Natural Releases of CO_2

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Cover image taken by Alexandre Halbwachs.

The cover image shows Lake Nyos, Cameroon with degassing operations underway.

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INTRODUCTION

THE NEED TO ENSURE SECURITY OF CO_2 STORAGE

Increasing concentrations of CO_2 in the Earth's atmosphere are enhancing global warming and subsequent climate change. One option for reducing anthropogenic CO_2 emissions to the atmosphere is the deployment of technologies for the capture and storage of CO_2 produced by the combustion of fossil fuels. This option, however, would be deployed as part of a portfolio of measures, including renewable energy, nuclear power, fuel switching and energy efficiency. The technology for capturing CO_2 from power plant is already available and could lead to significant reductions in CO_2 emissions, providing options are available for disposing of the captured CO_2. One of the most attractive methods being considered, which offers potential long-term containment of significant quantities of CO_2, is geological storage.

Geological storage of anthropogenic CO_2 involves injecting the CO_2 underground, for example in depleted oil and gas reservoirs, deep saline reservoirs and unminable coal seams, where it becomes secured in a similar way to hydrocarbons that have remained naturally trapped in gas and oil fields for millions of years.

Storage of CO_2 in gas or oil reservoirs is currently being demonstrated at a commercial scale at a number of sites. For example, since 1996 the Sleipner project has been capturing CO_2 from the natural gas extracted from the Sleipner West gas field in the North Sea and reinjecting it into a deep saline formation above the gas field.

Concerns have been expressed that if CO_2 capture and storage becomes widely deployed possible seepage from these underground storage sites could have a deleterious effect on the environment. These concerns have arisen largely because, over the past few decades, a few natural events involving the rapid emissions of large masses of CO_2 in volcanic areas have resulted in serious incidents.

To understand the circumstances that lead to these natural release incidents, the IEA Greenhouse Gas R&D Programme commissioned eminent geologists from the British Geological Survey and CRIEPI in Japan to provide a factual and balanced overview of natural CO_2 releases from underground sources and their relevance to geological CO_2 storage. This report provides a summary of their findings.

IEA GREENHOUSE GAS R&D PROGRAMME

This report has been produced by the IEA Greenhouse Gas R&D Programme (IEA GHG). IEA GHG is an international collaboration of governments and industries from many countries with several linked objectives:

- To identify and evaluate technologies that could be used to reduce the emissions of greenhouse gases arising from the use of fossil fuels;
- To disseminate the results of those evaluations;
- To identify targets for research, development and demonstration, and promote the appropriate work.

IEA GHG was established in 1991 and, since then, its main focus has been on capture and storage of CO_2. It has also examined a wide range of other technologies, including carbon sequestration in forests, renewable energy sources (biomass and wind energy) and methods for reducing emissions of non-CO_2 greenhouses gases. This helps to put in perspective the potential of capture and storage of CO_2.

NATURAL RELEASES OF CO_2

CO_2 EMISSIONS FROM VOLCANIC ACTIVITIES

The most important process by which naturally occurring CO_2 from underground sources can be emitted into the atmosphere is through the degassing of magma (molten rock) in volcanic areas. When magma rises towards the Earth's surface, the pressure on it is lowered and dissolved CO_2 is released. Most of the CO_2 originating from magma degassing is emitted through volcanoes and associated fissures, or hydrothermal sites.

Volcanic regions by their very nature are prone to eruptions, ground movement, earth tremors and explosions that can fracture the surrounding rocks. They may also contain magma chambers or voids that are capable of holding large volumes of gas (mostly water vapour) that can be suddenly released at high pressure as a result of these fractures.

Although CO_2 is also released rapidly from the central conduit(s) of volcanoes during violent eruptions. It has recently been recognised that non-eruptive diffuse degassing may be the principle mode of gas release from sites of both active and dormant volcanic activity. For instance around the Yellowstone hydrothermal area in the USA, diffuse degassing has been measured at 16 million tonnes CO_2 per year. In diffuse degassing, the CO_2 can percolate to the surface through porous zones on volcano flanks and through hydrothermal areas (Box 1).

Although they are not common, dormant or extinct volcanoes can also contain crater lakes; worldwide there are around 20-30 such examples.

Crater lakes are located at the top of volcanoes and are commonly surrounded by high crater walls. The lakes overflow down a spillway leading to a valley system. In tropical areas such lakes may be deep and still and the water column within them can become stratified, as there is little seasonal mixing of the lake waters. CO_2, or other gases percolating up highly permeable fissures and fractures into the crater lake floors can dissolve into the lower levels of the lake waters (increasing their density) until they become saturated with respect to CO_2.

BOX 1. AN EXAMPLE OF DIFFUSE DEGASSING

An eruption of Old Faithful, perhaps the world's best known geyser and a major tourist attraction, rises above Yellowstone's Upper Geyser Basin.

Yellowstone is the site of one of the world's largest hydrothermal systems and contains a number of different types of hydrothermal features; all of which release CO_2 by means of diffuse degassing. Geysers occur when CO_2-charged heated water rising from deep within the ground is released periodically and explosively. With hot springs, the water charged with CO_2 is released at a steady, non-explosive rate, whereas with mud pots (sometimes known as mud volcanoes) CO_2 release occurs through clayey mud. (Image courtesy of Smithsonian Institution)

BOX 2. THE DIENG INCIDENT

The Dieng incident was associated with a phreatic explosion that resulted in the formation of a new crater and the reactivation of a pre-existing fracture. Phreatic explosions normally release large volumes of superheated water with only small amounts of CO_2. It was considered that the pure gaseous CO_2 released must have accumulated in a shallow reservoir as a high density fluid before the explosion and was then released through fractures as they opened up due to the pressure build-up in the volcano prior to the explosion. (Image courtesy of Sumarma Hamidi, Volcanological Survey of Indonesia).

BOX 3. LAKE NYOS AND LAKE MONOUN INCIDENTS

Lake Nyos (image above after the CO_2 release) and Lake Monoun are both tropical crater lakes at considerable elevation compared to much of the surrounding topography. The lakes are not seasonally overturning and, due to low-level volcanic activity, springs in the lake bottoms are constantly supplying CO_2 to the bottom of the lakes. This dissolves in the lake water and results in a layer of dense, CO_2-saturated water building up above the bottom of the lake. At Lake Monoun an earthquake is thought to have upset the density stratification of the lake, whereas at Lake Nyos, geologists are uncertain what triggered the sudden release of CO_2; although some suspect a landslide. Whatever the cause, the event resulted in the rapid mixing of the CO_2 supersaturated deep water with the upper layers of the lake, where the reduced pressure allowed the stored CO_2 to effervesce out of solution leading to the sudden release of CO_2 from the crater lake. The cold CO_2 was confined by the crater walls and flowed down into adjoining valleys suffocating people and animals before it could dissipate.

become saturated with respect to CO_2. Once saturated, any disturbance that causes part of the lower lake waters to rise could cause CO_2 to come out of solution. Only a very few, like those at Lake Nyos and Lake Monoun in Cameroon (see below), have become saturated with CO_2. In contrast, the lakes commonly found in temperate regions are seasonally overturning and therefore pose much less potential danger from CO_2 build up, should it occur.

Impact of CO_2 emissions from volcanic activities

The impact of natural CO_2 emissions from volcanic activities on the environment is mainly dependent on the scale and location of the incident. Although CO_2 is non-toxic, a large rapid release of the gas is of concern because CO_2 is an asphyxiant. There are a small number of examples of natural disasters in volcanic areas caused by sudden emissions of large volumes of CO_2 that have led to loss of life.

One of these incidents occurred at the Dieng volcano complex in Indonesia and provides an example of the danger presented by sudden CO_2 emissions from volcanoes following a build-up of gas within them. In 1979, at the Dieng complex, diffusive CO_2 emissions occurred prior to a major eruption. About 200 000 tonnes of pure CO_2 was released and flowed from the volcano to the plain below as a dense layer resulting in the asphyxiation of 142 people (see Box 2).

The two other recorded disasters, however, were associated with sudden emissions of CO_2 from volcanic crater lakes at Lake Nyos and Lake Monoun, both of which are in Cameroon in West Africa (see Box 3). When Lake Monoun overturned in 1984, the sudden release of volcanic CO_2 led to the death of 37 people. In a similar incident at nearby

BOX 4. DIFFUSE DEGASSING AT MAMMOTH MOUNTAIN

Tree kill on the shore of Horseshoe Lake, Mammoth Mountain, California, was caused by CO_2 emerging through the ground along fault zones on the volcano's flanks, following a period of enhanced seismic activity. The gray area in bottom centre of the photo marks the location of trees killed by high concentrations of carbon dioxide gas in the soil. (Photograph by S.R. Brantley)

Lake Nyos in 1986, approximately 1.24 million tonnes of CO_2 was released from the lake in just a few hours and asphyxiated 1700 people. These releases, however, involved a set of specific geographical features and geological processes that contributed to each event and the loss of life that followed.

In addition to these major incidents, there have been a number of smaller incidents that can be attributed to natural CO_2 releases and which have lead to asphyxiation of animals and damage to plant life. In volcanic areas, diffuse degassing of CO_2 is commonplace. The CO_2 normally mixes with air, dissipates rapidly and generally is not considered to be hazardous to man. However, if the dispersion is restricted or there is a sudden increase in seismic activity, high concentrations of CO_2 can accumulate. Notable examples include the diffuse degassing of CO_2 through soil on the flanks of Mammoth Mountain, California, which resulted in localised ecosystem damage (see Box 4) and the sudden release of CO_2 in the Cava dei Sielci region of the Alban Hills volcanic complex in Italy, which resulted in the deaths of more than 30 animals. Both were associated with an increase in seismic activity in the area.

CO_2 EMISSIONS FROM SEDIMENTARY BASINS

CO_2 also occurs as a result of geological processes in large, sometimes high purity (>90% CO_2) reservoirs in many sedimentary basins. Sedimentary basins are widely spread around the world and many occur in tectonically stable regions, where there is little or no volcanic/hydrothermal activity.

CO_2 is commonly trapped within the porous and permeable reservoir rocks as a supercritical phase (a highly compressed gas) but may also dissolve in any salt water remaining in the rock formation. An overlying impermeable cap rock is often present which acts as a natural seal, in a similar manner to the presence of oil and natural gas fields in sedimentary basins. Naturally occurring CO_2 may also be retained in other geological settings, for example, confined in the pore spaces of sedimentary rocks folded into domes or other structures.

The best documented natural CO_2 field, as well as the worlds' largest supply of commercially traded CO_2, is the McElmo Dome in Colorado. The CO_2 reservoir is capped by over 700m of impervious salt, shale and sandstone which provides an effective seal and, at the time of discovery in 1948, contained an estimated 1.6 billion tonnes of high purity CO_2. A further notable example is the giant CO_2 field in the Pisgah Anticline, Mississippi, USA which is thought to be around 65 million years old and holds over 200 million tonnes of CO_2.

Mofettes are openings in the earth's surface from which carbon dioxide and other gases escape. The mofettes pictured here, where bubbles of gas constantly rise to the surface, is in the nature reserve Soos near Frantiskovy Lazne, Czech Republik. Image courtesy of André Künzelmann/UFZ

The Bublák mofette in the Eger Basin, Czech Republik. Here, the gas rises spontaneously from the earth's mantle to the surface and is more than 99 per cent CO_2. Image courtesy of André Künzelmann/UFZ

CO_2 leaks from sedimentary basins can occur through permeable rock and/or along any faults or fissures in the rock, although CO_2 can also be accidentally emitted from via boreholes. In some areas CO_2 leakages along faults can result in CO_2 charged groundwater emerging visibly in springs and through old well bores. More typically, however, CO_2 appearing at the ground surface is already dispersed to the surrounding strata, so that it emerges at very low seepage rates and over a larger area than that of the point of origin.

In offshore areas the migration of gases through the seabed commonly produces pockmarks or, where gases emerge along with mud, a mound on the sea floor called a mud volcano. Mud volcanoes may also occur onshore. The best documented natural CO_2 emission from the sea bed occurs in the Tyrrhenian Sea offshore from the Aeolian Islands in Italy. Here 25,000 tonnes of CO_2 per year are released over an area of 15km^2, most of which dissolves into the sea water.

Impact of CO_2 emissions from sedimentary basins

There are numerous natural CO_2 fields within sedimentary basins around the world some of which, due to the presence of an overlying impermeable cap rock, have held CO_2 for millions of years without evidence of leakage or environmental impact. Many others, however, do leak although there are no recorded incidents involving sudden large emissions of CO_2 from sedimentary basins. Leakage generally manifests itself as carbonated springs or dry seeps and can result in very localized ecosystem damage.

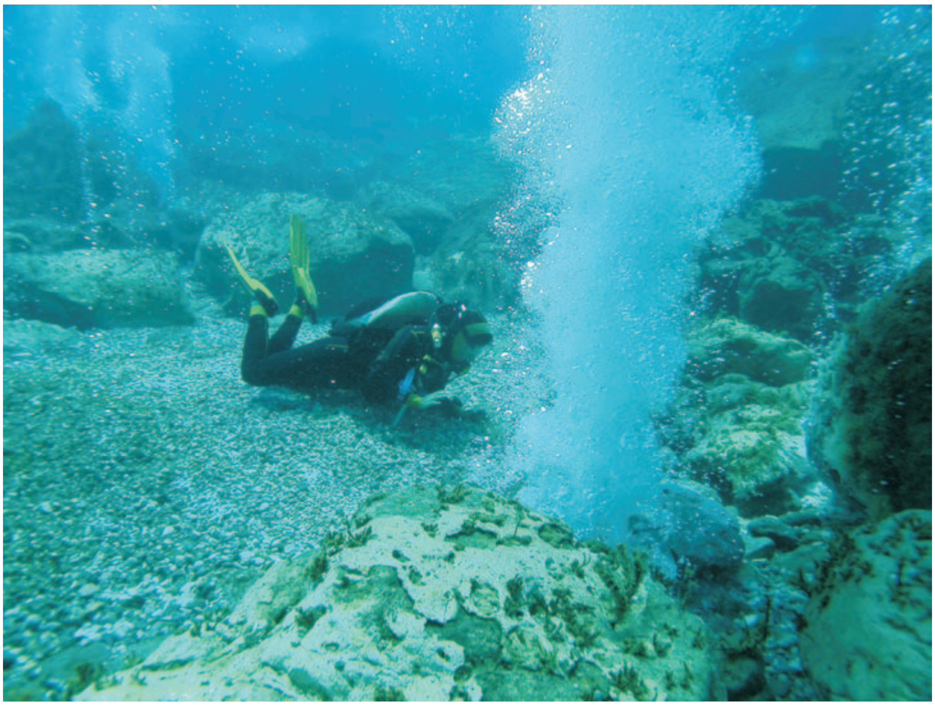
The environmental impact resulting from these leaks is significantly smaller than those occurring in volcanic regions. They depend ultimately on many factors that control the migration and accumulation of this gas. In many cases CO_2 emissions through the ground are not a significant hazard to man because they are dispersed by the wind. The main threat to man is where CO_2 is emitted in situations where it can build up to high concentrations, for example in buildings or in hollows in the ground. Leakages are more likely to have an adverse impact on vegetation, killing it or damaging it depending on the levels of CO_2 released.

There are a number of notable examples of CO_2 emissions from sedimentary basins which present, at most, only very local hazards to man or the natural environment. These include the Southeast Basin in France where several small CO_2 fields are located along major fault systems. The CO_2 dissolves in the groundwater and emerges in carbonated springs, many of which are exploited by the sparkling mineral water industries, such as Badoit, Vichy and Perrier.

The Colorado Plateau is also an interesting example because it contains both major CO_2 fields and areas where CO_2 is leaking. In some areas, such as the Paradox Basin, CO_2 seepage along faults results in CO_2 charged groundwater in several springs and through old well bores. The Crystal Geyser is a dramatic example of leakage along a well bore, which has since become a tourist attraction. The geyser first erupted in 1935 when a well being drilled intersected a CO_2-charged aquifer. Today the geyser erupts every 4 to 12 hours as a result of pressure changes in the aquifer.

Mátraderecske in northern Hungary provides an example of CO_2 leakage as a result of the presence of permeable caprocks above CO_2 fields. High levels of CO_2 have been recorded for some time in this area; however, in 1992 residents in two houses in the village suffered from headaches and since then control flushing systems have been installed.

The impacts of CO_2 emissions in off-shore areas are not well known. CO_2 may emerge at the seabed dissolved in water or as a free gas. If in a free gas phase it may form a train of bubbles that will rise through the water column and is unlikely to build up in high concentrations; although unless the emission rate is very high, the CO_2 is more likely to dissolve in the water column. The dissolution of CO_2 into seawater lowers its pH (increases its acidity), at least locally, and may impact on the marine environment, depending on the dispersion and duration of emissions.



This is the strongest vent in the Panarea degassing field. The average depth is around 10 meters and the seafloor is characterized by a gravel cover. The position is very close to the north point of the Bottaro islet. Image courtesy of Giorgio Caramanna, University La Sapienza, Roma

GEOLOGICAL STORAGE SITES FOR ANTHROPOGENIC CO_2

Geological storage of CO_2 involves injecting the CO_2 underground, such that it becomes trapped in the pore spaces between grains of sedimentary rock in exactly the same way that hydrocarbons are naturally trapped in oil and gas fields. The procedure offers the opportunity to remove large quantities of CO_2 to an underground storage site, using techniques that are both currently available and constantly improving.

ENVIRONMENTAL CONCERNS

Significant quantities of CO_2 are already injected underground around the world in enhanced oil recovery projects. Underground storage of natural gas, an analogous technique, is also widely practised. Nevertheless, because CO_2 is an asphyxiant and heavier than air, there may be concerns about the safety of underground CO_2 storage, either from possible slow seepage or sudden large-scale emission resulting from well failure. Slow seepage is unlikely to give cause for safety concerns unless the gas is inadvertently trapped. The risk of sudden large-scale release of CO_2 would have to be avoided in the same way as for other gases, such as by avoiding unsuitable sites. It is also important that CO_2 remains in the underground storage sites for a long period of time (up to 1000 years) to minimise climate change.

DEVELOPING CO_2 STORAGE SITES

Sites for the geological storage of anthropogenic CO_2 are most likely to be situated in stable sedimentary basins because storage sites will need to be contained in tectonically stable locations with a reasonable storage capacity. Depleted oil and gas reservoirs, in particular, have a number of attractive features as CO_2 storage reservoirs:

- the reservoirs are proven traps, known to have held liquids and gases for millions of years;
- the reservoirs have well known geology;
- a large number of potential sites exist, as thousands of oil and gas fields are approaching the ends of their economically productive lives; and
- exploration costs would be small.

Geological storage of CO_2 can be considered as closely analogous to natural CO_2 fields that occur in sedimentary basins. CO_2 storage sites would need to be sited at carefully selected locations, to take advantage of the geological factors that prevent gas leakage. For a storage operation to earn a permit, regulators would want assurance that any potential gradual CO_2 seepage would only occur at a very slow rate, that sudden releases are extremely unlikely and that any seeps cannot migrate to belowground confined spaces that are vulnerable to sudden release.

The regulatory process is likely to include:

- a rigorous characterisation of the storage site and surrounding area;
- the construction of geological models of the site and surrounding area;
- the simulation of CO_2 injection into the storage reservoir;
- a risk evaluation/management process
- monitoring of the stored CO_2.

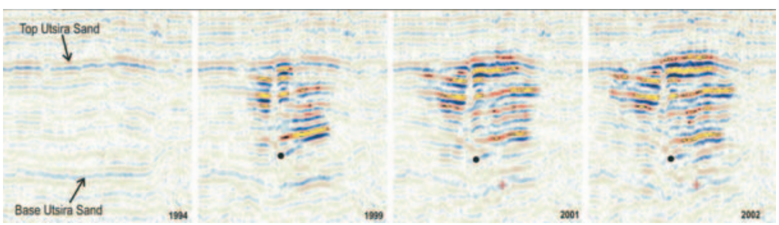
To cover the unlikely event that seepage might occur a remediation plan will also likely to be required. If the potential for seepage is identified a remediation plan may be required. During the site characterisation, any concerns over the integrity of the rock cap and its ability to contain CO_2 for the necessary timescales would need to be addressed. During CO_2 injection, monitoring and modelling of the site would be required to provide information needed to demonstrate the selected sites ability to contain CO_2 for the necessary timescales.

CO_2 STORAGE PROJECTS

There are a number of current geological CO_2 storage operations being undertaken worldwide. Many of the first CO_2 storage sites were old oil fields where CO_2 could be injected to boost production of crude oil (known as CO_2 enhanced oil recovery or CO_2-EOR). More recently, underground CO_2 storage is being performed at gas production sites, where raw natural gas produced at the site contains too much CO_2 for commercial use, so the excess is removed, compressed and then injected underground. Examples of such projects that are undergoing detailed monitoring of the surface and subsurface include the Sleipner project in the North Sea and the CO_2-EOR projects at Weyburn in Saskatchewan, Canada and Rangely, in Colorado, USA.

At the Sleipner gas field CO_2 is injected under pressure into the Utsira formation, which is a saline-water-saturated sandstone formation extending under a large area of the North Sea at a depth of about 800m. Approximately 1 million tonnes of CO_2 is removed annually from the raw natural gas and injected into the deep saline reservoir above the gas field. The CO_2 injection operation started in October 1996 and over the lifetime of the project, a total of 20 million tonnes of CO_2 is expected to be stored. The project has been closely monitored and no migration from the storage reservoir has been detected (see Box 5).

BOX 5. SEISMIC PROFILES OF THE SLEIPNER CO_2 INJECTION SITE



Time lapse seismic profiles through the Utsira Sand and CO_2 plume at the Sleipner CO_2 injection site acquired over the injection point (marked by a black dot) and storage area. The first was acquired in 1994, prior to any CO_2 injection. The subsequent surveys were taken as injection progressed between 1999 and 2002. The difference in reflectivity between the baseline survey (1994) and later surveys is due to the presence of CO_2 in the pore spaces of the reservoir rock.

The seismic profiles demonstrate that the CO_2 has spread out laterally from the injection point in a series of discrete layers. There is no evidence of faults or fractures in the cap rock above the injection site and no evidence that CO_2 is migrating out of the storage reservoir.

BOX 6. THE IEA GHG WEYBURN CO_2 MONITORING AND STORAGE PROJECT

The project has undertaken a comprehensive programme of sub-surface and surface monitoring. This has involved repeat seismic surveying, geochemical sampling of production fluids and soil gas sampling.

Soil gas sampling is designed to detect injected CO_2 that may have escaped from the reservoir and seeped to the surface. Sampling and analysis of gas above the injection site found fluxes for CO_2 and O_2 within the range of that for natural soils and comparable to an off-set reference location, indicating that there is no evidence so far for seepage of injected CO_2 from depth. Image courtesy of PTRC.

The Weyburn Project (Box 6) in Canada combines CO_2-EOR with a comprehensive monitoring and modelling programme to evaluate CO_2 storage. CO_2 injection commenced in 2000 and is anticipated that over the project lifetime some 20 million tonnes of CO_2 will be stored; currently 5 000 tonnes of CO_2 are injected daily. No leakage from the reservoir has been detected to date. Furthermore, long-term predictions indicate that the majority will remain permanently stored for 5000 years.

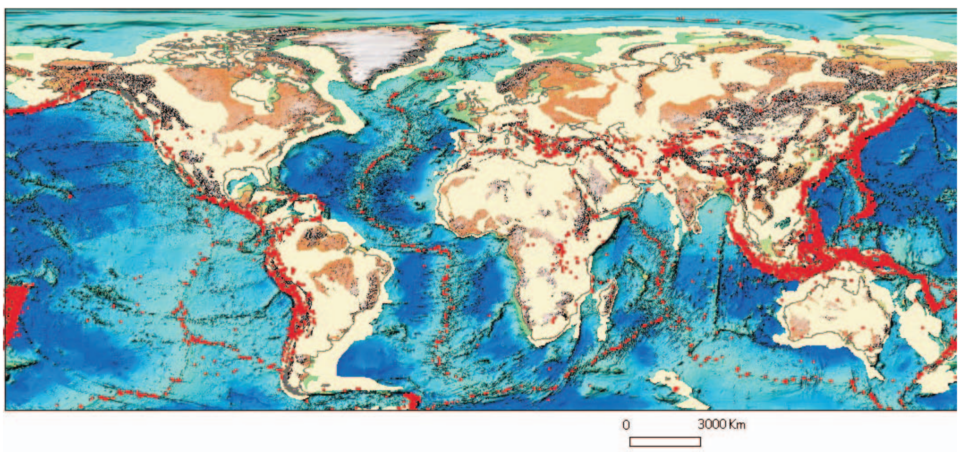
At the Rangely oil field in the USA around 23 million tonnes of CO_2 have been injected into the field since 1986. In 2000, a survey of the field and adjacent areas showed that CO_2 was emerging through the ground surface, albeit at very low seepage rates. Further investigations, however, suggest that this was largely due to the oxidation of methane originating from the oil reservoir or overlying strata, rather than leakage of injected CO_2.

RELEVANCE OF NATURAL CO_2 RELEASES TO GEOLOGICAL STORAGE

DISTINCTION BETWEEN NATURAL CO_2 RELEASES FROM SEDIMENTARY BASINS AND VOLCANIC AREAS

A major distinction can be made between natural CO_2 emissions that occur in volcanic areas and those that occur in sedimentary basins. Volcanic regions and associated hydrothermal areas, where natural emissions of CO_2 occur, are commonly tectonically unstable and may be liable to ground heave and fracturing. Moreover, because heat and steam are commonly present they can contain gas under great pressure, often in voids. The occasional large sudden emissions of CO_2 that have occurred in volcanic and hydrothermal areas are generally associated with seismic activity.

Volcanoes are located mainly around the Pacific rim, the east African rift, and the Atlantic ridge; the majority of the earth's surface is devoid of volcanic activity (see figure below).



Location of world earthquake centre. The red marks indicate earthquake centres above magnitude 5 for the previous 10 years. The yellow shading indicates high prospective or prospective areas. Courtesy of Geoscience Australia

By contrast, sedimentary basins are widely spread around the world and many occur in tectonically stable regions (see figure above). They commonly contain both porous/permeable reservoir rocks and impermeable cap rocks that can act as natural seals and prevent gases reaching the surface. The existence of natural barriers is proven by the presence of oil and natural gas fields in sedimentary basins.

RELEVANCE OF NATURAL CO_2 RELEASES

The major natural CO_2 emissions that have occurred can be regarded as representing fairly exceptional geological situations. These are either tropical craters lakes that do not seasonally overturn and are actively filling with CO_2 due to volcanic activity, or are the result of shallow CO_2 accumulations in voids or magma chambers (again originally from volcanic activity) that are released as a precursor to a volcanic eruption. Such geological situations have nothing in common with the stable sedimentary formations where it is proposed to store CO_2.

For example, at the Dieng volcano, the CO_2 was thought to have accumulated in a shallow reservoir as a high density fluid before the explosion and then released through fractures created due to the pressure build-up in the volcano prior to the explosion. This combination of large volumes of CO_2 gas in shallow reservoirs coupled with fracture development prior to an explosion would not occur in a sedimentary basin.

Similarly, the CO_2 releases at Lakes Nyos and Monoun were again the result of exceptional circumstances unlikely to be found at or near purpose designed CO_2 storage sites. These circumstances included the presence of stratified lakes at considerable elevation, the presence of a slow CO_2 leak into the bottom of the stratified lakes and the unobserved CO_2 saturation of the lower layer of the lake waters.

There are no recorded incidents involving sudden large emissions CO_2 from sedimentary basins. Seepage has been detected from some natural CO_2 fields along faults or as a result of boreholes, which in a few cases has resulted in very localized environmental damage. Although the environmental impact resulting from seepage are significantly smaller than those occurring in volcanic regions. With a rigorous site selection process, the risk of seepage occurring from geological storage sites in sedimentary basins can be minimised.

CONCLUSIONS

Geological storage offers the potential for long-term storage of significant quantities of CO_2. However, concerns over the security of underground storage of CO_2 have arisen largely because of a few natural events involving rapid emissions of large masses of CO_2 that have resulted in serious incidents.

The main incidents involving CO_2 emissions have all arisen in volcanically active regions and can be regarded as representing fairly exceptional geological situations.

Sites considered for geological storage of CO_2 are most likely to be situated in stable sedimentary basins and have nothing in common with the geological situations which resulted in the incidents that occurred in volcanic regions.

Seepages from natural CO_2 fields within sedimentary basins have been detected. However, any resulting ecosystem damage is generally localized and of modest impact. Some sedimentary basins have stored CO_2 for millions of years without any evidence of seepage.

Worldwide, there are a number of on-going geological CO_2 storage projects monitoring the fate of the injected CO_2 in geological formations which have given confidence in this option offering an effective solution for long term storage of significant quantities of CO_2.