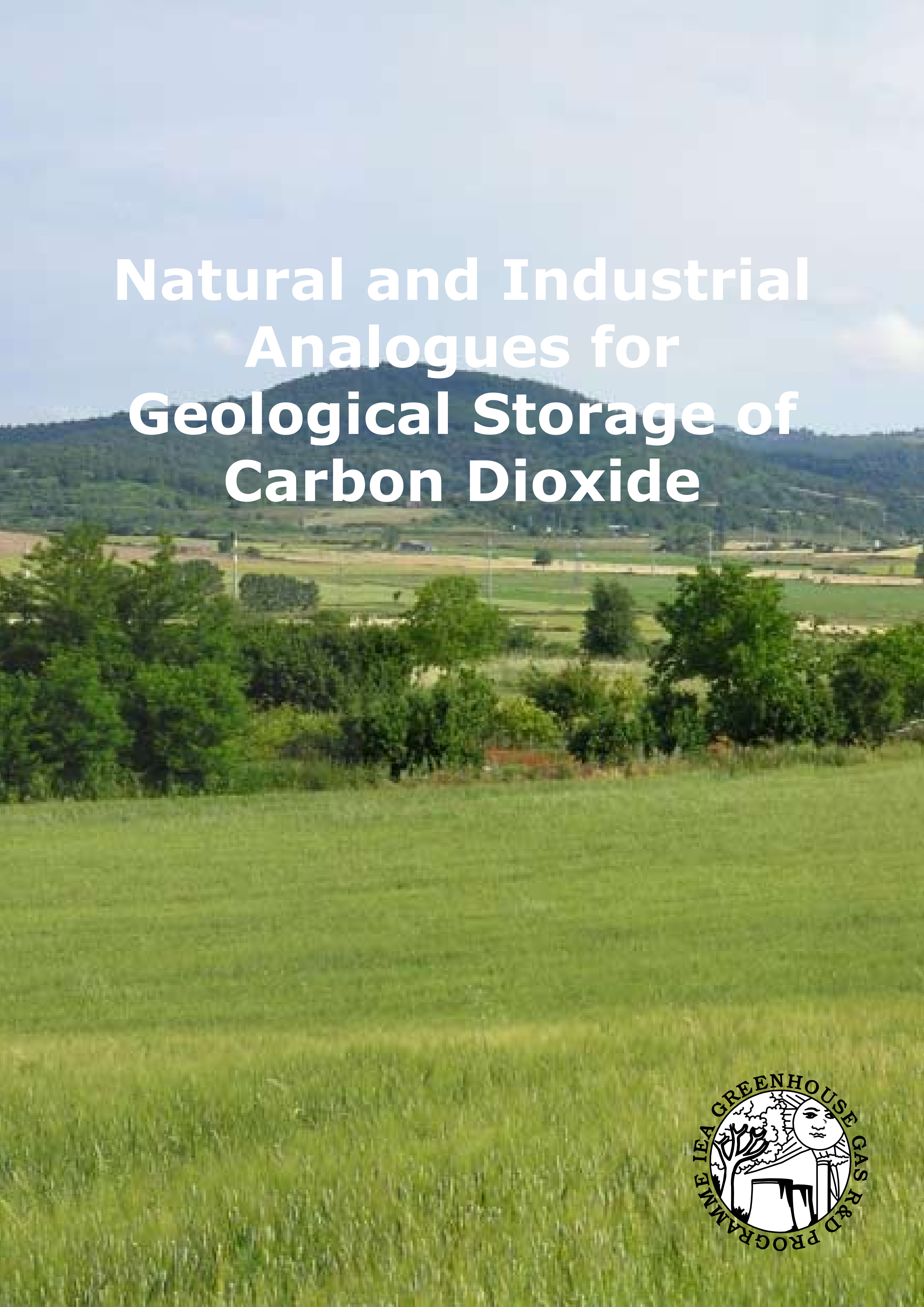

Natural and Industrial Analogues for Geological Storage of Carbon Dioxide

IEA GREENHOUSE GAS R&D PROGRAMME

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Report compiled by Mike Stenhouse, Monitor Scientific

Cover Picture : Cropped image of the Latera analogue site in Italy. Original courtesy of Professor Lombardi, University of Rome.

Contents

Executive Summary

Carbon dioxide capture and storage (CCS) is being actively pursued by many countries as one of the key options for reducing atmospheric carbon dioxide (CO_2) emissions. The geological storage component involves injecting large volumes of CO_2 into the pore space of target formations, typically more than 800 m below the surface.

Sedimentary basins are considered suitable targets for storing large volumes of CO_2, having characteristics that favour effective storage over hundreds of thousands to millions of years (geological time periods), as demonstrated by the widespread existence of natural CO_2 accumulations as well as hydrocarbons trapped in reservoirs.

It is important that regulators, the scientific community, and the general public become confident that geological CO_2 storage can be safe and secure. In this respect, evidence in the form of natural and industrial analogues can be used to show that geological storage of CO_2 can be carried out effectively and safely. As used here, analogues are examples or case studies that enable us to identify what features are effective for CO_2 storage and what features should be avoided. By studying such analogues, we can improve our understanding of both the technical concept and its application - in this case, large-scale geological CO_2 storage involving millions of tonnes of CO_2. Based on these analogue studies, a number of conclusions can be made concerning CO_2 storage.

The report addresses the topic by discussing the following subjects:

- Can CO_2 be stored successfully deep underground?
- Where can CO_2 be stored deep underground?
- Can the injected CO_2 remain underground?
- Can CO_2 in underground storage sites leak to the surface?
- Can CO_2 affect the rocks/minerals it is in contact with?
- Is geological CO_2 storage safe?

Introduction

What is geological storage of CO_2?

Carbon dioxide capture and storage (CCS) is being actively pursued by many countries as one of the key options for reducing atmospheric carbon dioxide (CO_2) emissions. The overall technology involves firstly an industrial process that separates and captures CO_2 (from other emissions) before it is released to the atmosphere. Geological CO_2 storage involves injecting large volumes of the captured CO_2 into the pore space[1] of rock formations typically more than 800 m below the earth's surface (see Figure 1). At such depths, the CO_2 is denser than a gas and occupies less pore space for the same amount (mass) of CO_2.

As shown in Figure 1, the three main types of target formation being considered for CO_2 storage are depleted oil and gas fields, deep saline formations, and unminable coal seams. The last option, unminable coal seams, involves a different storage mechanism and is outside the scope of this report.

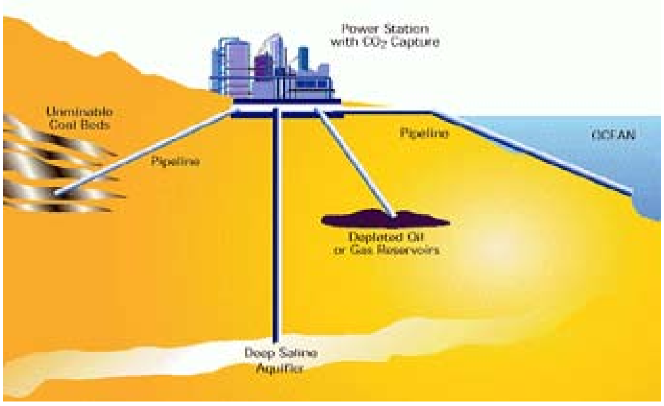

Figure 1: Schematic diagram of the main options for geological storage of CO_2 (IEA GHG): depleted oil or gas fields, deep saline aquifers, and unminable coal beds.

This brief report seeks to present some of the important insights that can be gained from studying natural and industrial analogues, and how such insights can be used to answer a number of key questions concerning geological CO_2 storage:

- Can CO_2 be stored successfully deep underground?
- Where can CO_2 be stored deep underground?
- Can the injected CO_2 remain underground?
- Can CO_2 in underground storage sites leak to the surface?
- Can CO_2 affect the rocks/minerals it is in contact with?
- Is geological CO_2 storage safe?

Appendix 1 contains summary information on projects involving geological storage of CO_2; both existing or planned (operational within the next few years) projects, some pilot studies, and large-scale projects involving the injection of at least 1 million tonnes CO_2 per year (Mt/year). The information includes, where available, the physical nature of the target formation(s), depth of injection, and basic geological setting as well as the estimated volumes of CO_2 to be injected/stored. As Appendix 1 indicates, there are numerous ongoing or planned geological CO_2 storage projects worldwide. Figure 2 illustrates the distribution of these projects. This also includes the many enhanced oil recovery (EOR) and enhanced coal-bed methane recovery (ECBM) projects taking place throughout the world as well as numerous injections of acid gas (CO_2+hydrogen sulphide gas) being carried out in Canada, principally in the Alberta province.

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[1] Rocks contain solid grains and pores, the spaces between grains, which do not contain solid material. Such pore space typically contains fluid (water, gas or oil in the case of hydrocarbon reservoirs).

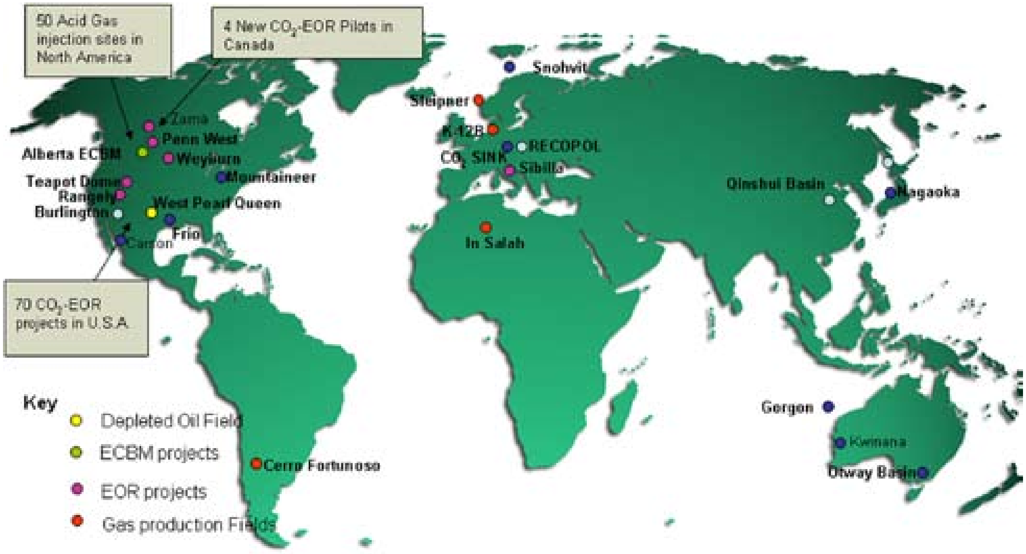


Figure 2: Some CO_2 storage projects throughout the world – actual and proposed (IEA GHG).

What is an analogue?

In general, analogues are examples that demonstrate one or more key aspects of some concept or technology that is being developed. By studying such analogues, we can improve our understanding of both the technical concept and its application - in this case, large-scale geological CO_2 storage involving one or more Mt of CO_2. In the context of this report, analogues are defined as examples or case studies that enable us to identify what features are effective for CO_2 storage and what features should be avoided. Rarely does an analogue provide insights into all aspects of a technology, but for good analogues, useful and relevant information can always be extracted. In the next few pages, natural and industrial analogues are discussed together with the important insights they provide.

Natural Analogues

Two main types of CO_2 occurrence are found in nature:

- Accumulations that have remained in place for thousands to millions of years with no evidence of leakage; and
- Accumulations that have leaked over time.

The former provides a good natural analogue for geological CO_2 storage, with isolation features that are directly relevant to storage, whereas the latter clearly does not demonstrate effective storage of CO_2. However, some examples of natural CO_2 leakage do provide valuable input regarding the types of geology that are unsuitable for storage reservoirs, and for this reason, they are included in the discussion below.

Natural accumulations of CO_2 with no evidence of leakage

Natural CO_2-rich gas reservoirs exist throughout the world and studies have been carried out to characterise many of these natural occurrences with a view to identifying their favourable features. Appendix 2 contains a summary of key information concerning the most studied examples of natural occurrences of CO_2, while Figure 3 gives a more detailed indication of natural CO_2 accumulations worldwide (CO_2 content at least 5%). The storage reservoirs in which the CO_2 accumulations are found are typically a porous rock such as sandstone, which has sufficient pore space to store significant volumes of CO_2 (Figure 4).

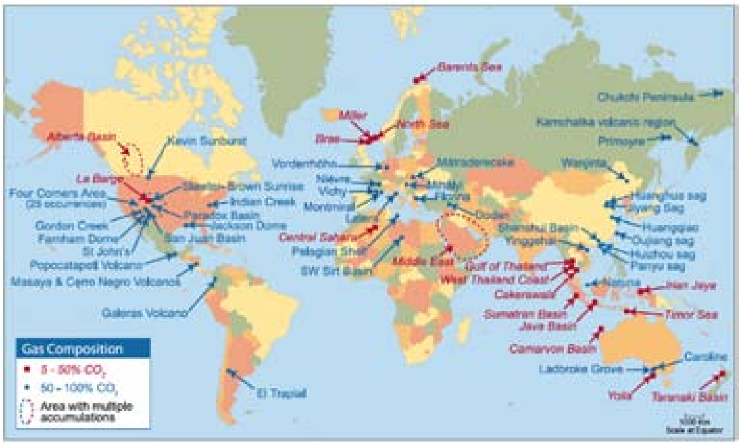


Figure 3: Natural CO_2 accumulations worldwide (IPCC, 2005).

The map gives an indication of the worldwide distribution of subsurface sites with gas compositions containing CO_2. The CO_2 content ranges from 50-100% in blue sites and from 5-50% in red sites. Note that not all of the sites are necessarily 100% tight, i.e. leak free, as discussed in the text.

Figure 4: Highly porous sandstone, typical of rock that would be suitable for containing CO_2 (IEA GHG).

As Appendix 2 indicates, other types of rock formation besides sandstone provide natural CO_2 reservoirs, in particular dolomite, a type of magnesium-rich carbonate.

The source of the CO_2 in the natural reservoirs listed in Appendix 2, while not always conclusively identified, is often a deep source, i.e., generated from below the earth's crust. This is true, for example, in the case of the natural CO_2 accumulations found in the Colorado Plateau and Rocky Mountain region of the USA (Figure 5). In such cases, as disruptive geological processes occur over time, the CO_2 has been able to migrate upwards through preferential pathways (faults or fracture zones) until it encounters one or more formations that prevent upward migration, resulting in the CO_2 accumulating in the porous rock below this physical barrier.

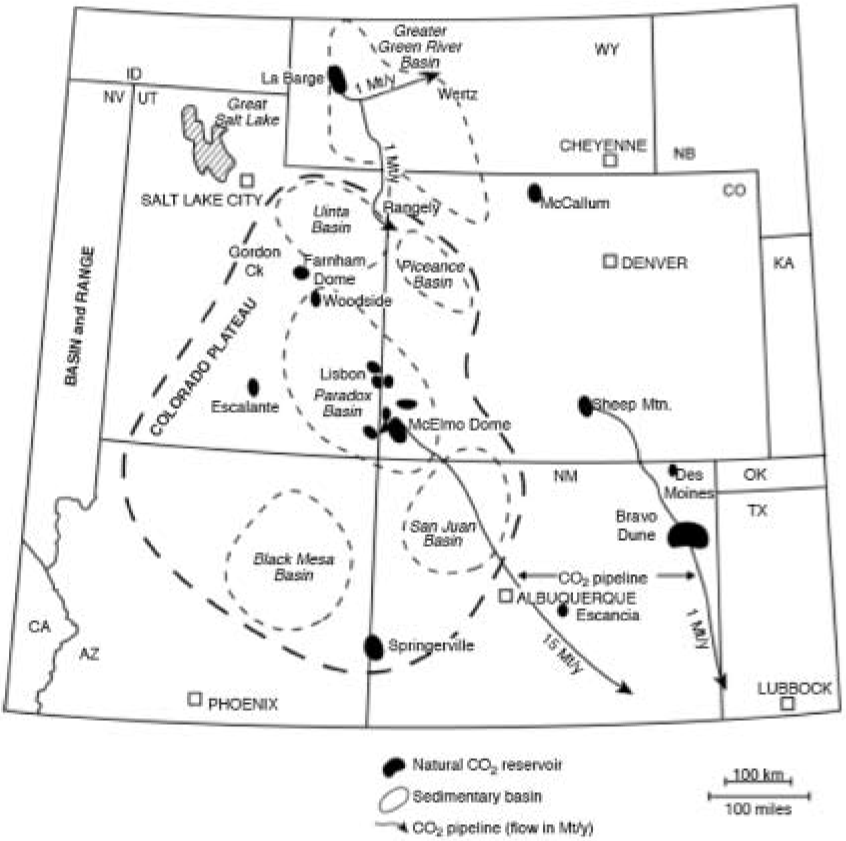


Figure 5: Natural CO_2 reservoirs in the Colorado Plateau region, western USA (from Haszeldine et al., 2004).

In addition to a porous rock as a storage reservoir, a common feature that storage projects and natural analogues have is the presence of a sealing system; a low-permeability formation extending over the top, and often the sides, of a reservoir. Such physical trapping is shown schematically in Figure 6; all of the types of physical trapping can be found in Appendix 2. The overlying seal or cap rock can range in thickness from a few metres to several hundred metres, and prevents the CO_2 from moving upwards out of the reservoir, or at least ensures that the rate of migration through the seal takes thousands of years. Figure 7 shows specific examples of such barriers for natural CO_2 accumulations.

In the case of geological CO_2 storage projects, CO_2 is injected initially into the pore space of a target reservoir, displacing the fluid(s) present and forming a CO_2-rich plume. The injected CO_2 is buoyant relative to the in-place fluids, i.e., has a tendency to migrate upwards. Thus, if able to do so, the CO_2 will migrate vertically out of the reservoir towards the surface. However, as illustrated by the natural analogue studies and the geological settings in which natural CO_2 accumulations are found, physical trapping keeps the CO_2 in place initially. Figure 8 shows two examples for geological CO_2 storage projects, for comparison with Figure 7. Thereafter, CO_2 can dissolve slowly in the reservoir formation water, at the surface of contact between the CO_2 phase and the pore waters (gas-water contact), becoming less buoyant.

In some examples of natural CO_2 accumulations shown in Appendix 2, the CO_2 is dissolved in the formation waters, which is known as solubility trapping. The CO_2 occurrences in the Southeast Basin of France demonstrate CO_2 dissolution, or solubility trapping. Many of the carbonated springs in the Montmiral area are the sources of sparkling mineral water produced by the industry (Pearce et al., 2004). This mechanism is also available for geological storage projects, particularly for deep saline aquifers.

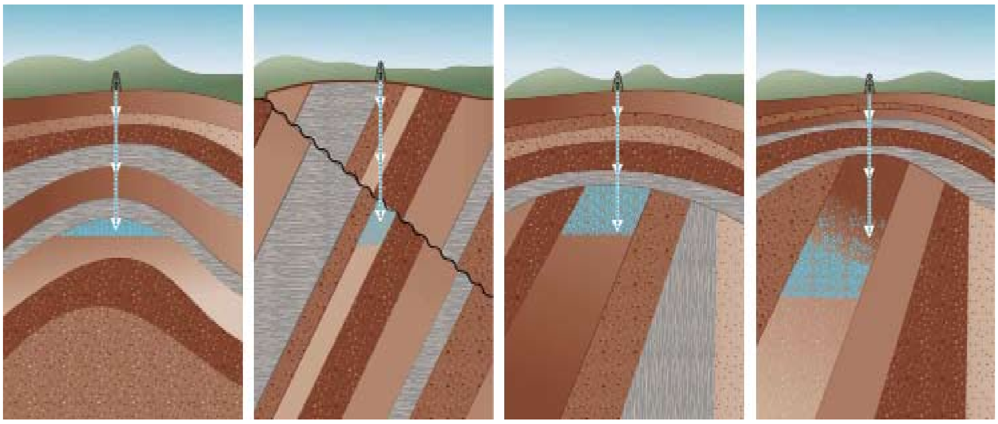


Figure 6: Different types of physical trapping (diagram courtesy of CO2CRC) - from left-hand side: structural (anticline); structural (fault); stratigraphic (unconformity); stratigraphic (change in type of rock, or a particular formation thinning out).

Another type of trapping can occur, hydrodynamic trapping, whereby there is no physical barrier (closed trap) preventing movement, allowing fluids (e.g., CO_2 and water) to migrate, but slowly and over long distances. For regional-scale systems, the cap rock may extend laterally for hundreds of kilometres and this, combined with slowly-moving formation waters, means that the CO_2, either as a separate phase (plume) or dissolved, will remain trapped for hundreds of thousands to millions of years (IPCC, 2005).

Dissolved CO_2 can also react chemically with the rock-water system(s) and can lead to the precipitation of certain minerals, which corresponds to mineral trapping. This mechanism is the most favourable form of trapping, but is believed to be a slow process, requiring hundreds to thousands of years.

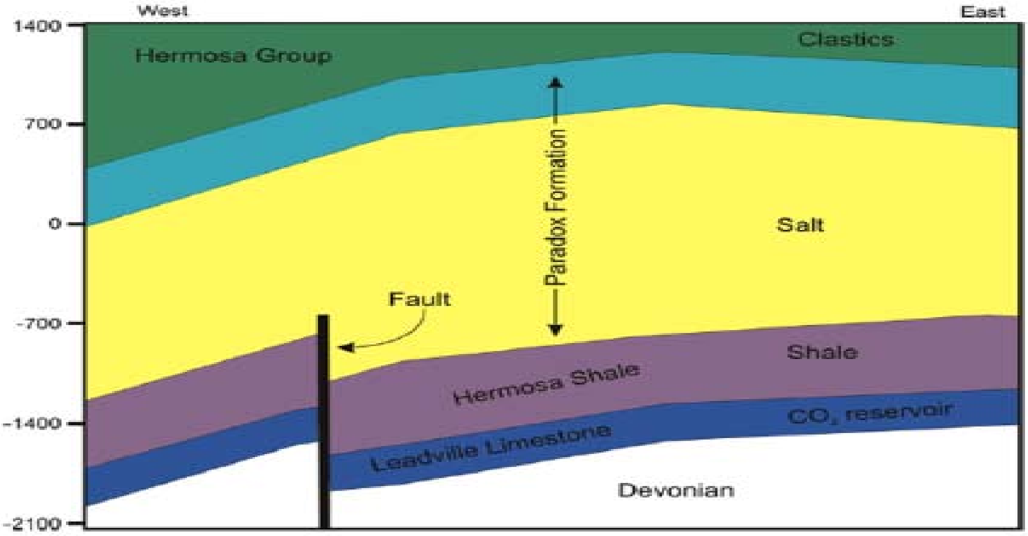


Figure 7: Examples of traps for natural accumulations. Left: simplified cross-section through McElmo Dome field, fault trap (Holloway et al., 2005); Right: cross section of the Mihályi-Répcelak area in Hungary, which hosts commercially producible quantities of CO_2 at depths between ~1,460-1,600 m. CO_2 gas, shown by the black and white shading, is trapped within a classic anticlinal structure and sealed by overlying silty clays and clay marl (BRGM).

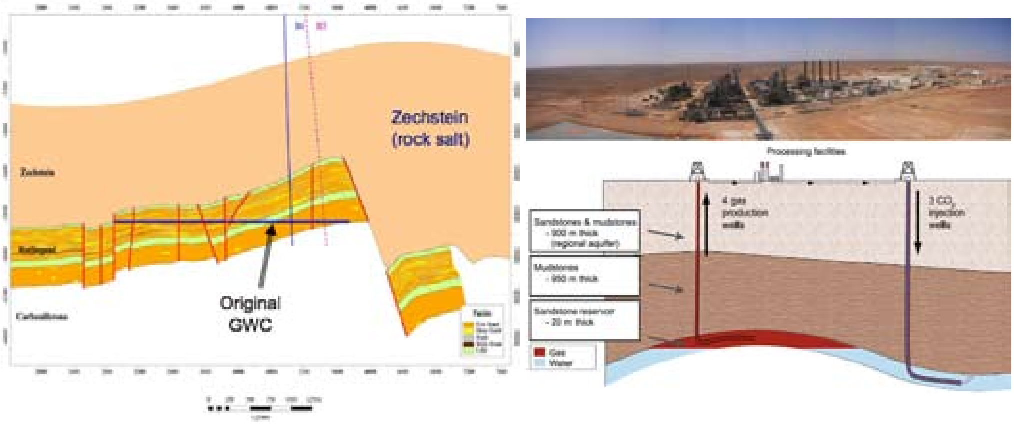


Figure 8: Examples of traps for geological CO_2 storage projects. Left: trap created by fault, K12-B project (van der Meer et al., 2006; GWC=gas-water contact); Right: structural trap (anticline), In Salah, Algeria (IPCC, 2005).

Not all trapping mechanisms are readily demonstrated in the field, in particular residual gas saturation, a potentially important storage mechanism, whereby during injection, a certain fraction of the CO_2 is forced into pores with narrow openings or 'throats'. Once injection has taken place and the pressure subsides, the CO_2 is unable to escape from these pores.

Where can injection and storage of CO_2 be carried out?

Figure 1 indicates schematically the three main options for geological CO_2 storage. Sedimentary basins, in which are found oil and gas reservoirs and saline aquifers, are considered the most suitable general target areas for storing large volumes of CO_2, having characteristics that favour CO_2 storage, in particular large (basinal) areas/volumes that have been stable over hundreds of thousands to millions of years (geological time), as demonstrated by the widespread existence of CO_2 accumulations and hydrocarbons trapped in reservoirs in such settings. Figure 9 gives an indication of the worldwide distribution of sedimentary basins that are potentially suitable for geological CO_2 storage. However, actual sites must be characterised in detail before being considered as candidates for storage.

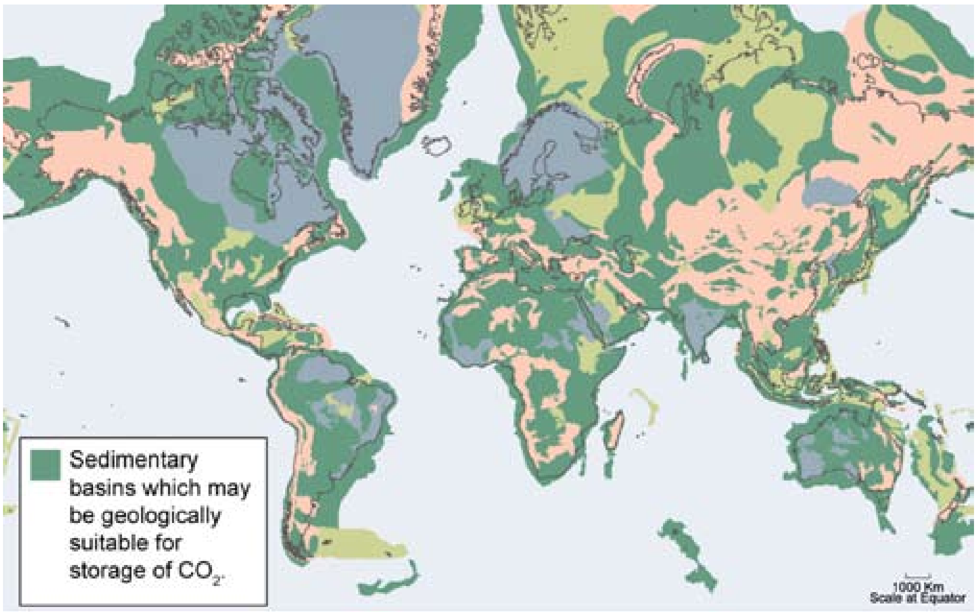


Figure 9: Worldwide regions that may be suitable for geological CO_2 storage (courtesy of IPCC; reported in IPCC 2005, after Bradshaw and Dance, 2004). Areas in brown are potentially the most suitable regions.

What can natural occurrences of CO_2 where leakage has occurred tell us?

While there are many examples worldwide of CO_2-rich gas being stored successfully in natural reservoirs for millions of years, there are also examples of sites where significant volumes of CO_2 have leaked in the past, or continue to leak, from deep underground. Appendix 3 contains a summary of the key information associated with natural occurrences of CO_2 where leakage is evident, including the few examples where CO_2 leakage has resulted in deaths to animals and humans.

As discussed previously, unlike natural accumulations of CO_2 that have been stored effectively underground without evidence of leakage, examples of leaking CO_2 are not valid analogues for geological CO_2 storage. Rather, the examples illustrate specific characteristics that should be avoided when considering specific sites for geological CO_2 storage. The most obvious feature that is common to many of the natural examples of leaking CO_2 is a relatively unstable geological environment, in particular a volcanically active zone. Thus, in developing criteria for assessing the suitability of sedimentary basins for geological CO_2 storage, Bachu (2003) identifies tectonic stability as the first criterion.

Besides volcanic activity, the presence of faults or highly-fractured zones that allow the CO_2 to migrate upwards to the surface, is apparent in most of the examples (for example, see Figure 10), such environments also being prevalent in volcanically active areas.

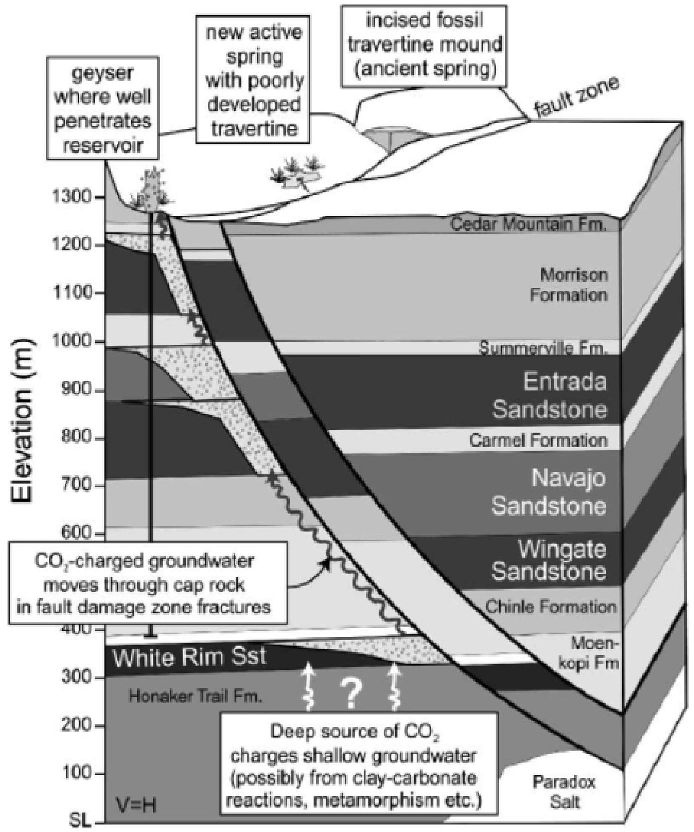


Figure 10: CO_2 leakage at Crystal Geyser, Utah, USA (Holloway et al., 2005); fracture and damaged zones around faults provide conduits for CO_2 leakage.

In many cases, the leakage of CO_2 to the surface does not constitute a problem, especially in areas with low population (for example, see Figure 11).

Figure 11: Children enjoying an eruption at Crystal Geyser. CO_2-charged water escapes from an abandoned well that penetrates a natural CO_2 reservoir. The geyser, the largest cold geyser in the world, was unintentionally created in 1936 when a prospective oil well was drilled about 800m deep into a fault zone above a natural CO_2 reservoir. Discharge occurs every 4-24 hours due to CO_2 charging. If necessary, this discharge could be prevented by sealing and capping the well. (Photo courtesy of Frank Gouveia, Lawrence Livermore National Laboratory.)

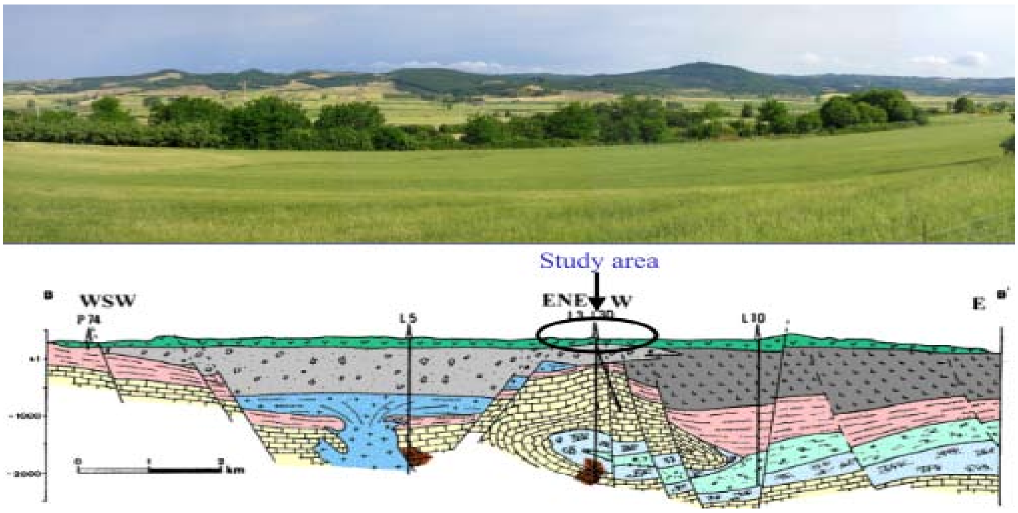
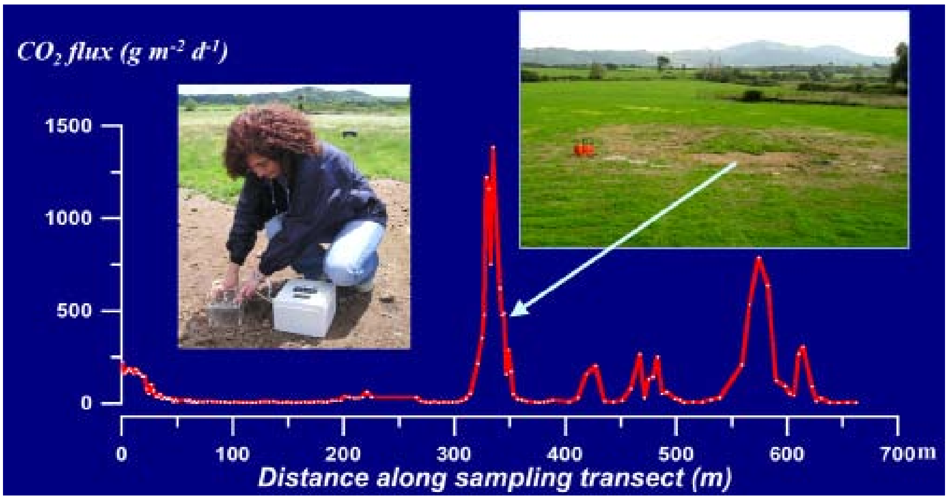


Figure 12: Upper: Latera caldera, an area of ~ 50 km², about 150 km NW of Rome. Gas seeps occur throughout the heavily cultivated valley, where people live and farming is practised. Lower: cross section of the geology of the caldera area showing extensive faulting (thin black lines), with a thin, fractured and faulted cover (cap rock, green shading). (Both diagrams courtesy of Professor Lombardi, University of Rome).

Another way in which natural CO_2 occurrences that leak can contribute useful information is by studying the nature of the leakage and associated environmental impacts. Figure 11 shows the leakage to surface of CO_2-charged water, but confined to a wellbore, i.e. highly localised. Other studies have indicated similar findings. For example, within a geothermally-active region of central Italy, the highly-faulted Latera caldera is a leaking natural site that has been studied in detail for decades (see Figure 12). The CO_2 is constantly being produced deep underground (> 2,000 m), but not all CO_2 leaks to the surface.



Soil gas measurements indicate that CO_2 leakage only occurs from highly-localised gas vents that coincide with one or more faults. Importantly, the faults do not allow flow along their entire length, with gas migration possible only along discrete sections of faults that are able to permit flow. As a result, CO_2 migration through these gas vents generates small areas of leakage at the surface (Figure 13) (Annunziatellis et al., 2008). Soil gas measurements indicate that the area with CO_2 in soil air (measured at a depth of 80 cm) above 20% by volume is relatively small ~ 0.01 km^2 or 0.02 % of the total area (Beaubien et al., 2008). As shown in Figure 13, the impacts of leaks, primarily on vegetation around the gas vent, are restricted to a small area around the vent.

Figure 13: Soil gas measurements around a gas vent at the Latera caldera area, central Italy. Measurements indicate discrete, small zones of leakage to the surface, through gas vents. The bare ground, where grass is absent, is confined to a small area, ~ 6 m in diameter around the gas vent responsible for the highest peak above, reflecting localised impacts (reported in Beaubien et al., 2008; photograph courtesy of Professor Lombardi, University of Rome).

Geochemical interactions involving CO_2-rock-water systems

When CO_2 is injected into the pore space of a reservoir, the CO_2 in contact with the formation waters can dissolve leading to a water that is weakly acidic, but one that may be reactive depending on the other constituents of the pore waters as well as the contacting rock minerals. Different minerals react differently with carbonic acid, the acid formed when CO_2 dissolves in water.

Geochemical reactions involving CO_2-rock-water systems can be beneficial or not, depending on the nature of the reactions. For example, some minerals can dissolve, resulting in greater pore volume, i.e. the porosity increases (secondary porosity). On the other hand, CO_2-rock-water interactions can also lead to the precipitation of minerals and a resultant decrease in the available porosity, with the potential for reduced migration. Importantly, if the mineral that precipitates contains the carbon from dissolved CO_2, this type of interaction (mineral trapping) can enhance the isolation capabilities of the formation into which the CO_2 is injected.

Studies of areas where natural accumulations of CO_2 exist, including CO_2 leakage, have provided evidence of both types of CO_2-rock-water interactions. For example, a relatively recent natural analogue study involved two CO_2–natural gas accumulations in the western Otway Basin, southeastern South Australia, located ~1 km apart, at the same depth and within the same sandstone formation. The gas in the two gas fields, Katnook and Ladbroke Grove differs widely in CO_2 content (<1% and up to 54% by mass, respectively; Watson et al., 2001), primarily because only the latter field had access to the volcanic source of CO_2, about 1 Ma ago. A detailed mineral comparison of the two sites as well as analysis of formation waters was able to identify the major geochemical changes that had taken place in the case of the CO_2-rich waters of the Ladbroke Grove, including minerals that had dissolved (calcium carbonate) as well as some that had precipitated (clay mineral and iron-rich carbonates). Overall, the porosity of the Ladbroke Grove formation increased.

In another example, at the Latera caldera structure in central Italy, a mature fault indicates the effects of CO_2-rock-water interactions that have taken place over a long period of time, resulting in a clay-rich impermeable fault core. Figure 14 shows the clay-rich, impermeable fault core (coloured zone) surrounded by highly permeable lateral damage zones.


[redacted]

Figure 14: Photograph of a mature fault within the Latera caldera structure (courtesy Professor Lombardi, University of Rome). The coloured zone is the fault itself, now comprising a clay-rich impermeable zone as a result of CO_2-rock-water interactions.

Geochemical modelling can be used to predict the geochemical interactions that can occur as a result of CO_2 injection into specific sites, although establishing how quickly the reactions take place is often a challenge. The above Otway Basin study provided insights into reaction rates involving CO_2 and potential changes to the sealing integrity of the overlying formations induced by CO_2-brine-rock interactions. For geological CO_2 storage, it is important to know what reactions might occur in both the reservoir and cap rock, and geochemical studies of natural analogues continue to provide valuable data in this regard.

Industrial Analogues

Two main types of industrial analogue can be used to build confidence in the effectiveness and safety of geological CO_2 storage projects.

- Enhanced oil recovery projects; and
- Natural gas storage.

Enhanced Oil Recovery Projects

As discussed above, EOR projects involve the injection of CO_2 into depleted oil reservoirs in order to increase the mobility of residual oil in place and promote additional hydrocarbon production (Figure 15). Such projects have been carried out effectively and safely for many decades and provide testament to the fact that the infrastructure and specific technology for CO_2 injection is well understood, tried and tested. As part of this technology, the special demands placed on wellbores, in terms of stainless steel casing to accommodate CO_2 injection, are recognised.

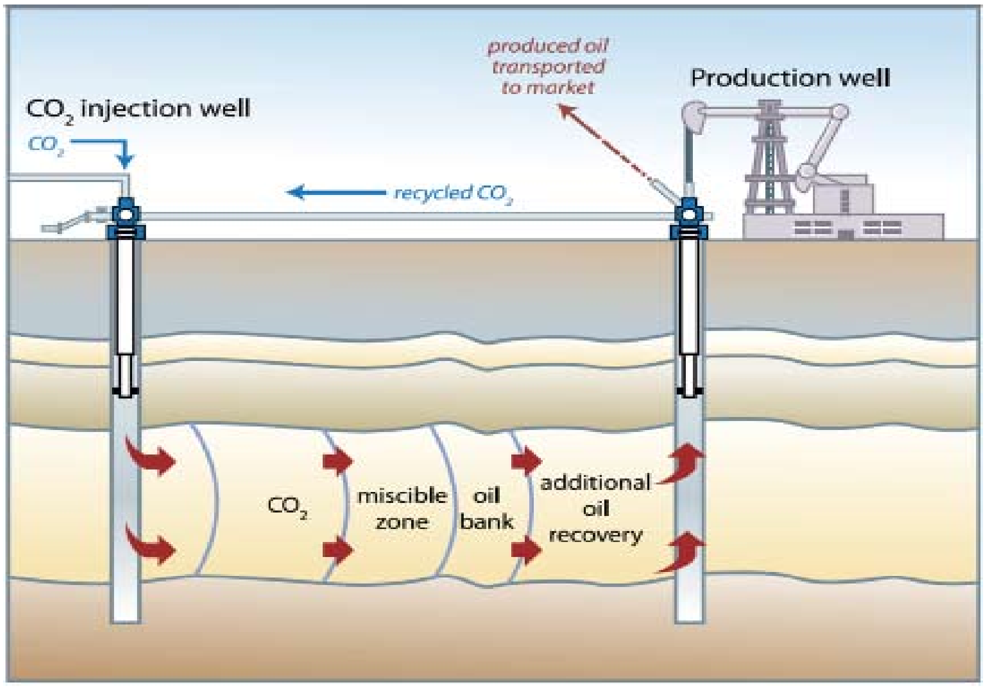


Figure 15: Schematic diagram of EOR operation (diagram courtesy of CO2CRC).

A number of EOR projects are currently being used to demonstrate a CO_2 storage aspect. In particular, Phase 1 of the IEA GHG Weyburn CO_2 Monitoring and Storage Project (Figure 16) has provided a wealth of data to characterise the effects of CO_2 injected into the oil (storage) reservoir. Based on the demonstrated successful outcomes to such projects, depleted oilfields are considered as one of the three main types of storage reservoir, although the contribution to overall storage from this option is relatively small.

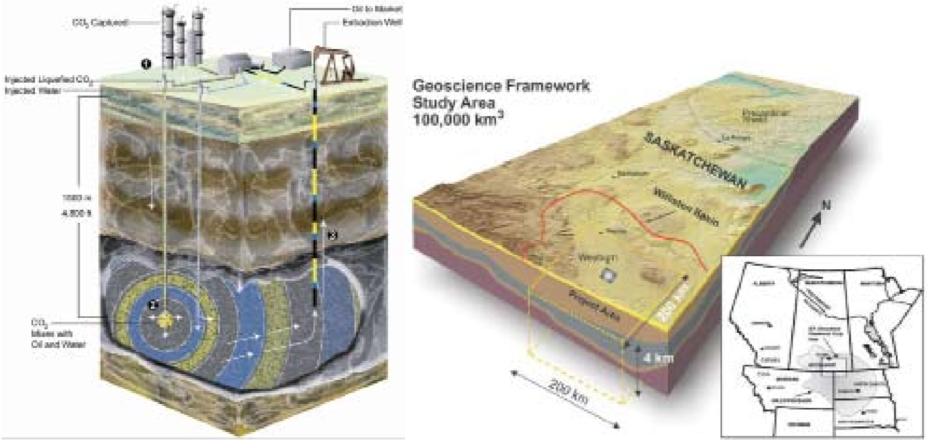


Figure 16: IEA GHG CO_2 Monitoring and Storage Project, Weyburn, Saskatchewan, Canada: EOR+CO_2 storage (courtesy Petroleum Technology Research Centre, Canada).

Natural gas storage

Natural gas, a potentially more dangerous gas than CO_2 owing to its flammability, has been stored successfully underground for decades and numerous natural gas storage sites exist throughout the world. Figure 17 gives an indication of the existing facilities throughout Europe and the USA, primarily depleted oil and gas fields (~87%), but also aquifer storage (~13%).

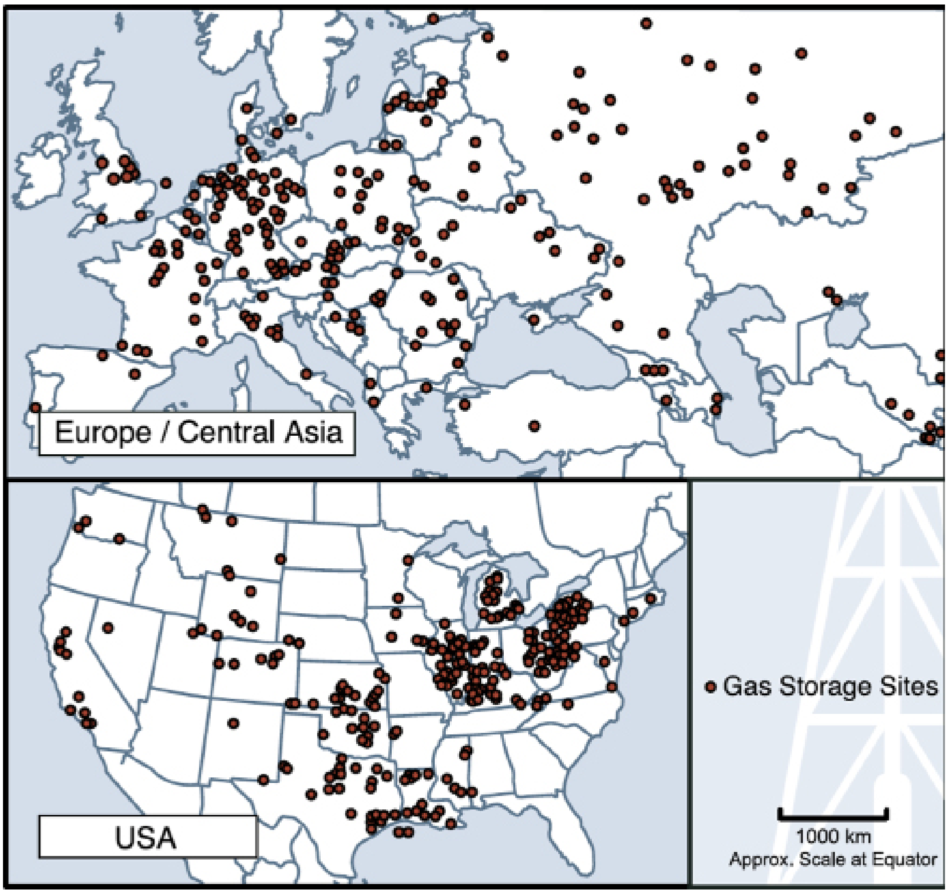


Figure 17: Natural gas storage in Europe and USA (diagram courtesy of CO2CRC).

Studies of underground natural gas storage in the USA and Europe, together with the broad experience from this industry, highlight several relevant observations (Benson et al., 2005; Perry, 2005):

- The industrial record for the natural gas storage industry is good. Supporting data indicate that leakage frequencies have been low over an operating period of about 90 years; ~10 in over 600 storage reservoirs in North America and Europe were identified as having leaked. Of these, only four were due to geological rather than human issues.
- Careful control of injection pressure and final reservoir pressure based on geo-mechanical characterisation is necessary to avoid damage to the cap rock. (Similar precautions are taken for EOR projects).
- Careful characterisation and selection of storage sites is essential. In particular, the need for an adequately thick cap rock, ideally with a secondary cap rock above the primary seal. (Leakage incidents involving aquifer storage were due mainly to leakage through a relatively thin cap rock).

All of the above findings demonstrate the benefits of following sound technical procedures at all stages of a project, i.e. ‘best practice’.

Conclusions

Based on the information presented in the previous pages, a number of conclusions can be drawn concerning geological CO_2 storage. Importantly, the questions posed in the Introduction can be answered:

Can CO_2 be stored successfully deep underground?

Yes. Many natural accumulations of CO_2 exist throughout the world without any evidence of leakage, indicating that storage is both possible and commonplace. Most natural accumulations tend to be associated with trapping features such as a dome or anticline. For example, the combined amount of CO_2 contained in the three major fields in the Colorado Plateau (McElmo, Jackson and St. Johns Domes) in western USA totals 2,400 million tonnes of high-purity CO_2.

Most CO_2 accumulations are found in formations that have an impermeable or low-permeability rock, a so-called cap rock, immediately above. This cap rock serves to prevent, or severely restrict upward migration of CO_2.

Where can CO_2 be stored deep underground?

The widespread distribution of natural CO_2–rich fields within large sedimentary basins in geologically stable regions suggest these regional basins are the most suitable places for storage sites. The locations of the numerous hydrocarbon fields, also in sedimentary basins throughout the world, support this conclusion. Natural CO_2 accumulations have also be found in regions that exhibit some geological instability provided the geological setting is conducive to storage.

By contrast, the presence of natural accumulations of CO_2 in which leakage has occurred has demonstrated certain geological features that should be avoided. The most extreme cases of leakage, especially eruptive emissions, are associated with geologically unstable regions, in particular volcanically active or geothermal areas. Such areas would not be considered suitable for geological CO_2 storage projects.

Leakage of CO_2 is also associated with faults or fracture zones, which can provide pathways for the CO_2 to migrate vertically to the surface. Adequate characterisation of potential sites will identify the presence of such features and their risk of leakage, and, where leakage risk is found, such areas can be avoided.

In terms of specific locations, the most suitable target formations for geological CO_2 storage are depleted oil or gas fields and deep saline formations, where potentially the greatest volume of CO_2 can be stored.

Can the injected CO_2 remain underground?

Yes. A number of mechanisms can act, independently or in sequence, to keep CO_2 underground. The primary physical trapping mechanisms that act initially (after CO_2 injection) are the same as those associated with naturally occurring CO_2 accumulations and hydrocarbon deposits. By analogy to natural CO_2-rich fields, CO_2 can remain underground for many thousands of years.

Additional mechanisms that can act to keep CO_2 underground include solubility trapping, where the CO_2 dissolves in the formation water, leading to chemical changes and the trapping of CO_2 as an electrically-charged species. Ultimately, over time mineral trapping can occur, whereby geochemical interactions involving the CO_2-rock-water system lead to the precipitation of minerals that contain carbon from the CO_2. This type of trapping is the most beneficial for long-term, essentially permanent confinement (sequestration), although it can take thousands of years to occur.

Can CO_2 in underground storage sites leak to the surface?

Studies of natural CO_2 accumulations indicate that many sites provide effective storage, while others do exhibit leakage. Comparison of the geological features of both types helps to identify those features that are likely to lead to leakage and, therefore, to be avoided.

While the key objective of all geological CO_2 storage projects is to avoid leakage, there is a small possibility that some CO_2 can move out of the original storage reservoir, whilst neither desirable nor intended. Lateral migration, whereby CO_2-charged formation water moves horizontally away from the storage reservoir but remains at depth, is unlikely to pose a problem. Vertical leakage to the surface or near-surface environment only becomes a potential problem if the rate of leakage is relatively fast, while some recent studies of naturally leaking sites indicate that the impacts from leakage are highly localised. Again, based on the differences between natural CO_2 accumulations that are intact and those that leak, the geological settings that lead to significant leakage can be avoided.

Can CO_2 affect the rocks/minerals it is in contact with?

Yes. When CO_2 dissolves in formation waters, the resulting weakly-acidic solution can react with other water constituents as well as minerals in contact with the freshly-altered water. Depending on the reactions that subsequently take place between the water and the mineral constituents of the storage reservoir and/or cap rock, dissolution or precipitation of minerals can occur, with possible changes to the pore volume. This can be beneficial or not. However, geochemical knowledge supported by field experience associated with natural accumulations has increased our understanding of what reactions can occur, and, therefore, what minerals are favourable and which are unsuitable. Geochemical characterisation of a proposed storage site can provide the necessary information to avoid unwanted chemical reactions or take advantage of favourable reactions.

Is geological CO_2 storage safe?

Yes it can be, for well selected and managed sites. Natural CO_2 accumulations throughout the world testify to the ability of specific geological settings to provide effective storage of CO_2. Provided sites are adequately characterized, the key geological features for effective and safe storage can be identified. These include a geologically stable setting, porous reservoir, adequate seal in terms of a thick cap rock extending over the entire reservoir and beyond (ideally with one or more secondary seals above the primary seal), lack of faults and fracture zones in the vicinity, and rock minerals that are non-reactive or lead to mineral trapping.

Furthermore, the broad experience of the EOR industry throughout the world demonstrates that the technology and infrastructure already exist for the CO_2 injection component of geological CO_2 storage. In addition, research and development efforts continue to improve the technology, e.g., by identifying materials and techniques that increase the long-term effectiveness of seals and well-plugging materials.

The safety record of the natural gas storage industry, which relies on gas storage in depleted oil and gas fields as well as saline aquifers - two of the three main candidates for geological CO_2 storage - is excellent. Experience from this industry, together with the experience already gained from geological CO_2 storage projects, has identified and developed a set of best practice requirements in terms of adequate characterisation of storage sites, sound operational procedures during the injection phase, and supporting monitoring activities to confirm predictions of storage performance.

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Appendix 1: Compilation of Geological CO_2 Storage Projects

Project	Location	Status	Depth / Basic Gelogical Setting	Seal / Trapping mechanism	Amount of CO_2 / Time Period	Comment / Reference
Sleipner	North Sea; offshore Norway	Ongoing	~1000 m; Utsira sandstone formation (saline aquifer) ~250 m thick (Miocene-Pliocene); ~30 m-thick "packages" of sands separated by thin ~ 1 m shale layers; unconsolidated very fine- to fine-grained sand	Shale cap rock 80 m thick; physical / dissolution trapping	21 Mt total; ~ 1Mt/year; 1996-	CO_2 extracted during natural gas production. // www.statoil.com
Weyburn	Williston Basin, south-eastern Sakatchewan Canada	Ongoing	~1450 m; shallow marine deposits; marine carbomate-evaporite sediments; Midale detrital carbonate; overlying Midale Marly = dolomitic mudstones; Midale Vuggy = limestone; shoal and inter-shoal strata.	Primary seal Midale evaporite cap rock 4-7 m thick; secondary seal thick shale sequence ~200 m thick (Watrous formation); physical / dissolution trapping	21 Mt total; ~ 1Mt/year; 2000-	EOR + CO_2 Storage Wilson and Monea (2004)
In Salah	Sahara, Algeria	Ongoing	>2000 m; carboniferous reservoir ~20 m thick; no significant faults in region	Carboniferous mudstone ~ 950 m thick; physical / dissolution trapping	17 Mt total; 1 Mt/ year; 2004-	CO_2 extracted during natural gas production. Wright (2005)
Frio Brine Pilot	Texas, USA	Injection completed	1500 m; Frio "C" Sandstone; (Fluvial) sandstone, ~24 m thick, steeply dipping layers; relatively homogeneous high permeability sandstone.	Numerous thick shales; small fault block;	4 kT / 2004-2008	Test project Hovorka (2008)
Test project Hovorka (2008)	South-west Victoria, Australia	Ongoing	2100 m; series of thick layers of sandstone	Mudstone cap rock	100 kT / 2008-	Pilot project. CO_2 extracted from natural gas and re-injected.
Minami-Nagaoka Gas Field	Nagaoka, Japan	Injection completed	~1110 m; sandstone reservoir (Haizume Formation, Pleistocene), ~ 60 m thick.	Closed anticlinal structure; mudstone seal ~160 m thick; structural trap	10 kT / 2002-2006 (Injection 2003-2005)	Test project. Mid-Niigata Chuetsu Earthquake occurred during injection phase (October 2004), but no impact on stored CO_2 (Tanase et al., 2008)
K-12B Gas Field	Offshore (North Sea), Northwest of Amsterdam, Netherlands	Ongoing	3500-4000 m; field within number of (independent) tilted fault blocks; Rotliegend clastics; depleted gas field; Upper Slochteren Member; highly heterogeneous reservoir; aeolian and fluvial sandstones interspersed with shale; quartz- and halite/anhydrite-cemented faults; none of reservoir faults reaches top of seal.	Anhydrite/halite/shale seals >200 m thick; evaporite seal; primarily halite; structural trap	Small-scale test (Phase 2) of 0.2 Mt/year followed by Phase 3 (large-scale) 0.3-0.5 Mt/ year, 8 Mt total; 2004-	CO_2 separated from natural gas and re-injected into same gas field. Data shared with CATO, CASTOR and CO2GeoNet programmes (Geel et al., 2006)
Teapot Dome, EOR Pilot	Wyoming, USA	Under study	Several potential formations; siliciclastic (conglomerate, sandstone, breccia) and carbonate reservoirs. Tensleep Sandstone most promising – thick Aeolian sandstone > 30 m thick, > 1600 m depth.	Shale, carbonate and anhydrite cap rocks; anticline above thrust fault	1.6 Mt/year	Test project. // www.co2capture-andstorage.info
Gorgon Project (Barrow Island)	Northwest coast, Western Australia; under Barrow Island	10 Mt/year approved; Upgrade to 15 Mt/year under environmental review	2300 m; Jurassic Dupuy Formation sandstone ~500 m thick	Open anticline; Basal Barrow Group shale, with additional seals above	15 Mt/year; 1.4-2.6 trillion cu.ft.	CO_2 to be separated from natural gas production. // www.gorgon.com.au

Project	Location	Status	Depth / Basic Gelogical Setting	Seal / Trapping mechanism	Amount of CO_2 / Time Period	Comment / Reference
Ketzin	Germany		600-800 m; saline aquifer; siltstone / sandstone interbedded with mudstone; target formation ~80 m thick with sand channels up to 20 m; some faults in the area but > 250 m away	Gypsum and clay seals; anticlinal structure;	0.03 Mt/year over 2 years; 2008-	Pilot project under CO2-SINK. Site of former natural gas storage at depths of ~250 m and 400 m. //www.co2sink.org
Snohvit Gas Field	Barents Sea, offshore Norway	Injection started April 2008; ongoing	2600 m; sandstone aquifer; Tubasen Sandstone Formation 45-75 m thick	Shale cap rock	0.7 Mt/year; 2008-	CO_2 separated from natural gas production. //www.statoil.com/snohvit
Atzbach-Schwanenstadt Gas Field	Rohoel, Austria		Nearly depleted oilfield in clastics; reservoir interval in Upper Puchkirchen Formation; relatively shallow depth; 1600 m; sandstone; gas zone thickness 30-50 m		Source ~0.2-0.3 Mt/year; 2010-; storage capacity ~14.5Mt 3.5 Mt (Rossi)	Project part of CASTOR programme, Polak and (2008), Polak et al., (2008); Grimstad (2006); Rossi et al. (2007)
RECOPOL Project	Katowice, Poland	Original pilot project completed	900-1250 m, Upper Silesian Coal Basin coal seams 1-3 m thick; Carboniferous. Fault block bounded by two major normal fault; faults pre-Miocene. Carboniferous deposits >1000 m thick, alternating layers of sandstone, clay and coal.	Coal seams disconcordantly covered by Miocene shales; sealing capacity proven by pockets of natural gas	0.8 Mt injected 2004-2005	Possible test study site within CASTOR programme; ECBM. van Bergen et al. (2003); also //recopol.nitg.tno.nl
Casablanca Oilfield (depleted)	Offshore, Mediterranean Sea, Repsol, Spain		2500 m; carbonate reservoir; karstified limestone; complex structure	Marly-shaly formations; "three way dip faulted closures below unconformity combination trap types, related to tilted fault blocks and horst-like features"	0.5 Mt/year	Project part of CASTOR programme; one component of study is to evaluate geochemical reactions //www.co2castor.com

Project	Location	Status	Depth / Basic Gelogical Setting	Seal / Trapping mechanism	Amount of CO_2 / Time Period	Comment / Reference
Big Sky	USA, DOE Regional Carbon Sequestration Partnership Program Validation Phase (2005-2009) involved injection of ~1-5 kt CO_2 into test sites, so not reported here Phase III involves large volume injection, so focus on these.	Phase III under planning	Target for CO_2 injection is deep basalt formation, State of Washington; formations currently under evaluation.		Small-scale test: 3-5 kt	Integrated gasification combined cycle plant + CCS www.netl.gov/publications/factsheets/project/Proj440.pdf
Plains CO_2 Reduction Partnership (PCOR)		Phase III underway; no injection yet	Two large-scale tests: Williston Basin Project, > 3,000 m, carbonate Devonian-Duperoy or Mississippian Madison Group saline formations, oil-bearing; Fort Nelson Project, 2,100 m, deep saline sandstone formation, Alberta Basin, north-eastern British Columbia, Canada,	Hydrocarbon regime; anticline + impermeable cap rock	Up to 1 Mt CO_2/year EOR+Storage 1.8 Mt CO_2 over 6 years (CO_2+H_2S)	//www.netl.gov/publications/factsheets/project/Proj446.pdf Acid gas re-injection. 2.5 Mt CO_2 and 2.0 Mt H_2S has already been re-injected in western Canada
Southwest Partnership; Farnham Dome, Utah		Phase III underway; no injection yet	Several deep (Triassic / Permian – Jurassic and older) Entrada sandstone units / saline formations	Anticline; shale/gypsum/siltstone (Jurassic) cap rock, ~ 130 m thick	0.9 Mt/year; 4 years	CO_2 from nearby CO_2 field or separated from nearby coalbed methane //www.netl.gov/publications/factsheets/project/Proj443.pdf
West Coast Regional Carbon Partnership; (WESTCARB)		Phase III underway; injection planned 2010-	San Joaquin Basin saline formation; 240 m-thick Olcese sandstone 2400 m; 150 m-thick Vedder sandstone 2700 m	Thick shale units	0.25 Mt/year / 4 years; 1 Mt total; 2010-	Kimberlina, Central Valley, California CO_2 from zero-emissions oxy-fuels combustion power plant //www.netl.gov/publications/factsheets/project/Proj444.pdf Surles (2007)
Midwest Geological Sequestration Consortium (MGSC); Decatur, Illinois		Phase III underway; no injection yet	1800-2300 m; Mt. Simon Sandstone saline formation, > 450 m thick	Anticline; regional impermeable shale, > 100 m thick	1 Mt total over 3 years; 2009-	CO_2 from methanol plant used as source; Mt. Simon formation used for natural gas storage in Illinois //www.netl.gov/publications/factsheets/project/Proj441.pdf
Southeast Regional Carbon Sequestration Partnership (SECARB)		Phase III underway; no injection yet	Tuscaloosa Massive Sandstone, two locations; > 3150 m; Lower Tuscaloosa Formation, Cranfield Unit, southern Mississippi.	Hydrocarbon regime	1 Mt/year / EOR field Two injection rates (0.1 / 0.25 Mt/year) for 4 years.	//www.netl.gov/publications/factsheets/project/Proj442.pdf
Midwest Regional Carbon Sequestration Partnership		Phase III underway; no injection yet	1200 m; Mt. Simon sandstone Project 3 (G3), Michigan: 860-980 m; Sylvania Sandstone saline formation		1 Mt over 4 years	CO_2 from ethanol plant. //www.netl.gov/publications/factsheets/project/Proj445.pdf

Appendix 2: Complilation of Natural Occurences of CO_2

Occurence	Location	Source	Depth / Geological Setting	Seal / Trapping Mechanism	Amount of CO_2 / Time	Comment / Reference
Pisgah Anticline, north and east of Jackson Dome	Central Mississippi, USA	Direct mantle degassing, probably associated with Jackson Dome igneous intrusion (Late Cretaceous)	North and east of Jackson Dome igneous intrusion. Jurassic sandstone and dolomite reservoir rocks ~ 4660-4960 m Jurassic Formations Norphlet (~150-365 m thick), Smackover, and Buckner (10-30 m thick)	"Structural closure and permeability barriers" Reservoir rocks folded into anticlines in places; Pisgah Anticline; crestal area ~30 x 8 km. CO2 reservoirs separated by low-permeability rocks (anhydrite, dense carbonate); "impermeable carbonates and evaporates, plus shale more than 30 m thick over Buckner.	215 Mt; ~65 M years ago; produces ~5.5 Mt/year.	Jackson Dome intrusion ~70 Ma ago; no evidence of leakage; Number of smaller CO_2 accumulations nearby. Reservoir pressure ~50% above hydrostatic; overpressuring in Norphlet, indicating effectiveness of carbonate seal. Stevens et al. (2004)
McElmo Dome, southeastern Paradox Basin, Colorado Plateau	Southwest Colorado, USA	Potential sources include thermal decomposition of Leadville Limestone, mantle source. Most likely source degassing of mantle associated with Ute Mountains intrusion.	~2100 m (1800-2600 m); lower Carboniferous carbonate reservoir; dolomitic carbonate; main reservoir is Mississippian Leadville Limestone - sequence of carbonate rocks (inter-bedded limestone and dolomite) 75-90 m thick. Dolomites best reservoir rock (most porous). Colorado Plateau (southwest USA; southern Colorado and Utah) confined on all sides by uplifted structural highs; structurally deformed (folded and faulted); Main reservoir rock is Mississippian (Early Carboniferous) Leadville Limestone (Figs. 11&12).	Combination structural-stratigraphic trap; Hermosa shale, ~60 m thick + Paradox salt cap rock; upper Carboniferous salt (halite) cap rock ~400 m thick. Any faulting in the area does not penetrate the cap rock.	1600 Mt in place; provides ~15 Mt/year; cumulative production 190 Mt (2001)	Additional occurrences in Colorado Plateau region. Faults in southern portion of field do not appear to be sealing within Leadville reservoir. Stevens et al. (2004)
Bravo Dome	North-eastern New Mexico, USA	Mantle (magmatic) origin	580-900 m; main reservoir (Permian Tubb sandstone) 600-700 m; fine to medium-grained sandstone, up to ~ 150 m thick	Structural-stratigraphic trap; anhydrite seal up to 30 m thick + structural dip to S and E and loss of reservoir thickness and permeability to N and W	10 Tcf	Dome covers area of >3500 km2 Cassidy and Ballentine (2004) Stevens et al. (2004)
Sheep Mountain	Colorado, USA		1000-1800 m; Cretaceous Dakota and Jurassic Entrada Sandstones	Complex geological structure; numerous folds and faults	~110 Mt	Relatively small CO_2 field. //www.kindermorgan.com
Farnham Dome	Utah, USA		600-800 m; Jurassic Navajo sandstone	Anticline	No longer being exploited	Migration into trap 10-60 Ma ago. Site of Southwest Partnership Phase III injection. Morgan et al. (2005).
St. Johns Dome, southern edge of Colorado Plateau	Arizona / New Mexico, USA	Mantle origin of CO_2; direct migration upwards.	Large asymmetric dome; CO_2-reservoirs within Permian Supai Formation 200-700 m, ~500 m thck; main reservoir (~ 500 m) are siltstone and fine-grained sandstone.	Evaporitic anhydrite and gypsum layers within Supai Formation, ~ 250-1000 m; permeability < 0.01-0.02 mD	Estimated 730 Mt	Extensive karst features (dissolution features such as sinkholes / caves) noted in other areas of Colorado Plateau but limited in St. Johns Dome area. (Stevens et al. (2004)
Dodan, offshore Abu Dhabi	Turkey		1500 m; carbonate reservoir		27 Mt; ~ 1.2 Mt/year produced	Limited information.

Appendix 3: Summary of Natural Leakage of CO_2

Site	Location	Source of CO_2	Depth / Geological Setting	Amount of CO_2 / Time	Comments / Reference
Rangely Oilfield	Colorado, USA	CO_2 from EOR activities in Rangely Field	Two fault systems to west and north of oilfield;	-- 170-3800 t/year; chemical reactions indicated from reaction of CO_2 with rock-water system.	Multiple small earthquakes in the area, postulated to be due to high fluid pressures from deep water well injection associated with oil production. Soil gas measurements indicate leakage of CO_2 (EOR activities) to surface. Klusman (2002); also Moran (2007) at: //www.emporia.edu/earthsci/student/moran4/index.htm
Latera geothermal field	Italy	Postulated to be decarbonation of carbonate minerals.	Low-permeability flysch (shales interbedded with greywacke sandstone) rocks and laterally-sealed fractures.	Not available	Carbonate-rich springs and CO_2-rich gas vents. Gas reservoirs older than 0.1 M years. Pearce et al. (2004); Beaubien et al. (2008); Annunziatellis et al. (2008).
Matraderecske	Hungary	CO_2 accumulates in karst water reservoir	~1000 m; andesite volcanoes close to fault zone; hydrothermally-altered volcanic rocks; overlain by clays and sands. Migration through faults and fractures.	Not available	Pearce et al. (2004)
Carbogaseous area of France, e.g. Montmiral	Southeast Basin of France	Mantle or deep crustal origin	Region bounded by Alps (east) and Pyrenees (south); widespread occurrence of naturally carbonated springs (Perrier, Vichy); CO_2 occurrences located along major fault systems; reservoirs in Jurassic and Triassic limestones, dolomites and sandstones, 2000-5000 m; open fractures. Montmiral field ~2450 m Clayey-marl seals, Early to Middle Jurassic age, depth ~1840-2340 m	Not available.	Montmiral field exploited as source of CO_2 gas for industrial uses. Evidence of CO_2 migration along pre-existing fractures in Rhaetian limestones overlying Triassic reservoir at Montmiral. These limestones subjected to prolonged and episodic history of fracturing related to basin development and subsequent uplift. Pearce et al. (2004).
Crystal Geyser, northern Paradox Basin	Utah, USA	Deep source of CO_2; upward migration to sandstone units; potential source diagenetic reactions during deep burial of clay-rich carbonate rocks, thermal decomposition of Leadville Limestone	Anticline cut by two fault complexes (Little Grand and Salt Wash) CO_2 leakage along wellbore; CO_2-bearing reservoir rocks thought to be sandstone units > 700 m below ground; series of stacked reservoirs with partially breached local seals; damaged zones of fractured shales around faults provide conduits; fracture networks main pathways for migration.	Not available.	Geyser where well penetrates reservoir; CO_2 eruptions every 4-12 hours since 1935. Holloway et al. (2005).
Florina CO_2 field. Florina Basin	Northern Greece	Unknown	Reservoirs vertically stacked, limestone and sandstone units; poorly consolidated sediments, Miocene sand alternating with silt and clays; top of reservoir 300 m deep; CO_2 dissolved in groundwater. Several tens of metres of clay forming local seal. Migration through faults in overlying sediments.	0.02-0.03 Mt/year produced. Storage sites will be much deeper.	CO_2 leakage occurred after exploration well was drilled into Florina basin; leakage occurred originally ~100 m from well; then along well itself from depth of ~97 m to final depth of 559 m. Cement base used for drilling rig collapsed. CO_2 leakage induced by drilling wells! //www.bgs.ac.uk/nascent/
Mammoth Mountain	California, USA		Volcanic activity began ~200,000 years ago		Diffuse CO_2 degassing. Areas of tree kill appeared from ~1990. Total area affected is ~480,000 m2 . Eruptions as recently as 700+/-200 years ago; currently displays only weak fumarolic activity and no summit activity. Holloway et al. (2005).
Yellowstone volcanic field	Wyoming, USA		Three volcanic cycles spanning 2 million years; volcanism, crustal deformation, high heat flow; site of one of world's largest hydrothermal systems	~16 Mt/year	Non-eruptive, diffusive release (degassing) Holloway et al. (2005).

Site	Location	Source of CO_2	Depth / Geological Setting	Amount of CO_2 / Time	Comments / Reference
Dieng volcanic complex	Indonesia		Two or more stratovolcanoes, numerous small craters and cones; hydrothermal features including fumaroles, solfataras, mud pools, hot springs abundant; extensive fissure system	Total emanation in 1979 estimated at ~0.2 Mt.	Rapid CO_2 emanations in 1979 leading to 142 deaths; effusion occurred from both fracture (reactivated) and crater itself; CO_2 'flowed' downwards forming dense 'sheet' of CO_2 over ground surface. Holloway et al. (2005).
Mount Etna	Italy		Volcanic emissions;	~25 Mt/year ??; "calculated at 13+/-3 Mt/year" JP	Additional CO_2 dissolved in Etna's aquifers, with additional ~0.25 Mt escaping this way. Highest soil emissions delineate active fault systems. Holloway et al. (2005).
Lake Nyos	Cameroon	Mantle-derived CO_2	Volcanic lake / top of volcano; saturated with CO_2; => overturning of water saturated with CO_2 => release of large volumes of CO_2	Large amount of CO_2 erupted from lake in 1986 over several hours; gas moved downstream and blanketed local villages. Estimated release of CO_2~1.24 Mt	Gas outburst from lake asphyxiated people; 1746 inhabitants and large number of livestock killed. Benign gas release remediation programme now in operation. Studies after catastrophe indicated large amount of CO_2 present in deep water mass. Maximum water depth 208 m. Holloway et al. (2005).
Lake Monoun	Cameroon	Mantle-derived CO_2	Volcanic lake / top of volcano; saturated with CO_2; => overturning of water saturated with CO_2 => release of large volumes of CO_2	Estimated release of CO_2 ~0.05 Mt	Similar gas outburst to Lake Nyos occurred in 1984; 37 people killed. Holloway et al. (2005).

IEA Greenhouse Gas R&D Programme,
Orchard Business Centre, Stoke Orchard,
Cheltenham,
Glos. GL52 7RZ, UK.

Tel: +44 1242 680753 mail@ieaghg.org
Fax: +44 1242 680758 www.ieagreen.org.uk