCUS and CO_2 storage as a solution for hard-to-abate industries and a way to decarbonize at a realistic pace	▪ Public generally has positive perception of technology or energy start-ups ▪ Most projects are linked to geothermal or DAC
Market and economic risks	Risks associated with project costs, CO_2 storage/CCUS business models, the ability of companies developing storage to raise the funds they need for projects	▪ Typically developed by larger companies with substantial balance sheets and existing relationships with lenders ▪ Operating projects may provide increased investor confidence	▪ Most companies active in space are start-ups with limited capital ▪ Costs are less defined ▪ Large-scale operation not demonstrated ▪ Mineralized CO_2 may require less monitoring if it can be demonstrated ▪ Actors within voluntary carbon markets looking at certification methodologies for mineralization projects
Exploration risk	Investment risks related to exploration with no guarantee of return	▪ More historic data are available in sedimentary resources to support initial resource screening	▪ Very high risk due to limited penetrations into these resources ▪ Defined screening criteria are required ▪ Higher costs related to drilling places more capital at risk
Legal and regulatory	Risks related to regulatory frameworks	▪ Relatively well-defined frameworks in several jurisdictions	▪ Frameworks mainly defined for sedimentary storage ▪ Frameworks may not suit aqueous injections ▪ Resource trespass may be more of a risk

Notes: CCUS = carbon capture, utilization, and storage; DAC = Direct air capture.

In addition to the public perception differences that may exist between mafic or ultramafic CO_2 storage and sedimentary CO_2 storage, it is important to assess the narrative around the safety of different trapping mechanisms. Mineral trapping, or "turning CO_2 into stone", as described by the BBC and many other sources, is easier for the public and non-technical specialists to understand than residual, solubility, and structural trapping. It is easy to understand why trapping CO_2 in a mineral is more compelling and perceived as safer than trapping CO_2 under an impermeable caprock.

Given that it can be difficult to conclusively demonstrate mineralization and that mineralization efficiency will likely be much lower for sites injecting free-phase CO_2, it may be advisable to refer to this type of CO_2 storage as mafic and ultramafic storage rather than CO_2 mineralization or mineral storage. It is likely that large-scale projects will have lower mineralization efficiencies than the small-scale projects operating today. If this type of storage continues to be discussed predominately through the lens of rapid mineralization and large-scale projects do not rapidly mineralize CO_2, there may be public perception problems in the future.

Mitigation methods

Public perception risks exist with all types of CO_2 storage. Community engagement, starting early and continuing during project development, is the gold standard for mitigating this risk. Existing public acceptance work on sedimentary CO_2 storage can help guide community outreach and engagement efforts.

Transparent operations, actively listening to and then addressing stakeholder concerns about safety, and making the findings of research projects and/or monitoring programmes publicly available can help reduce the risk of public perception impacting CO_2 storage projects of all types.

6.2.2. Market and economic risks

All types of CO_2 storage will face market risks. They relate to technical risks, the feasibility of individual sites, and the maturity of business models.

Projects in all resource types face cross-chain risks related to the timing of storage development versus capture development and risks related to insufficient investment in capture. Counterparty risk related to insufficient CO_2 volumes can put the capital spent on exploration and site development at risk. Beyond the known market risks related to CO_2 storage operations, mafic and ultramafic CO_2 storage sites face risks related to technological maturity and scalability, project integration experience, investor confidence, and uncertain costs. As seen with sedimentary CO_2 storage, public grant funding – such as that Carbfix has received to support the development of Silverstone and the Coda Terminal – can offset limited access to conventional lenders (European Commission, n.d.).

Differences between resource types

Today, several mafic and ultramafic CO_2 storage projects in development are associated with direct air capture (DAC) projects. If mafic and ultramafic storage developers continue to pursue storing air-captured or biological CO_2, they may be able to capitalize on carbon dioxide removal (CDR)-oriented market mechanisms such as the advance market commitments made by Frontier members (Frontier, n.d.). However, advance market commitments may not provide sufficient capital to develop a large-scale site, and start-ups may not have sufficient credit and/or liquidity to put up the financial guarantees or securities that most jurisdictions require.

While mafic and ultramafic storage has been demonstrated at small scale and in specific environments, it has not yet been demonstrated at a scale where it is competitive with sedimentary storage or has achieved climate relevant injection volumes. Given the current level of technological maturity of CO_2 storage in mafic and ultramafic rocks, there is a significant risk that scaled-up projects will not be able to perform as expected and/or designed. If a site is unable to perform as expected, it places the operator at risk of default. This risk, and the maturity of the technology, can make conventional investors hesitant to invest and potentially limit access to project finance and/or conventional lenders. Venture capital and private equity firms have shown a willingness to invest in companies like 44.01, Cella, and others (44.01, 2024; Trendafilova, 2023b). However, the amount of capital these companies have raised is less than the amount required to develop a large-scale CO_2 storage site.

As a rule of thumb, large, highly injective resources will typically have a lower unit cost of storage than small resources, or those with poor injectivity. We have a poor understanding of the injectivity and size of potential mafic and ultramafic resources. If these resources require more wells to reach injection volumes comparable with those of a sedimentary resource, costs will typically be higher, unless offset by shallower injections or reduced monitoring requirements. An increased well count can result in higher capital, operational, and abandonment expenditure and increased leakage risks. Additionally, as discussed in Section 5.2, assuming the companies are engaging similar classes of rigs, the costs associated with drilling mafic or ultramafic resources are likely to be significantly higher than the cost of drilling sedimentary resources. Many ultramafic rocks, such as peridotites, have lower permeability than mafic rocks, such as basalt, so there may be cost differences between the two individual resource types.

Differences between injection styles

Aqueous CO_2 injections add additional cost components compared to supercritical injections. This type of injection requires additional infrastructure – pumps, monitoring of mixing, and water production wells if not using wastewater – which in turn will lead to increased cost. Project operators may also be required to pay a fee for water extraction and/or treatment. The additional capital and operational expenditure associated with aqueous CO_2 injections may increase unit cost to a point where it could be uncompetitive with alternative CO_2 storage options. But more work on scale-up is needed before this can be assessed with any degree of confidence.

Mitigation methods

Mitigating market and economic risks associated with poorly constrained costs relates to business model development. Global and regional business model development for CO_2 storage in all resource types will help to de-risk investment in mafic or ultramafic CO_2 storage projects.

Scaling up to 100 ktpa or more across a range of resources and geographies is an important first step to mitigating market risks faced by mafic or ultramafic CO_2 storage sites. At current its current technology readiness level (TRL), the costs of mafic and ultramafic storage are poorly constrained. Increased exploitation is required to estimate the nth of a kind (NOAK) operating cost for storage in these resources. Continued development in monitoring, resource assessment, and modelling technologies can generate learnings, but it will only result in marginal cost reduction due to the overall maturity of drilling technologies. Cost reductions from learning and efficiency improvements may also be offset by increased material costs related to ongoing inflation, geopolitical uncertainty, and sectoral decarbonization goals.

6.2.3. Exploration risk

Exploration risk is a common financial risk for the oil and gas and minerals sectors. It is the risk and uncertainty of investing in resource exploration with no guarantee of return. A sizable portion of this risk is tied to technical risks, but it is included here due to its financial impact.

Historically, governments, via geological surveys, de-risked speculative exploration by producing resource atlases or maps of natural resource deposits in their territory. Those studies were usually sufficient to support licensing rounds for exploration licences. Certain jurisdictions also offer subsidy schemes, tax credits, or tax deductions to incentivize natural resource exploration and reduce exploration risk related financial exposure. Examples of such schemes include Canada’s Mineral Exploration Tax Credit, Australia’s Exploration Development Incentive, and the United States’ Intangible Drilling Costs Deduction.

Differences between resource types

The exploration risk associated with mafic and ultramafic resources is significantly higher than the exploration risk associated with sedimentary resources. More subsurface exploration has occurred in sedimentary basins than igneous systems due to historic and ongoing oil and gas production. As a result, more data are available on sedimentary rock sequences than on mafic or ultramafic systems. These data can support early screening exercises in sedimentary CO_2 storage resources.

In contrast, most data available on mafic or ultramafic rocks are restricted to the surface or near surface, except in regions with extensive deep mines and/or geothermal activities. Often there are few to no deep boreholes or wells in these resources, suggesting that significant primary exploration would be beneficial given the potential offered by these resources.

The upfront costs associated with drilling mafic and ultramafic resources can be higher than the equivalent drilling in a sedimentary resource due to a slower rate of penetration, the need for specialized hard-rock drill bits, and the risk of mud loss. This also can increase exploration risk.

Mitigation methods

Exploration risk can never be fully mitigated, but it can be reduced by improving rough mapping of these resources and defining screening criteria. Government-backed or supported drilling campaigns can further develop drilling experience in these rocks and help to characterize large formations.

Adopting the resource classification terminology used by the Storage Resource Management System (SRMS) will not explicitly reduce exploration risk, but it can help to communicate the maturity of individual CO_2 storage resources (see Section 4.2).

6.2.4. Legal and regulatory risk

CO_2 storage projects across all resource types can only occur in jurisdictions with legal and regulatory frameworks that allow for the exploration and exploitation of pore space for the purpose of CO_2 storage. Legal and regulatory frameworks mitigate socio-economic risks because they define the regulatory conditions associated with storage resource development and exploitation. In the absence of CCS-specific legal and regulatory frameworks, storage developers may not be able to legally access pore space and/or develop storage sites.

Most countries do not explicitly have legal and regulatory frameworks for CO_2 storage. However, countries with an interest in CCUS either have frameworks in place or are starting to develop them. The Global CCS Institute's CCS Policy, Legal and Regulatory Review for 2024 provides an overview of where jurisdictions around the world are with CCUS regulations (GCCSI, 2024b).

Differences between resource types

Existing legal and regulatory frameworks typically focus on free-phase CO_2 injections and/or the features exhibited by sedimentary CO_2 storage resources, in part due to the immaturity of CO_2 storage in mafic and ultramafic rocks at the time of their drafting. Many newer frameworks link to or follow the terminology used by International Organization for Standardization (ISO) Technical Committee 265 in ISO Standard 27914 Carbon dioxide capture, transportation, and geological storage – Geological storage. That standard has also been predominantly informed by sedimentary CO_2 storage. Although most regulations take a technologically neutral approach, they may not always be fit for purpose for mafic or ultramafic CO_2 storage. The guidance documents for both the US Environmental Protection Agency (US EPA) Class VI program and the EU CCS Directive mention CO_2 mineralization and/or CO_2 storage in basalts; however, neither set of documents is legally binding.

Most mafic and ultramafic reservoirs do not have vertically confining features that meet the standard definition of a caprock. If the term "caprock" is used in regulatory text rather than "confining feature" or something similar, it may pose an issue for developing mafic or ultramafic resources. The body of the EU CCS Directive does not contain the term "caprock", but it does appear in Annex 1 in relation to the criteria for characterization and assessment of resources. US EPA Class VI text focuses on "confining zones", which may have more flexibility.

Differences between injection styles

Both the US EPA Class VI and EU CCS Directive appear to be drafted with a focus on storing free-phase CO_2. This appears to be more of an issue in the EU CCS Directive than the US EPA Class VI program due to slight differences in the definition of CO_2 stream.

US EPA Class VI 40 CFR § 146.81 – Applicability states:

> *Carbon dioxide stream means carbon dioxide that has been captured from an emission source (e.g., a power plant), plus incidental associated substances derived from the source materials and the capture process, and any substances added to the stream to enable or improve the injection process. This subpart does not apply to any carbon dioxide stream that meets the definition of a hazardous waste under 40 CFR part 261.*

This definition appears to leave open the possibility for aqueous injections if the addition of water can enable or improve the injection process.

The EU CCS Directive (EC/2009/31) appears to have a stricter definition of CO_2 stream: "CO_2 stream means a flow of substances that results from CO_2 capture processes." This definition is further expanded in Article 12, where the directive states:

> *A CO_2 stream shall consist overwhelmingly of carbon dioxide. To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter. However, a CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration. Concentrations of all incidental and added substances shall be below levels that would:*
>
> *(a) adversely affect the integrity of the storage site or the relevant transport infrastructure;*
>
> *(b) pose a significant risk to the environment or human health; or*
>
> *(c) breach the requirements of applicable Community legislation.*

Article 12 of the CCS Directive explicitly allows for trace substances to be added for the purpose of monitoring, but it does not appear to allow the addition of substances that improve or enable the injection process. The European Commission attempted to address this in their 2024 update to the CCS Directive Guidance Documents, wherein they stated that "'Mineralisation' CO_2 storage operations are also permissible under the CCS Directive since the water injected is not considered to be part of the CO_2 stream." (European Commission, 2024a). The non-binding guidance documents do not explain whether additional permits are required for the water co-injectant, what type of matter the water would be classified as, or whether only specific types of water can be used.

Given that many legal frameworks, including the two discussed above, do not explicitly allow for aqueous injections, project developers are advised to analyse their jurisdiction's regulations against their project's specific characteristics.

In addition to the above, aqueous CO_2 storage sites may face uncertainties as to how and when long-term liability can be transferred to the state, if allowed in the jurisdiction where the site operates, as conditions for transfer that apply to supercritical CO_2 storage sites may not be appropriate for aqueous sites. Monitoring challenges related to imaging aqueous CO_2 and/or mineralization may make it challenging to demonstrate conformance as it is conventionally understood.

Box 8. Pore space ownership and resource trespass

Ownership of subsurface natural resources, including groundwater, mineral, and pore space rights, varies between jurisdictions.[37] In many countries, federal or subnational governments hold the mineral rights, but in other jurisdictions the mineral or pore space rights are held by the surface landowner. For example:

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[37] Very few jurisdictions without CO_2-specific regulatory frameworks define pore space ownership. However, it is an aspect that is commonly addressed during the development of CCUS legal and regulatory frameworks.

- In the United Kingdom, the Crown is the landlord of the United Kingdom's territorial seabed. The North Sea Transition Authority is the regulator in charge of permitting offshore CO_2 storage projects, but since the Crown owns the pore space, project developers must also receive a pore space lease from the Crown Estate or Crown Estate Scotland (North Sea Transition Authority, 2023).
- In the United States, landowners typically own the mineral rights that are below their property unless the rights have already been separated from the surface plot. Recently legislation in several states has assigned pore space ownership to surface estate rights, but in other states it is not as clear (Murthy, 2024). Due to the subsurface ownership framework in the United States, CO_2 storage project developers typically need to sign access and/or lease agreements with several property owners.
- In the European Union, pore space ownership is managed at a member state level and pore space is typically owned by the government.

Resource trespass occurs when there is unauthorized development, use, or occupation of a property or resource. In the case of CO_2 storage, resource trespass could occur if CO_2 were to migrate into a zone in the subsurface that the project developer does not have the legal right to occupy; pressure migration could also potentially qualify as resource trespass, but it is not yet clear how different jurisdictions are treating this. Depending on the legal and regulatory framework, such migration may or may not also constitute leakage.[38] Typically, discussions on CO_2 storage risks and liabilities focus on leakage risk and do not specifically address resource trespass. Nevertheless, trespass risk must be considered, and mafic or ultramafic CO_2 storage sites may be more exposed than sedimentary sites.

The risk of resource trespass occurring in sedimentary CO_2 storage sites is relatively low because most regulatory frameworks require a buffer zone beyond the modelled extent of the plume. If a site operator were to observe significant migration of a CO_2 plume in a direction that does not align with its modelling, it would typically trigger mitigation processes to bring the site back into conformance.

In mafic and ultramafic sites, the risk is harder to estimate. Due to the difficulties in imaging these rock types, it can be challenging to identify all major fractures and map lateral and vertical connectivity. Fluid injection tests and tracer tests can help identify fluid circulation pathways, but uncertainty will remain. Since fluids flow via fractures rather than through connected porosity, rapid movement away from the injection zone is possible. If CO_2 were to rapidly migrate via an undetected fracture, it could exit the target zone and potentially into an area where the operator does not have rights. However, mafic and ultramafic CO_2 storage sites also can experience rapid mineralization, which could limit the spread of the injected CO_2 and decrease the long-term risk of resource trespass.

Once CO_2 is in aqueous form it is trapped via solubility trapping unless it reacts with other substances in the fluids or outgases from the water (called exsolution). Exsolution will occur if pore pressure or CO_2 solubility in water decreases. This can happen if the CO_2 migrates out of zone to lower-pressure areas. Aqueous CO_2 is challenging to

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[38] The definition of leakage varies between jurisdictions. The IEA defines leakage as "the unintended release of CO_2 from a storage complex" (IEA, 2022b).

monitor using standard techniques. This can be relevant to resource trespass depending on how a framework approaches leakage. For example, the EU CCS Directive defines leakage as “any release of CO_2 from the storage complex”, but the updated Guidance Documents add a note stating that leakage “refers to CO_2 in free-phase, i.e. it does not include CO_2 that has been dissolved in water, mineralised, or otherwise transformed through chemical reactions” (European Commission, 2024b). This note suggests that as long as aqueous CO_2 remains in solution it can migrate out of the storage complex without being considered leakage. Since the CCS Directive does not outline pore space ownership, this definition could introduce ambiguity around whether resource trespass can occur if CO_2 in any phase migrates out of the storage complex.

Mitigation methods

Project developers focused on mafic and ultramafic storage can collaborate with legal professionals to ensure that their planned activities comply with existing regulations in the relevant jurisdiction(s).

Governments and regulators interested in mafic and ultramafic storage can ensure that existing regulation is fit for purpose and/or that new regulation is agnostic of resource type and injection style.

Close up of a columnar basalt. Image by KPokraka via pixabay.

Chapter 7. Research needs and synergies to explore

Key takeaways

From a technology maturity perspective, mafic and ultramafic CO_2 storage is around 30 years behind sedimentary storage, with significant need for further research, piloting, and demonstration. Without scale-up efforts, we will not know how much mafic and ultramafic CO_2 storage can contribute to durable emissions reduction or carbon dioxide removal (CDR). That said, we have the technologies available today to start scaling up this type of storage.

Areas for continued research, such as improving resource identification and assessment, modelling, drilling, and monitoring, can support current scale-up efforts and drive forward the technology readiness level (TRL) of mafic and ultramafic CO_2 storage. There is also a strong feedback loop between scale-up efforts and incremental improvements in those areas. Other research areas such as microbial trapping and catalysts to accelerate mineralization are more speculative but could contribute to advancing the TRL of this type of CO_2 storage.

Beyond areas for continued research, project developers can also explore synergies that exist between this type of storage and other new energy or energy transition technologies.

Links already exist between geothermal operations, direct air capture (DAC), and mafic CO_2 storage. Other potential synergies that are being explored are the use of CO_2 to enhance subsurface mineral extraction from ultramafic rocks or volcanogenic massive sulphide deposits, harnessing the serpentinization process to produce hydrogen while storing $CO_{2,}$ and the collocation of mafic or ultramafic CO_2 storage with renewable energy installations.

Mafic and ultramafic CO_2 storage has been discussed since the 1990s and the first, very small pilot, took place over 20 years ago. Nevertheless, there is still a need for continued research. Research projects can target testing proofs of concept and validating this type of CO_2 storage in field environments. In addition to continued research needs, synergies between mafic and ultramafic CO_2 storage and other low-carbon or energy transition technologies can be explored.

7.1. Areas for continued research

Research organizations and laboratories around the world are working on mafic and ultramafic CO_2 storage. Examples of projects, research themes, and actors can be found in Table 21. Further research across a range of topics can support the development and scale-up of mafic and ultramafic CO_2 storage.

7.1.1. Resource identification and assessment

Chapter 4 discusses the resource assessment and characterization process and some of the difficulties related to identifying, assessing, and characterizing mafic and ultramafic resources. Improved geological mapping of these rocks would support more refined regional assessments. The methodologies discussed in this report highlight initial attempts to estimate resource potential. Learnings from resource potential estimation methodologies for sedimentary resources can be transferred to mafic and ultramafic resources; for example, it is likely that a storage efficiency factor that accounts for reservoir pressure response and sweep efficiency will be required to estimate mafic and ultramafic CO_2 storage resource potential with any confidence. Unlike sedimentary CO_2 storage, given the reactive nature of mafic and ultramafic rocks, a mineralization efficiency or a correction factor that accounts for the volume of carbonate minerals produced may be required.

Current estimations for mafic and ultramafic CO_2 storage potential are based on significant assumptions relating to porosity, permeability, sequence thickness, mineral composition, and other variables. Using the same methodology and different assumptions, resource potential estimates can differ by more than several orders of magnitude for a single resource and similar variability can be observed using different methodologies and the same assumptions. While assumptions are used throughout the geosciences, a better understanding of the geochemical and geomechanical constraints that affect injectivity and resource capacity are needed before the potential of mafic and ultramafic resources can be estimated with any degree of confidence. The lack of subsurface data about individual mafic or ultramafic formations further hampers resource assessment.

Additionally, assessment and characterization processes can be improved by standardizing initial resource assessment criteria. This has been done for sedimentary resources, and it supports the creation of resource atlases that identify the geographic distribution of potential resources and provide rough estimations of the potential. The criteria used for sedimentary resources can provide a starting point that can then be further developed by researchers and project developers.

Table 21. Research projects related to CO_2 storage in mafic and ultramafic rocks

Project	Entities involved	Research area	Funding source
PERBAS Project	GEOMAR; The Arctic University of Norway; Volcanic Basin Energy Research AS; Institute for Energy Technology; Lawrence Berkely National Laboratory; Colorado School of Mines; National Geophysical Research Institute India; Indian Institute of Technology Roorkee; Indian Institute of Science Education and Research Bhopal; TEEC GmbH	CO_2 storage in marine basalt complexes	Accelerating CCS Technologies Initiative
Supercritical CO_2 Based Mining for Carbon-Negative Critical Mineral Recovery	Pacific Northwest National Laboratory (PNNL)	Use of supercritical CO_2 for in situ enhanced mining of mafic and ultramafic rocks and CO_2 storage	Advanced Research Projects Agency-Energy
Block Modeling of the Carbonation Potential of Ore Deposits Using Cutting-Edge Core Scanning Technology and Advanced Machine Learning Algorithms	Colorado School of Mines and others	Block modeling of CO_2 sequestration in mafic or ultramafic ore bodies	Advanced Research Projects Agency-Energy (ARPA-E)
Energy-relevant Elements Recovery from CO2-reactive Minerals during Carbon Mineralization	Virginia Tech; Phinix; Colorado State University; Western Rare Earths; Columbia University; Virginia Department of Energy; Uitool	Combined carbon mineralization and metal extraction technology (CMME) that enables the recovery of energy-relevant elements	Advanced Research Projects Agency-Energy (ARPA-E)
Carbon Negative Reaction-driven Cracking for Enhanced Mineral Recovery: In-Situ Test at a Ni-Co-PGE Deposit	University of Texas at Austin; Columbia University; Canada Nickel Company	Reaction driven fracturing of mafic or ultramafic rocks; use of CO_2 to induce fracturing	Advanced Research Projects Agency-Energy (ARPA-E)
Sitio Experimental UNESP (Araraquara-SP)	Unesp	13 shallow wells (60-80m) to study rocks within the Paraná LIP	Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP); Petronas; Unesp; LEBAC
The lost ocean of eastern Australia and its critical metals endowment	University of Queensland	Tectonic models of ultramafic bodies in Australia	Australian Research Council
Unlocking mine waste potential: carbon sequestration and metals extraction	Murdoch University	Ex-situ mineral carbonation of ultramafic tailings	Australian Research Council

Project	Entities involved	Research area	Funding source
Enzyme-enhanced CO_2 storage in rocks	CSIRO	The use of carbonic anhydrase enzymes to accelerate mineral carbonation.	CSIRO CarbonLock
Creating a toolkit for in-situ CO_2 mineralisation in basaltic rocks	CSIRO	Engineering challenges related to CO_2 storage in basaltic rocks	CSIRO CarbonLock
Looking into fundamental geochemical processes of mineral carbonation	CSIRO	Reaction mechanisms, kinetics, and changes to individual minerals exposed to CO_2-enriched fluids	CSIRO CarbonLock
Identifying the geological properties of ultramafic rocks for carbon storage potential	CSIRO	Identification and mapping of priority mineral carbonation targets across Australia	CSIRO CarbonLock
GEOMIMIC	Universidade da Coruna	Fluid flow and fracture-matrix interaction in fractured mafic reservoirs	Horizon Europe
Kemetco Research Inc.	Kemetco Research Inc.	Carbonation of ultramafic rocks combined with mineral storage	Natural Resources Canada: Energy Innovation Program
Canada Nickel Company Inc.	Canada Nickel Company Inc.	Ex-situ mineral carbonation of ultramafic tailings	Natural Resources Canada: Energy Innovation Program
Development of coupled direct-air capture and accelerated carbon mineralization technology towards net-zero emissions in Atlantic Canada	McMaster University	Coupling of direct air capture and basalt carbonation processes	Natural Sciences and Engineering Research Council of Canada
Unraveling carbonation mechanism for enhancing carbon storage through mineralization	Chalmers University of Technology	The dissolution and crystallization mechanisms in the carbonation reaction	Swedish Research Council
DemoUpStorage and DemoUpCARMA	ETH Zurich	Evaluate safety and security of storing Swiss CO_2 in Icelandic basalts	Swiss Federal Office of Energy and Federal Office for the Environment
VICCO Centre	University of Oslo	Potential of volcanic-sedimentary storage systems on the Norwegian continental shelf	The VISTA programme
CarbonStone	TotalEnergies	Primary research and potential pilot concept development for CO_2 storage in basalts	TotalEnergies
Enabling CO_2 mineralisation through pore to field-scale tracking of carbonate precipitation: INCLUSION	University of Edinburgh	The interaction between pore-scale and field-scale processes during CO_2 storage in mafic rocks	United Kingdom National Environment Research Council (NERC)
CO_2Basalt	University of Oslo	Basaltic reservoir properties	University of Oslo

Project	Entities involved	Research area	Funding source
Pore-Confinement Effects on Mineral Crystallization Behaviors in Geologic Multiphase Flow Systems	University of Columbia	Porous and fractured media modelling	US Department of Energy
CaRBTAP	Carbon Solutions	Community focused technical assistance oriented toward supporting the development of CO_2 storage activities in the Columbia River Basalt Group	US Department of Energy
Geo-processes in Mineral Carbon Storage (GMCS)	University of Minnesota	Scale up of CO_2 storage in mafic and ultramafic rocks via development of fundamental science and engineering processes	US Department of Energy
Closing Critical Knowledge Gaps in Rates of CO_2 Mineralization in Soils, Rocks, and Aquifers as a Scalable Climate Change Mitigation Solution	Indiana University	Mineral dissolution and precipitation reactions and the use of isotope tracers to improve modelling and evaluate model uncertainties	US National Science Foundation
AIMS^3	University of Bremen; marum; GEOMAR; Fraunhofer; Sea and Sun Technology	CO_2 storage in ocean crustal rocks on slow-spreading ridge flanks	Various federal and state agencies in Germany

Notes: This table was assembled from publicly available information, peer-reviewed papers, grant databases, press releases, and conference proceedings. It provides a snapshot of active research projects and the entities behind them. When the full list of entities could not be identified “and others” is used. It is biased towards funding sources and agencies with English-language award databases. Omissions or absences are not intentional. Further researchers and research groups can be identified from the authors cited throughout this work.

Box 9. International collaboration on resource identification

Mission Innovation (MI) is a global initiative of 23 countries and the European Commission focused on catalysing action and investment in clean energy research, development, and demonstration (Mission Innovation Secretariat, n.d.). The MI Carbon Dioxide Removal (MI-CDR) Mission was launched at the UNFCCC 26th Conference of the Parties (COP26) with the goal of enabling the deployment of novel CDR technologies capable of achieving a net reduction of 100 Mtpa of CO_2 by 2030.

Enhanced mineralization is a core theme of MI-CDR and a designated technical track co-led by Australia and Saudi Arabia. The workplan for this technical track was launched at COP28 and initially focuses on mapping the mafic and ultramafic rock formations to assess their suitability as CO_2 storage resources. This effort aims to facilitate collaboration between member countries to catalyse action and chart a pathway towards deployment of this type of CO_2 storage.

7.1.2. Modelling

Section 4.1 discusses difficulties related to modelling mafic and ultramafic reservoirs and reservoir processes. Chief among them is the problem that mafic and ultramafic sites will exhibit strong differentiation in flow pathways and regimes since they function either as fractured porous media or fractured media. Modelling methods for fractured porous media and highly fractured media are still being refined and developed. Even though significant advances were made in the last 10 to 15 years, applying these models at reservoir scale and incorporating multi-phase flow and geochemical models remains a significant challenge (Berre et al., 2019; Gimenez et al., 2025).

Improving reservoir modelling of mafic and ultramafic resources will require substantial amounts of subsurface field data to create, test, and validate models. Additionally, given the reactivity of mafic and ultramafic rocks, conventional reservoir modelling will need to be combined with reactive transport models to constrain the fate of injected CO_2. Researchers are already working on this type of modelling to assess weathering processes and basalt CO_2 storage, but currently most models only partially couple geochemical and hydrological systems (Favier et al., 2024; Postma et al., 2022b).

As discussed in Section 2.3.2, silicate dissolution is the main rate-controlling limiter for mineral carbonation. The thermodynamics of silicate dissolution and mineral carbonation are relatively well understood and have been evaluated at laboratory scale and modelled for natural systems. Modelling suggests that aqueous injections should nearly always result in rapid dissolution and carbonate mineralization, but similar models find that supercritical CO_2 injected at large-scale sites are likely to mineralize over centuries rather than over years (Postma et al., 2022a). Large-scale pilots or demonstrations across the range of injection styles and rock types are needed to collect data that can be used to improve reservoir modelling, to validate the difference in mineralization potential between injection styles, and to evaluate whether mineralization is necessary for safe and secure storage in mafic and ultramafic rocks.

7.1.3. Drilling and well design

Even though drilling and well design are both mature, drilling and well design for CO_2 storage in mafic and ultramafic rocks are relatively immature. Significant good and best practices are transferable from geothermal projects and the oil and gas sector; there is scope for specific improvements and developments that are directly related to mafic and ultramafic storage.

Drilling mafic and ultramafic rocks can result in significant fluid loss into fracture zones. Additionally, drilling fluid can clog near-wellbore permeability at the injection point of the well. There is scope for research and development on drilling circulation systems and drilling fluids to reduce the risk of near-wellbore clogging or improve well control, and there is a need to consider well design and optimization for these fractured rocks. As discussed in

Box 10. Open subsea sites

Serpentinization and carbonation reactions in the ocean crust demonstrate its ability to act as a CO_2 filter. Patent US9193594B2 outlines a methodology for enhancing rates of carbonation in subsea sites (Kelemen and Matter, 2015). It includes deploying a down-well fracturing module to increase permeability and a heating module to increase the initial reservoir temperature since silicate dissolution favours higher temperatures.

This storage concept capitalizes on the fact that the ocean crust is a hydrologically active system with open circulation. Large chemical gradients are required to drive reactions, which can be achieved with CO_2 injection, fracturing, and heating. However, it may be difficult to ensure that injected CO_2 is contained in a defined area and/or that there is no fluid exchange with bottom waters. Modelling such a site and the behaviour of the CO_2 injected into it is likely to be beyond current modelling capabilities due to the complexities of the flow and mixing regimes.

7.1.4. Other injection styles

In addition to supercritical, aqueous and water-alternating-gas (WAG) injections, research is being conducted into the use of micro- or nanobubbles to enhance CO_2 storage in multiple resource types.[39] In sandstone, micro- and nanobubble CO_2 injections resulted in improved pore space utilization and could be an efficient injection method for low-porosity reservoirs (Jiang et al., 2019; Xue et al., 2014). Limited experimental work has been done on the use of micro- or nanobubbles for mafic or ultramafic storage, although some work suggests that they could accelerate silicate dissolution (Wang et al., 2024).

7.1.5. Monitoring of injected CO_2

Section 5.3 discusses difficulties related to monitoring CO_2 injected into mafic and ultramafic rocks. Like sedimentary CO_2 storage, monitoring represents a continuing research topic for mafic and ultramafic CO_2 storage. Relevant research areas include improving subsurface imaging technologies and data processing methods for mafic and ultramafic rocks,

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[39] Patent US9091156B2 covers the injection of CO_2-H_2O emulsions into geological formations for the purpose of CO_2 sequestration (Schaef and McGrail, 2015).

geochemical monitoring methodologies, methods for detecting CO_2-charged water, quantifying mineralization, detecting and modelling fracture flow, and many other areas.

Project developers can support continued research and development for both monitoring and modelling by developing technologies in-house and by partnering with research groups or technology companies. Governments can also support continued research and development on monitoring by encouraging data sharing and providing research and development funding.

7.1.6. Microbial trapping

A fifth CO_2 trapping mechanism – microbial trapping – has been proposed by researchers based on the incorporation of injected CO_2 into biomass. Today, there is clear evidence that microbial life can be found in the mafic and ultramafic subsurface across a range of rock types and environments. They have been found living on mineral surfaces and accessible interfaces such as pores, fractures, and other voids in the ocean crust, large igneous provinces, and ophiolites (Anderson et al., 1998; Colman et al., 2025; Jungbluth et al., 2013; Kraus et al., 2021; Ménez et al., 2012; Orcutt et al., 2011; Rempfert et al., 2017; Stevens and McKinley, 1995; Trias et al., 2017).

Research suggests that microbial life present in reservoirs may convert injected CO_2 into biomass, thereby immobilizing it for an undefined timeframe (Daval, 2018; Trias et al., 2017). Depending on the microorganisms found in the reservoir, metabolic processes can also contribute to enhanced mineral dissolution or precipitation. Due to the gelatinous nature of biofilms, if CO_2 injection causes microorganisms to rapidly multiple in the reservoir, it could result in injectivity decline due to pore clogging and reduced connectivity between pores.

Biomass has the potential to immobilize CO_2 in the subsurface, at least over short time periods. Therefore, at low-temperature sites, a mass balance approach based on breakthrough time, concentration of dissolved elements, and certain isotopic ratios, may result in an overestimation of mineralization.[40] If this occurs, there may be long-term ramifications on project financials if the project issues carbon credits linked to mineralization rather than just to CO_2 storage.

Box 11. Microbial life in the subsurface

Trias et al. (2017) documented that CO_2 injections into low-temperature (20-50°C) basalts can result in rapid and large changes in the indigenous microbial communities. The divalent cations released by basalt dissolution stimulated the growth of bacteria that could incorporate injected CO_2 into biomass. The study was unable to quantitatively establish how much injected CO_2 was incorporated into biomass, but qualitative observations found significant biofilms colonizing fracture surfaces in the core drilled after injection was complete. Additionally, the project experienced a drop in well transmissivity (following the addition of H_2S to the injection mix) that could be at least partially attributed to a bloom of biofilm-forming bacteria (Trias et al., 2017).

The work by Trias and co-authors, along with research on the microbial communities found in ophiolites, serpentinites, and the ocean crust, suggest that at low

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[40] The upper temperature limit of microbial life remains debated, but it is typically considered to be around 120°C (Kashefi and Lovley, 2003).

temperatures, microbial communities can trap CO_2 in biomass. The effectiveness and duration of microbial trapping remains poorly understood. Microbial communities in the subsurface can also contribute to clogging of pore space and fractures, thereby potentially decreasing injectivity or resource performance.

7.1.7. Catalysts

Metal-organic frameworks can be used to accelerate the dissolution of silicate minerals, which is a rate-limiting step in carbonation (Di Lorenzo et al., 2018). If combined with catalysts that accelerate carbonation, this could increase carbonate mineralization rates. Carbonic anhydrase enzymes can increase the rate of carbonate mineralization, although they may inhibit silicate dissolution (Di Lorenzo et al., 2018; Talekar et al., 2022). In addition to metal-organic frameworks and carbonic anhydrase enzymes, nickel nanoparticles are being explored as a catalyst to improve carbonate mineralization by accelerating the rate of carbonic acid formation (Zhang et al., 2022). To date, much of the work on catalysts has focused on ex situ mineralization, but there may be applications for in situ mineralization as well. Catalysts remain an area open for further research.

7.2. Synergies with other energy technologies

Mafic and ultramafic CO_2 storage can be synergistic with other energy and energy transition technologies. As project developers work to scale up this type of storage, they can investigate whether their project can be collocated or linked to other energy transition activities.

7.2.1. Geothermal

The synergies between geothermal energy and mafic or ultramafic storage are clearly demonstrated with Carbfix. The start-up was initially established as a subsidiary of Reykjavik Energy, a global leader in geothermal energy development. Carbfix uses geothermal effluent to dissolve CO_2 that is captured either from DAC plants or from geothermal operations. The CO_2-charged water is then reinjected into the same aquifer from which it was produced. Open-loop geothermal operations commonly reinject their effluent to maintain the hydraulic head of the aquifer and to reduce environmental impacts that could occur if the effluent were discharged at the surface. Since reinjection is already occurring, dissolving CO_2 into the water can represent an incremental additional cost with potentially significant climate benefits.

In addition to proven synergies with geothermal operations in Iceland, CO_2 is being considered as a working fluid for enhanced geothermal systems. It has several advantages over water, including its specific heat and natural buoyancy compared to most formation fluids (Fleming et al., 2022; Randolph and Saar, 2011). Research is ongoing into the feasibility of CO_2 plume geothermal systems across a range of storage types. Since a portion of CO_2 remains in the reservoir and the CO_2 produced for heat extraction is reinjected, CO_2 plume geothermal systems can result in permanent storage. Mafic rocks located in areas with shallow thermal gradients, such as Hawaii, Indonesia, and the Philippines, may represent an interesting target for both CO_2 storage and energy generation.

7.2.2. Mineral extraction

Silicate dissolution to release divalent metal cations is a critical step in mafic and ultramafic CO_2 storage if mineralization is targeted. Due to its acidity, aqueous CO_2 can enhance the rate of silicate dissolution. This is being explored as a method of subsurface mining for the metals that can be bound in the silicate mineral crystal lattice. Researchers have discovered that nitriloacetate salt can greatly enhance the CO_2 mineralization of olivine while also allowing for the recovery of nickel and cobalt (Wang and Dreisinger, 2023). Similarly, organic ligands can be used to improve the co-recovery of nickel from serpentine minerals, while precipitating carbonate minerals are a co-product (Katre et al., 2024). It is unclear whether enhanced metal and mineral extraction paired with in situ CO_2 storage is being tested outside laboratories, although in 2022 Talon Metal Corporation in partnership with Rio Tinto received a US Department of Energy grant to explore carbon storage potential at the Tamarack Nickel Project in Minnesota (Rio Tinto, 2022).

7.2.3. Hydrogen production

The serpentinization process naturally produces hydrogen while also having the potential to immobilize CO_2 in new minerals. Researchers are exploring whether CO_2 injection into peridotites or basalts can be used to stimulate hydrogen production and also store CO_2 (Al-Yaseri et al., 2025; Wang et al., 2019). Simulated geological hydrogen production based on the serpentinization process is at a TRL of 4, but given global interest in hydrogen, it is potentially a synergy worth exploring (Templeton et al., 2024). If hydrogen can be produced as a byproduct of mafic or ultramafic CO_2 storage, it could make these storage operations more economically viable even at small scale.

7.2.4. Renewable energy sites

Renewable energy projects can be synergistic or competitive with CO_2 storage projects. There have been tensions between offshore wind and CO_2 storage projects in part because it will be very difficult to acquire seismic data around an offshore wind farm due to navigation restrictions (Buljan, 2023). Onshore, navigation around wind turbines poses less of an issue. The turbines can also serve as a noise source for passive seismic acquisition. Solar panel arrays may introduce access constraints that could impede seismic data collection.

Using renewable energy to power CO_2 storage sites in any resource type can reduce the carbon emissions associated with storing CO_2, therefore improving the lifecycle analysis across the value chain.

7.2.5. Direct air capture

Synergies between mafic or ultramafic storage and DAC are demonstrated though Carbfix's collaboration with Climeworks. Carbfix is currently injecting CO_2 sourced from the Orca and Mammoth DAC plants. The operations that Cella is developing in the Great Rift Valley in Keyna are also linked to CO_2 sourced from DAC plants. Additionally, it is likely that geothermal energy will be used to power those DAC plants.

A range of DAC technologies are available, but solid sorbent DAC like Climeworks' technology is still smaller scale than liquid sorbent DAC as developed by Carbon Engineering. Since solid sorbent DAC projects are currently at a similar scale to mafic and ultramafic CO_2 storage operations, they may be able to grow together.

Image by Makalu via pixabay.

Chapter 8. Conquering the megatonne challenge

Key takeaways

In carbon capture, utilization, and storage (CCUS) we often talk about the gigatonne challenge, with the aim of reaching a gigatonne of annual CO_2 capture in the early 2030s. Mafic, ultramafic, and metamorphic rocks can serve as storage resources if CO_2 storage in them can be scaled up to handle larger annual injection rates.

Before they can meaningfully contribute to the gigatonne challenge, however, they must first be demonstrated at large scale (> 100 ktpa CO_2 stored in a single site). Such demonstration can provide confidence that this type of storage can substantially contribute to the goal of durable emissions reduction or CO_2 removal.

Scale-up from the tonnes or thousands of tonnes of annual injection today to hundreds of thousands of tonnes requires a supportive policy framework, fit-for-purpose legal and regulatory frameworks, technology improvements, and the ability to finance these projects.

The International Energy Agency has described CO_2 storage resources as “a strategic asset for energy transitions” (IEA, 2022a). This is true regardless of rock type. Given that CO_2 storage is the most scalable way to return carbon to the lithosphere, exploiting CO_2 storage resources is aligned with the goals of the Paris Agreement.

CO_2 storage is often framed in relation to the gigatonne challenge, or moving from millions of tonnes of CO_2 stored a year to billions of tonnes. This challenge is appropriate for CO_2 storage in general and sedimentary resources. Mafic and ultramafic CO_2 storage must first conquer the megatonne challenge or move from thousands of tonnes of CO_2 stored per year to millions of tonnes.

Mafic and ultramafic rocks may offer CO_2 storage opportunities in geographies with limited access to sedimentary resources. These potential storage resources may also positively contribute to gross domestic product (GDP) while supporting emissions reduction. Therefore, if large-scale mafic and ultramafic CO_2 storage is technically and commercially feasible then CO_2 storage activities can expand into new geographies where it could also support Paris Agreement-aligned industrialization or development.

For this potential to be realized, it is necessary to demonstrate that mafic and ultramafic CO_2 storage is scalable. As discussed throughout this report, the scalability of CO_2 storage in these resources will remain an open question until we have a better understanding of how mafic and ultramafic reservoirs respond to sustained, large-scale CO_2 injection. In Chapter 3, this report defines large-scale mafic or ultramafic CO_2 storage sites as those with a nominal injection capacity of 100 ktpa or greater. Developing and operating sites of that size will be a critical step in demonstrating the scalability of this type of CO_2 storage.

Today, mafic and ultramafic CO_2 storage has successfully been piloted at small scale in Iceland, the United States, the United Arab Emirates, Oman, and Saudi Arabia, but all completed or operating sites are one to five orders of magnitude smaller than the smallest dedicated sedimentary CO_2 storage site. Outside Iceland, it does not appear that any project or site has achieved 1 kt of injection. In Iceland, between 2012-2023 annual CO_2 injection was below 14 ktpa (Icelandic Environment and Energy Agency, 2025a; Environment Agency of Iceland, 2024). Based on a permit approved in May 2025, this will soon scale up to 106 ktpa via four wells, the largest of which has a nominal injection capacity of 47 ktpa (Icelandic Environment and Energy Agency, 2025b).

Successfully scaling up from tonne- or kilotonne- to megatonne-scale injections requires a supportive policy environment, fit-for-purpose legal and regulatory frameworks, demonstrated measurement, monitoring, and verification (MMV) methodologies, proven large-scale demonstration, and an economic environment that supports financing projects.

8.1. Policy levers

Policies that support CO_2 storage and carbon management are key to accelerating the development of a carbon management industry. The same policy levers that support widespread deployment of sedimentary CO_2 storage resources can support the scale-up and further development of mafic and ultramafic storage. Such policies can include:

- Government-led or funded resource assessment and drilling campaigns
- Funding for research and development of relevant technologies and modelling methodologies
- Public support for demonstration-scale projects

- Implementation of policies that encourage CO_2 storage investment.

General policy support for carbon management and CCUS will help mafic and ultramafic CO_2 storage only if it is inclusive of all potential CO_2 storage resource types. Policies that explicitly reference sedimentary resources due to their maturity may inadvertently prevent a mafic or ultramafic project from developing even if it has high potential.

That said, given the current maturity of CO_2 storage in the different resource types, it may be appropriate to have dedicated research and development funding for mafic and ultramafic CO_2 storage. Public funding may stimulate the development of pilot or demonstration projects that can accelerate the maturity and commerciality of this type of storage. Additionally, public research and development funding typically comes with knowledge-sharing requirements. Since data from field-scale deployment are needed to refine mafic and ultramafic reservoir modelling, mandating data and knowledge sharing as a condition of receiving support could accelerate advancements related to this type of CO_2 storage.

8.2. Legal and regulatory frameworks

As discussed in Section 6.2.4, existing legal and regulatory frameworks for CO_2 storage may not be completely applicable to mafic and ultramafic storage and/or to aqueous CO_2 injections for the purpose of storage. Furthermore, some countries with geology highly relevant to mafic or ultramafic CO_2 storage, such as Kenya and India, do not have legal and regulatory frameworks for any type of CO_2 storage.

Countries currently developing CCUS legal and regulatory frameworks can consider regulation that allows for CO_2 storage across all resource types and injection styles. This can include:

- Specifically addressing aqueous and/or water-alternating-gas (WAG) injections in addition to free-phase injections or addressing a broader CO_2 stream injection like that of the US EPA Underground Injection Control Program, versus a narrower definition like that of the EU CCS Directive (see discussion in Section 6.2.4).
- Focusing on vertically confining features and/or active vertical monitoring rather than using a term like “caprock”.
- Ensuring that legally prescribed monitoring is technology agnostic and focused on the aims of monitoring rather than the methods used. The regulation should allow projects to select monitoring technologies that are appropriate to their resource type, injection style, and site design.
- Allowing for some flexibility in the defined workflow for resource assessment and characterization and in storage site modelling requirements to ensure that the whole range of resources are accounted for.

In addition to the inclusion of mafic and ultramafic CO_2 storage and aqueous injections in national and subnational CO_2 storage regulations, the treatment of this type of storage in international law may also need to be evaluated by project developers.

The 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Protocol) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) are both reverse lists. This means that their signatories can only dispose of waste or matter if it is explicitly defined as eligible in the appropriate annex (Annex 1 of the London Protocol, Annex 2 of OSPAR). Both treaties allow for the subsea disposal of CO_2 into geological formations so long as the CO_2 streams consist overwhelmingly of CO_2. They do not specify resource type so long as injected CO_2 is retained permanently. Even though both treaties allow for incidental associated substances, it is unclear whether the water used for aqueous injections would qualify as an incidental associated substance and water disposal is not explicitly discussed in either treaty. Parties interested in developing offshore aqueous CO_2 storage sites in jurisdictions that are signatories to either convention should assess whether this could be a barrier to their project.

8.3. Technology for large-scale demonstration

The technology readiness level (TRL) of mafic and ultramafic CO_2 storage appears to sit between TRL 5 and 6. Via their various projects, Carbfix, 44.01, Aramco, and Pacific Northwest National Laboratory have validated mafic and ultramafic storage in a relevant environment. Based on peer-reviewed literature and known operating parameters, none of those projects approach the safe operating limits of the resources they inject into. Since it is not yet possible to evaluate the initial operational deployment of this type of storage, it is unlikely that mafic and ultramafic storage has achieved TRL 7. Additionally, the scale of existing projects is well below that of even the smallest dedicated sedimentary CO_2 storage site.

In many ways, TRL is an imperfect metric to evaluate the technological maturity of mafic and ultramafic resources. In most cases the needed technology exists, but it has not been adapted to or demonstrated for these specific resources. Areas for continued technological development and refinement specifically for mafic and ultramafic CO_2 storage include:

- Subsurface imaging to improve visualization of mafic and ultramafic resources and potentially mineralization fronts
- Drilling technologies for hard rocks to increase efficiency and rate of penetration
- Reservoir modelling for hybrid porous and fractured systems
- Well testing to identify fractures and fracture flow
- Methodologies to quantify and verify subsurface mineralization.

While these areas for technological development are significant, pilots and operating small-scale projects have demonstrated that mafic and ultramafic storage is possible. Scale-up of this type of storage is less constrained by overall technological maturity and more by our understanding of the resources themselves. Mafic and ultramafic resources do not just have significant geochemical, geophysical, and geomechanical differences when compared to sedimentary reservoirs, they also have significant differences across individual mafic and ultramafic rock types. Rock age and degree of alteration may also affect the suitability resources with the same rock type.

One way to accelerate technology deployment and scale-up of this type of storage is to develop it more widely. Small-scale CO_2 injections into a range of rock types and ages with extensive monitoring and data sharing can help improve reservoir modelling. Such sites can serve as a test bed for imaging technologies and methods to quantify and verify subsurface mineralization.

That said, small-scale sites are not a substitute for medium- to large-scale demonstration projects. There has been extensive theoretical work done on geochemical controls and reaction rates, but laboratory experiments often exhibit faster reaction rates than can be achieved in the field. Additionally, at reservoir scale, mafic and ultramafic CO_2 storage will be pressure limited. Large-scale demonstration is required to robustly assess the limitations that may be exerted by geochemical, geophysical, and geomechanical processes within the reservoir and the rock that surrounds it.

Further piloting and demonstration need to be linked to extensive knowledge and data sharing. Public–private partnerships between companies and state-owned enterprises or research organizations along with international collaboration can enhance knowledge exchange and data sharing. Government support in the form of research grants and support for piloting or demonstration can include data sharing or knowledge transfer requirements. Sharing data collected during monitoring, information about site engineering, or modelling methodologies and improvements can help develop mafic and ultramafic CO_2 storage in the same way that data and knowledge sharing helped the development of sedimentary CO_2 storage. Dedicated sedimentary CO_2 storage sites like Sleipner, Snøhvit, and Quest have shared monitoring data, details about injection rates, costs, and other critical aspects of design and operations with researchers and the wider CCUS community. These data have been used to test and validate reservoir models, demonstrate the safety of CO_2 storage, and identify monitoring technologies. Given its current maturity level, mafic and ultramafic CO_2 storage would benefit from a similar openness around data and knowledge sharing.

8.4. Project economics and financing

As discussed in Chapter 5 many variables will affect the cost of mafic and ultramafic CO_2 storage projects. CO_2 storage projects typically exhibit strong economies of scale; this suggests that scaling up mafic and ultramafic CO_2 storage sites will be necessary if they are to be competitive with sedimentary CO_2 storage. The drilling costs for wells in mafic and ultramafic rocks are likely to make this type of CO_2 storage more expensive than sedimentary CO_2 storage. Additionally, if aqueous CO_2 injections are selected, this will also inherently increase project costs due to additional energy requirements to pump water and dissolve CO_2.

That said, if CO_2 is demonstrated to have been mineralized, sites may have shorter post-closure monitoring requirements, which can result in reduced project costs. Mineralized CO_2 may also reduce long-term liabilities and leakage risks.

All current mafic and ultramafic CO_2 storage projects are operating at small or very small scale. Most of these sites are pilots or demonstration projects. Direct air capture with storage has been a critical supplier of CO_2 for Carbfix's sites, allowing some of their work to receive support from credits sold on voluntary carbon markets. Advance market commitments can support the development of small-scale storage sites, but neither they nor venture capital-backed equity raising are likely to provide sufficient capital to develop large-scale sites. The only large-scale site in advanced development today is the Coda Terminal and that project has received a EUR 115 million EU Innovation Fund grant (European Commission, n.d.).

Banks and traditional finance entities are likely to be hesitant to provide loans for mafic or ultramafic CO_2 storage until its scale-up is demonstrated. In Chapter 4, this work advocates that mafic and ultramafic storage developers should start using the SRMS to classify their resources. This will generate confidence in the maturity of mafic and ultramafic CO_2 storage. The SRMS provides a framework to assign a book value to a storage resource. As CO_2 storage deployment expands, it will be more important to align resource classification frameworks and terminologies so that companies can confidently list their CO_2 storage capacities as an asset.

Assigning a book value to a resource can also enhance financing opportunities in the long run. Because the market for CO_2 storage is still developing, it is unlikely that a commercial bank will currently consider a CO_2 storage resource as an asset on a company's balance sheet. However, that will hopefully change in the future.

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Appendix 1. GIS data

GIS data were collected from publicly available sources, including maps from geological surveys and peer-reviewed literature. Appendix Table 1 lists the data sources and outlines which data were used.

A1.1 Data classification and processing

GIS metadata, including legends and lithological descriptions associated with shapes, were processed to aggregate data into five categories of CO_2-reactive rocks (Appendix Table 2). Sedimentary rocks, felsic and intermediate igneous rocks, and non-relevant metamorphic rocks were all classified as not relevant and were not mapped.

Appendix Table 2. Categories of CO_2-reactive rocks used in this study

Category	Lithological descriptions used for classification
Mafic	Mafic, basic, basalt (with any adjectives), gabbro, dolerite, diabase, alkaline volcanic rocks*, tephrite, basanite, pillow lavas, troctolite, lamprophyre, norite
Ultramafic	Ultramafic, ultrabasic, peridotite (and various subgroups), pyroxenite (and various subgroups), komatiite (and various subgroups), carbonatite, chromitite, hornblendite, exotic alkaline rock†
Relevant metamorphic	Meta + relevant mafic or ultramafic rock type e.g. “metagabbro”, mafic granulite, brucite, ortho + rock or mineral if clearly from a mafic or ultramafic protolith. If the following were in close geographic proximity to mafic or ultramafic rocks they were also included: amphibole, greenschist, greenstone
Ophiolite	Ophiolite, serpentinite, lithological descriptions that included mafic, ultramafic, and metamorphic rocks
Undifferentiated mafic/ultramafic	Mafic/ultramafic, basic/ultrabasic

* Alkaline volcanic or plutonic rocks are not always mafic or ultramafic; however, most data that used the term “alkaline” separately classified felsic and intermediate igneous rocks as “felsic and intermediate” or “acidic”.

† Exotic rocks can be used to describe silica-poor ultramafic rocks such as carbonatites.

Notes: When adjectives appeared modifying rock composition, e.g. “andesitic basalt”, the primary rock type was used in classification. When descriptions included hyphenations, e.g. “gabbro-diorite”, the first lithology was considered primary. This study assumes that the ocean crust is mafic or ultramafic except where it is overlain by substantial sediments.

Most geological maps defining rock distribution are based on mapping campaigns and field work that is primarily focused on surface geology and includes limited sampling. One field geologist may describe a rock as an andesitic basalt, and another may describe it as a basaltic andesite. In the case of this study and the boundaries it draws, an andesitic basalt would be included since the defined lithology is mafic, while the basaltic andesite would be excluded since the defined lithology is an intermediate igneous rock.[41]

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[41] Depending on their composition, intermediate igneous rocks may also be targets for the type of CO_2 storage discussed throughout this report. As with any analysis, explicit boundaries had to be established for data analysis related to the mapping work. As a result, anything that was clearly classified as an intermediate igneous rock was excluded.

Appendix Table 1. Overview of data sources for mapping exercise

Region	Data source	Reference	Data notes	Resolution
Africa	RCMRD	RCMRD et al. (2017)	Differentiated as “intrusive”, “extrusive”, “volcanic”, “metaigneous”, and “ultramafic”. Chorton (2007) was used to refine classification of rock features	Varies (compilation of different African datasets)
Africa, South America (Global)	Geological Survey of Canada	Chorlton (2007)	Encompassing "mafic and/or ultramafic" rock features and differentiated as "intrusive" and "volcanic". Used to refine features in Africa and merged with Schenk et al. (1999) to create a compilation covering South America (excluding Brazil and Venezuela)	1:35 million
Arabian Peninsula	USGS	Pollastro (1998)	Age-based units, hard rocks divided by "volcanics" and "intrusive”	1:2.5 million and 1:3 million
Asia	GSJ CCOP	CCOP (2021)	Differentiated by igneous rock type and in- or extrusive; metamorphic rocks classified by grade (low, intermediate, high)	1:2 million
Australia	Geoscience Australia	Raymond et al. (2012)	In-depth lithological descriptions	1:1 million
New Zealand and Pacific Islands	USGS	USGS (1999)	Age-based units, hard rocks divided by "volcanics" and "intrusive” and "ophiolites and ultrabasics". Medium level of lithological detail	1:3 million
Brazil	SGB	SGB (2004)	In-depth lithological descriptions	1:1 million
Europe	EGDI	EGDI (2018)	In-depth lithological descriptions	1:1 million
Europe	IGME	Asch, K. (2003)	In-depth lithological descriptions	1:5 million
Russia and Central Asia (Map classified as “Former Soviet Union”)	USGS	Drummer (1998)	Age-based units, hard rocks divided by "volcanics" and "intrusive”; Siberian Traps manually categorized as mafic based on expertise. Low level of lithological detail.	1:7.5 million
India	SimpleMaps	simplemaps.com (n.d.)	Boundary of the state of Maharashtra	Not given

Region	Data source	Reference	Data notes	Resolution
Iran	USGS	Pollastro et al. (1999)	Age-based units, hard rocks divided by "volcanics" and "intrusive". Low level of lithological detail	Compiled from a map at 1:2.5 million, adjusted using a map at 1:3 million, and generalized
Mexico	SGM	SGM (2017)	In-depth lithological descriptions	1:250,000
North America (excluding Mexico)	USGS - GMNA	Garrity and Soller (2009)	Differentiated "plutonic", "volcanic", "sedimentary" and "metamorphic". Medium level of lithological detail	1:5 million
Oman (Asia)	GSJ	GSJ (2018)	Differentiated as “intrusive”, “ultramafic” and “ophiolite”, or broadly categorized as sedimentary, extrusive and metamorphic. Low level of lithological detail	1:10 million
South America	CGMW	Gómez, J. et al. (2019)	Lithological descriptions include "Alkaline", "Basaltic"	1: 5 million
South Asia	USGS	Wandrey (1998)	Age-based units, hard rocks divided by "volcanics" and "intrusive"; Deccan Traps manually categorized as mafic based on expertise. Low level of lithological detail	1:10 million
United States	USGS	Blondes et al. (2022)	Differentiated by "surface mafic", "surface ultramafic" and "subsurface ultramafic", with further lithological detail available for most rock features. Medium level of lithological detail	1:100,000 to 1:5 million
Venezuela	USGS	Garrity et al.	In depth lithological descriptions	1:750,000
Global	BGR / CGMW	Asch et al. (2022)	Continental slope boundaries, global distribution of ophiolites	1:70 million
Global	Tellus	Robertson Tellus (CGG) (2009)	Sedimentary basins	Mostly 1:2.5 million and 1:5 million
Global	GEBCO	GEBCO Bathymetric Compilation Group 2024 (2024)	Bathymetry and topography	15 arc seconds (raster resolution)
Global	Natural Earth	Natural Earth (2020)	Bathymetry	Not given
Global	NOAA	Straume et al. (2019)	Offshore sediment thickness	5 arc minutes (raster resolution)

Region	Data source	Reference	Data notes	Resolution
Global	US Dept of State	US Department of State (2018)	Continent boundaries	1: 250,000
Global	Flanders Marine Institute	Flanders Marine Institute (VLIZ), Belgium (2023)	Exclusive Economic Zones (EEZ)	Not given
Global	Natural Earth	Natural Earth (2009)	Ocean boundaries	Not given

Notes: RCMRD = Regional Centre for Mapping of Resources for Development; USGS = United States Geological Survey; GSJ = Geological Survey of Japan; CCOP = Coordinating Committee for Geoscience Programmes in East and Southeast Asia; EGDI = European Geological Data Infrastructure; IGME = International Geological Map of Europe and Adjacent Areas; SGM = Servicio Geológico Mexicano; GMNA = Geologic Map of North America; BGR = Federal Institute for Geosciences and Natural Resources of Germany; CGMW = Commission of the Geological Map of the World; GEBCO = General Bathymetric Chart of the Oceans; NOAA = National Oceanic and Atmospheric Administration;

Several data sources included GIS shapes with descriptions that list multiple lithologies. The classification process depended on how the data were provided:

- If the lithologies were listed in alphabetical order, then the shape was classified by the most frequently appearing rock type. If more than 50% of the listed lithologies were relevant to the study, then the data were included.
- If the lithologies were listed in order of importance, then the first listed lithology was used for classification. If it was not relevant to the study and more than 50% of other listed lithologies were, then the first listed relevant lithology was used for classification.

The ophiolite classification is an exception to the above. As discussed in Section 2.2.2, ophiolites are a sequence of uplifted oceanic crust. Since serpentinization is a key process leading to the formation of ophiolites, any lithology that was listed as serpentine or serpentinite was classified as an ophiolite and not as relevant metamorphic. If a shape included a description with mafic, ultramafic, and relevant metamorphic rocks it was classified as an ophiolite since those three different rock types are mainly found in close proximity in ophiolite sequences.

After reprocessing the legends and lithological descriptions of the collected data, the data were reprojected onto a common two-dimensional (2D) coordinate reference system. Data were collected across a range of different resolutions, but down sampling did not occur.

A1.2. Data gaps and omissions

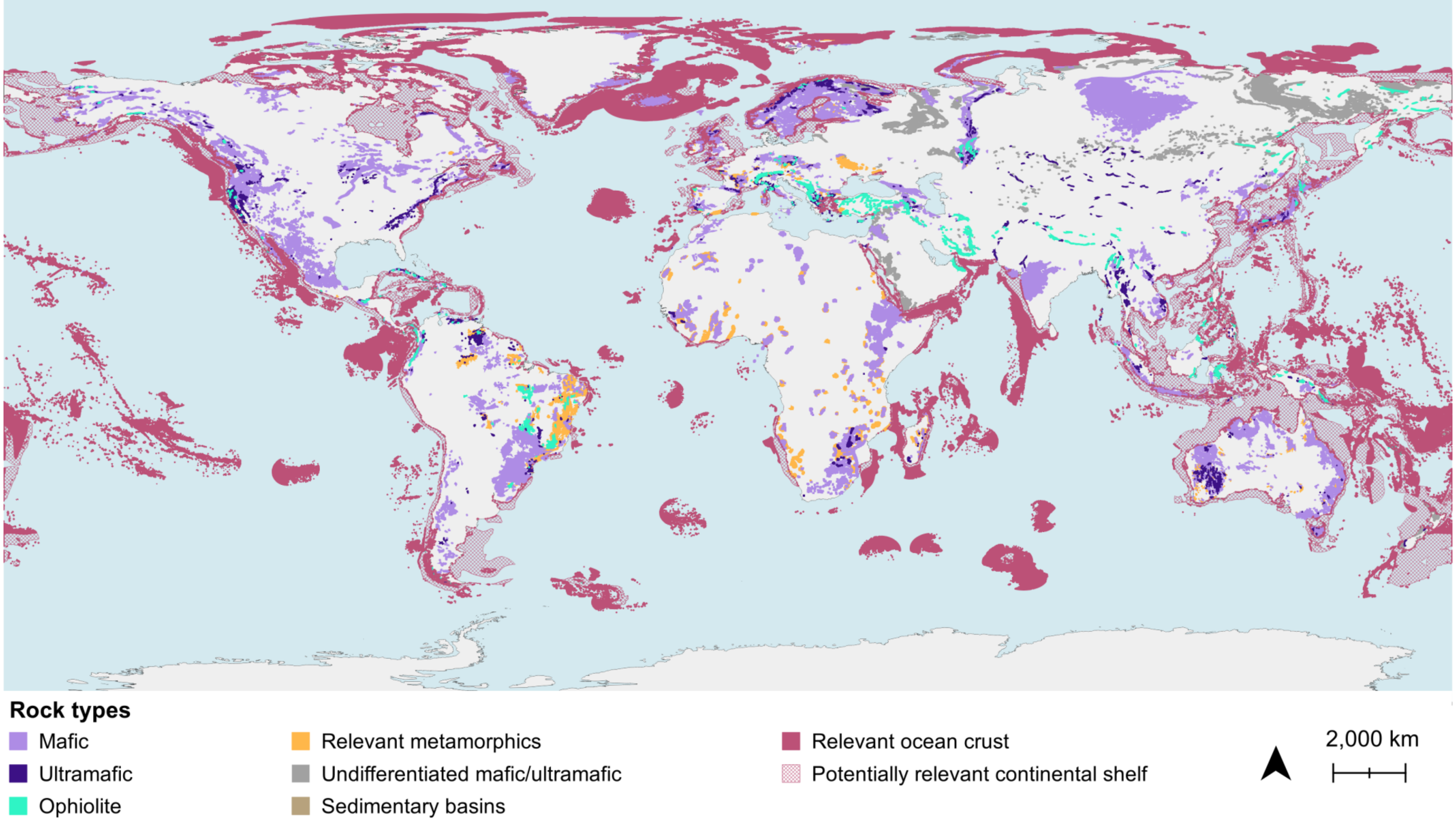
As briefly discussed in Section 4.4, there is very little standardization in how hard rocks appear on geological maps. Maps generated by the same geological survey may use different terms to describe the same rock types. For example, the United States Geological Survey (USGS) was the source of several GIS datasets used during this mapping exercise. The survey's geological maps cover most world regions and while all of them use age-based classifications of sedimentary rocks, there is limited to no harmonization across the different maps on the terminology they use to classify different intrusive, volcanic, or metamorphic rocks. Some maps will break it down into individual rock compositions (e.g. alkaline, basic, diorite, granite), others differentiate by volcanic or intrusive, and others will group a variety of different rock types into one legend key (e.g. basic, ultrabasic, and alkaline intrusive rocks).

Depending on the type of metamorphic rock, its protolith is not always immediately identifiable and some maps only include metamorphic grade. For this study, reactive metamorphic rocks are defined as metamorphic rocks formed from mafic or ultramafic protoliths since they have the highest amount of CO_2-reactive minerals. If protolith could not be determined and/or the identified rock was not known to be CO_2-reactive, it was excluded. As a result, any metamorphic rocks that were described as low-, intermediate-, or high-grade were excluded unless there was additional lithological information available.

Due to this lack of standardization and the relatively poor quality of global data, the maps in this work have known omissions. Regions of the world with poor data include Central and East Asia (excluding Japan), Russia, and Africa.

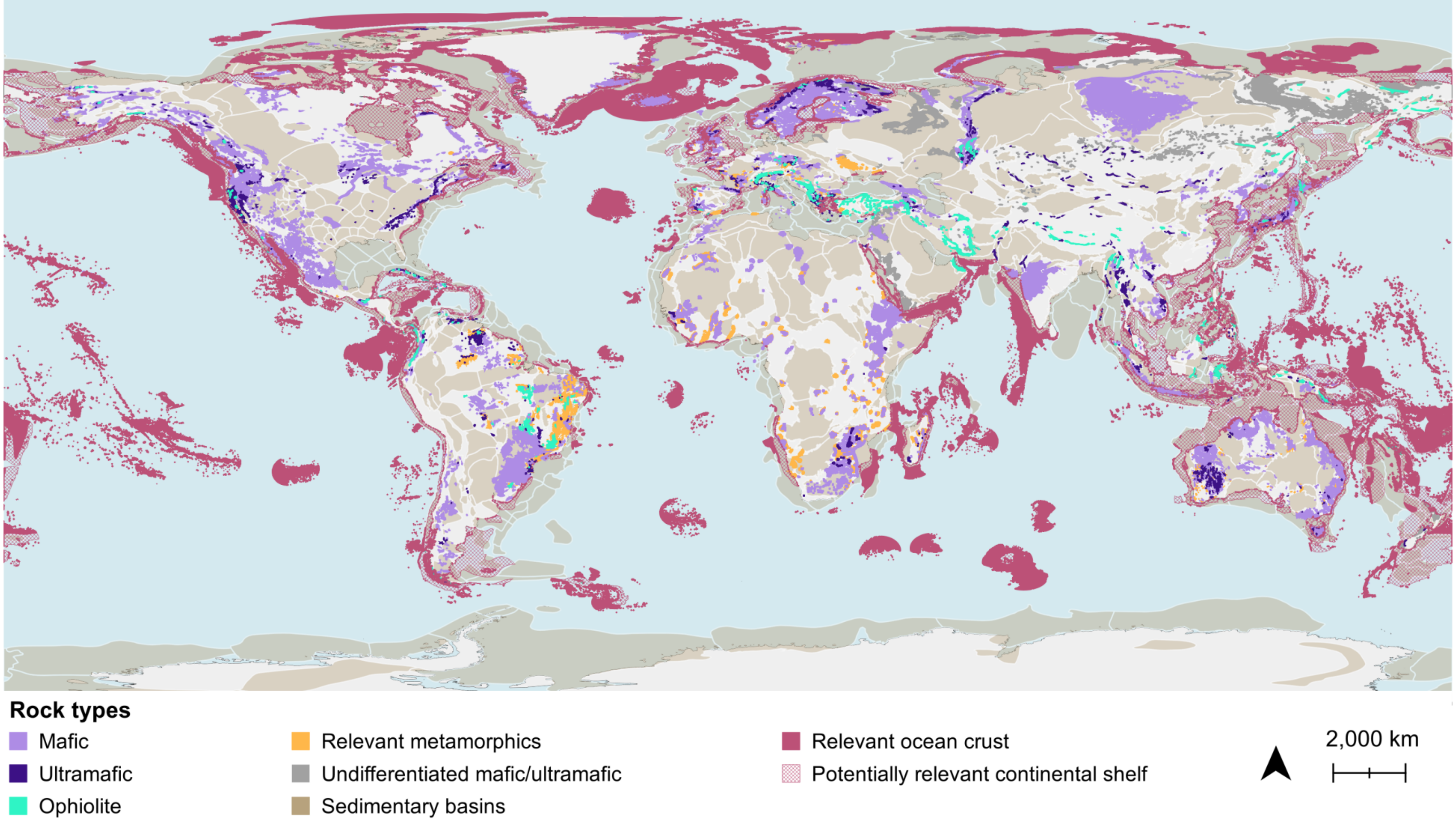
A1.3. Maps including the continental shelves

Appendix Figure 1. Global map with potential mafic and ultramafic resources including the continental shelf



Notes: Undifferentiated mafic/ultramafic corresponds to data that were identified as “mafic and ultramafic” or “basic and ultrabasic”. See Appendix Table 1 for underlying data sources.

Appendix Figure 2. Global map with potential mafic and ultramafic resources including the continental shelf and sedimentary basins



Notes: Undifferentiated mafic/ultramafic corresponds to data that were identified as “mafic and ultramafic” or “basic and ultrabasic”. See Appendix Table 1 for underlying data sources.

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