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ORIGINAL ARTICLE

# Natural and industrial analogues for leakage of $CO_2$ from storage reservoirs: identification of features, events, and processes and lessons learned

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**Abstract** Instances of gas leakage from naturally occurring $CO_2$ reservoirs and natural gas storage sites serve as analogues for the potential release of $CO_2$ from geologic storage sites. This paper summarizes and compares the features, events, and processes that can be identified from these analogues, which include both naturally occurring releases and those associated with industrial processes. The following conclusions are drawn: (1) carbon dioxide can accumulate beneath, and be released from, primary and secondary shallower reservoirs with capping units located at a wide range of depths; (2) many natural releases of $CO_2$ are correlated with a specific event that triggered the release; (3) unsealed fault and fracture zones may act as conduits for $CO_2$ flow from depth to the surface; (4) improperly constructed or abandoned wells can rapidly release large quantities of $CO_2$; (5) the types of $CO_2$ release at the surface vary widely between and within different leakage sites; (6) the hazard to human health was small in most cases, possibly because of implementation of post-leakage public education and monitoring programs; (7) while changes in groundwater chemistry were related to $CO_2$ leakage, waters often remained potable. Lessons learned for risk assessment associated with geologic carbon sequestration are discussed.

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## Introduction

The injection and storage of anthropogenic $CO_2$ in deep geologic formations is a potentially feasible strategy by which to reduce $CO_2$ emissions and atmospheric concentrations (e.g., International Energy Agency 1997; Reichle et al. 1999). While the purpose of geologic carbon storage is to trap $CO_2$ underground, $CO_2$ could migrate away from the storage site into the shallow subsurface and atmosphere if permeable pathways (such as well bores or faults) are present. While limited $CO_2$ leakage does not negate the net reduction of $CO_2$ emissions to the atmosphere, adverse health, safety, and environmental risks associated with elevated $CO_2$ concentrations must be evaluated, particularly if the release at the surface occurs quickly and/or is spatially focused. Cases of $CO_2$ and $CH_4$ leakage from reservoirs to the near-surface environment as a result of natural and industrial processes serve as analogues for the potential release of $CO_2$ from geologic storage sites (e.g., Allis et al. 2001; Stevens et al. 2001a, b; Benson et al. 2002; Beaubien et al. 2004; Shipton et al. 2004; NASCENT 2005). Analysis of these analogues thus provides important insight into the key characteristics of $CO_2$ leakage; the resulting impact of the leakage on human health and safety, ecology, surface water, and groundwater; and quality, and the effectiveness of remedial measures applied. Lessons can then be learned from natural and industrial analogues for risk assessment associated with geologic $CO_2$ injection and storage.

The features, events, and processes (FEPs) relevant to the geologic disposal of radioactive waste have been compiled and used in systems analysis to assess performance and safety (e.g., NEA/OECD 2000). Based on this work, Savage et al. (2004) developed a framework for compiling a database of generic FEPs for the evaluation of $CO_2$ storage sites. However, FEPs associated with geologic sequestration of $CO_2$, in particular potential $CO_2$ leakage from storage sites, have not been identified from actual cases of leakage from natural $CO_2$ reservoirs. The purpose of this paper is to summarize and compare the FEPs of $CO_2$ leakage examples from natural geologic reservoirs and $CH_4$ from natural gas storage sites. To this end, a broad (although not exhaustive) set of natural and industrial analogues for $CO_2$ leakage is summarized (Appendices A and B; online supplementary material). In addition, several examples of $CH_4$ leakage associated with industrial processes are described. Based on this summary, the causes and consequences of $CO_2$ leakage resulting from natural and industrial processes are described, with particular emphasis on (a) the geologic model for $CO_2$ accumulation in the reservoir, (b) events leading to the leakage of the $CO_2$ from the reservoir, (c) pathways for $CO_2$ migration to the surface, (d) the magnitude and consequences of the release, and (e) remedial strategies applied. Implications for geologic carbon storage and the related risk assessment work are then discussed.

## Overview of natural and industrial analogues

Leakage of $CO_2$ has occurred naturally from geologic reservoirs in numerous volcanic, geothermal, and sedimentary basin settings worldwide. These systems serve as natural analogues for the potential leakage of $CO_2$ from geologic carbon sequestration sites and provide information on both the short and long-term causes and effects of $CO_2$ leakage. It should be noted, however, that in some environments the rates of $CO_2$ filling of natural geologic reservoirs may not be comparable to (i.e., may be lower than) $CO_2$ injection rates at storage sites. In these cases, natural analogues may not provide information on processes related to relatively rapid injection rates, such as pressure-induced geomechanical damage.

Leakage of $CO_2$ from geologic reservoirs resulting from industrial processes has occurred relatively infrequently. A limited number of examples of $CO_2$ and $CH_4$ leakage associated with exploration for or exploitation of geothermal, $CO_2$, natural gas, and water resources have been reported in the literature. Nonetheless, these relatively rare leakage events serve as analogues for the potential release of $CO_2$ from sequestration sites caused by human-related practices. Because most reported events of industrial $CO_2$ leakage are associated with well construction and injection and withdrawal practices, and few events have been reported associated with abandoned wells, industrial analogues usually provide information on short-term causes and effects of $CO_2$ leakage. Although the densities and solubilities of $CH_4$ and $CO_2$ are different, they have similar viscosities and behave as buoyant fluids. Furthermore, $CO_2$ injection rates into storage reservoirs will likely be comparable to $CH_4$ injection rates into natural gas storage sites. Thus, examples of $CH_4$ leakage from natural gas storage sites can serve as industrial analogues for $CO_2$ leakage.

Together, natural and industrial analogues for $CO_2$ leakage provide important information about the key FEPs that are associated with leakage, as well as the health, safety, and environmental consequences of leakage and mitigation efforts applied. Appendices A and B (online supplementary material) describe these aspects of natural and industrial analogues, respectively, for $CO_2$ leakage. Appendix A begins with a more detailed summary for Mammoth Mountain (USA) due to the large amount of data available for this site, and follows with more generalized descriptions of $CO_2$ leakage in other volcanic, geothermal, and sedimentary basin systems. While the Appendices (online supplementary material) do not represent an exhaustive list of natural and industrial cases of $CO_2$ leakage that have occurred worldwide, a suite of well-documented cases representing a range of geologic settings is included. In addition, several examples of $CH_4$ leakage related to industrial processes are given. Focus is placed on $CO_2$ leakage cases presented in the peer-reviewed literature. Also, emphasis is placed on natural rather than industrial analogues because (1) they provide information on both the short- and long-term causes and effects of $CO_2$ leakage and (2) a relatively large number of examples of natural $CO_2$ leakage events are reported in the literature.

To compare the key characteristics of $CO_2$ or $CH_4$ leakage associated with natural and industrial processes detailed in Appendices A and B (online supplementary material), leakage cases are classified according to the key features of the $CO_2$ or $CH_4$ accumulation, the events leading to the leakage of $CO_2$ or $CH_4$ from the reservoir, and the processes by which the $CO_2$ or $CH_4$ was released at the surface (Tables 1, 2). In Tables 1 and 2, columns 1 through 3 describe these key features, including site location, the source of the $CO_2$ or $CH_4$ in the accumulation, and the geologic

**Table 1** Summary of FEPs of natural leakage of $CO_2$ (see Appendix A for references)

| Site | $CO_2$ source | Geologic model for accumulation | Event triggering leakage | Pathway for leakage | Type of surface leakage |
|---|---|---|---|---|---|
| **A1.** Mammoth Mountain, CA USA | Magmatic + thermal decomposition of carbonates | Accumulation at ~2 km depth in porous/fractured rock under caprock | Seismic activity and reservoir pressurization | Faults and fractures | Fast, diffuse, vent, spring |
| **A2.** Solfatara, Italy | Magmatic + thermal decomposition of carbonates | Relatively shallow zone of fractured rock contains gas phase and overlies aquifers, then magma body at several km depth | No specific leakage event captured | Faults and fractures | Diffuse and vent |
| **A3.** Albani Hills, Italy | Magmatic + thermal decomposition of carbonates | Deep pressurized reservoirs in structural highs of sedimentary bedrock | Slow releases with several sudden large releases also occurring, possibly triggered by seismic activity | Faults and fractures | Diffuse, vent, spring/well, 1995 and 1999 events fast |
| **A4.** Clear Lake, CA, USA | Thermal decomposition of metasedimentary rocks, minor magmatic component | $CO_2$ derived from liquid-dominated geothermal reservoir hosted in marine metasedimentary rocks | No specific leakage event captured | Faults and fractures | Gas vents, springs |
| **A5.** Latera caldera, Italy | Thermal decomposition of carbonates, magmatic component | $CO_2$ accumulates in liquid-dominated, carbonate geothermal reservoir capped by hydrothermally altered volcanics | No specific leakage event captured | Faults and fractures | Diffuse, vent, spring |
| **A6.** Mátraderecske, Hungary | Geothermal/copper-zinc mineralization | $CO_2$ accumulates in karst water reservoir (~1 km depth) | No specific leakage event captured | Faults and fractures | Diffuse, vent, spring |
| **A7.** Dieng, Indonesia | Magmatic | Unknown | Volcanic, possibly "pneumatic", eruptions | Fissure | Eruptive, gas vents, springs |
| **A8.** Southern Negros, Philippines | Geothermal | Unknown | Unknown | Faults | Gas vents, springs, diffuse (kaipohans) |
| **A9.** Rabaul, Papua New Guinea | Magmatic | Unknown | Unknown | Fractures | Fast, vent |
| **A10.** Lakes Monoun and Nyos, Camaroon | Magmatic | Accumulation in deep lake and stable stratification | Rapid lake turnover triggered at Monoun by landslide; Nyos trigger unknown | NA | Eruptive (limnic) |
| **A11.** Laacher See, Germany | Magmatic | NA | Seasonal lake overturn and mixing | NA | Diffusive and bubbling from lake surface, diffuse from lake shore |
| **A12.** Paradox Basin, UT, USA | Thermal decomposition of carbonates | Reservoirs are vertically stacked, sandstone units, in fault-bounded anticlinal folds, capped by shale/siltstone units | No specific leakage event captured | Faults and fractures | Diffuse, gas seeps, springs |
| **A13.** Florina Basin, Greece | Thermal decomposition of carbonates | Reservoirs are vertically stacked, limestone and sandstone units (upper unit at 300 m depth), capped by silts and clays. | No specific leakage event captured | Slow leakage along rock discontinuities | Springs, gas seeps |

*NA* not applicable

**Table 2** Summary of FEPs of industrial leakage of $CO_2$ or $CH_4$ (see Appendix B for references)

| Site | $CO_2$ or $CH_4$ source | Geologic model for accumulation | Event triggering leakage | Pathway for leakage | Type of surface leakage |
|---|---|---|---|---|---|
| **B1**. Sheep Mountain, CO, USA | Thermal decomposition of carbonates | Reservoir is anticlinal fold, bounded on one side by thrust fault, sandstone, ave. depth 1500 m, capped by marine sediments and a laccolith | Well blowout | Well | Free flowing $CO_2$ gas from well, $CO_2$ leakage from fractures above drill site |
| **B2.** Paradox Basin, UT, USA | Thermal decomposition of carbonates | Reservoirs are vertically stacked, sandstone units, in fault-bounded anticlinal folds, capped by shale/siltstone units | Well blowouts | Wells | Cold geysers |
| **B3.** Florina Basin, Greece | Thermal decomposition of carbonates | Reservoirs are vertically stacked, limestone and sandstone units (upper unit at 300 m depth), capped by silts and clays | Well blowout | Well | $CO_2$ gas leakage from soils, water-filled pool formation around well |
| **B4.** Torre Alfina geothermal field, Italy | Geothermal | Geothermal reservoir with a gas $CO_2$ cap at ~660 m depth, capped by sequences of shales, marls, and limestones | Well blowout | Well | Free flowing $CO_2$ gas from well, diffuse emissions from ground around well |
| **B5.** Travale geothermal field, Italy | Geothermal | Shallow (<1,000 m) sedimentary reservoirs overlying deep (3,000–4,000 m) metamorphic and intrusive igneous reservoir, capped by low-permeability sedimentary rocks | Well blowout | Well | Free flowing steam and gas from well |
| **B6.** Yaggy gas storage facility, KA, USA | Injected natural gas | Gas injected into salt caverns at 150–200 m depth | Cracked well casing | Wells and fractures | Free flowing/geysering gas and water from abandoned wells |
| **B7.** Leroy gas storage facility, WY, USA | Injected natural gas | Gas injected into confined sandstone and dolomite aquifer at 1,000 m depth | Corrosion of well casing | Wells | Bubbling gas through surface water bodies near wells |
| **B8.** Kingfisher, OK, USA | Natural gas accumulation | Sedimentary reservoir at ~2,900 m capped by shales | Well blowout | Well and fractures | Geysering gas and water through surface water bodies |

**Table 3** Additional aspects of $CO_2$ or $CH_4$ leakage associated with natural (N) and industrial (I) processes (see Appendices A and B for references)

| Site | Geographic setting/land use | Magnitude of surface $CO_2$ or $CH_4$ leakage | Consequences of release | Monitoring and remedial measures |
|---|---|---|---|---|
| **A1.** Mammoth Mountain, CA USA (N) | Recreational area (US national forest, ski resort) | ~250 t $day^{-1}$ from 480,000 $m^2$ area | Formation of tree kill areas, one person with symptoms of asphyxiation, four people killed | Temporal and spatial monitoring of $CO_2$ concentrations and fluxes in tree kill areas; measurements of groundwater chemistry; public education |
| **A2.** Solfatara, Italy (N) | Recreational area (private park/ campground) surrounded by urban area | 1,500 t $day^{-1}$ from 0.5 $km^2$ area | No vegetation in degassing area | Temporal and spatial monitoring of soil $CO_2$ fluxes, monitoring of heat release; monitoring of fumarole gas chemistry; seismic and deformation monitoring; public education |
| **A3.** Albani Hills, Italy (N) | Urban area | 74 t $day^{-1}$ as surface gas emissions (61,000 $m^2$ area) and 506 t $day^{-1}$ as dissolved $CO_2$ in shallow ground water | High $CO_2$ concentrations in homes; deaths of livestock (1999 event); past human deaths | Measurements of soil $CO_2$ fluxes and concentrations; monitoring groundwater chemistry; identification of residential areas at risk, development of zoning bylaws, and development of public education programs |
| **A4.** Clear Lake, CA, USA (N) | Rural | ~1 t $day^{-1}$ | Four people killed | Measurements of soil and vent $CO_2$ fluxes and concentrations, mineral pool closed to public |
| **A5.** Latera caldera, Italy (N) | Rural, small towns | Unknown | Vegetation stress or kill | Soil gas concentration surveys, hazard mapping |
| **A6.** Mátraderecske, Hungary (N) | Rural area, village | Average $CO_2$ flux ~200–400 g $m^{-2}$ $day^{-1}$ (total degassing area unknown) | High $CO_2$ concentrations in homes, death of several people | $CO_2$ detection and control devices installed in homes, demolition of homes with hazardous $CO_2$ levels, public education |
| **A7.** Dieng, Indonesia (N) | Rural | Unknown | ~145 people killed, vegetation stress or kill | Vent gas chemical analysis |
| **A8.** Southern Negros, Philippines | Rural | Unknown | Vegetation stress or kill, animals killed | Vent and diffuse gas chemical analysis |
| **A9.** Rabaul, Papua New Guinea | Rural | Unknown | Three people killed, birds killed | NA |
| **A10.** Lakes Monoun and Nyos, Camaroon (N) | Rural, villages | Nyos: 240,000 t $CO_2$ in eruptive event | Loss of human (~1800 combined) and animal life (e.g., thousands of cattle), vegetation damage | Controlled lake degassing using pipes, monitoring of lake chemistry, public education |
| **A11.** Laacher See, Germany (N) | Rural | ~14 t $day^{-1}$ | NA | Monitoring $CO_2$ fluxes and concentrations from lake surface and shore |
| **A12.** Paradox Basin, UT, USA (N) | Rural | Soil $CO_2$ fluxes up to 100 g $m^{-2}day^{-1}$; total emission rate unknown | NA | Measurements of soil $CO_2$ fluxes; monitoring groundwater chemistry |
| **A13.** Florina Basin, Greece (N) | Rural, small towns | Unknown | NA | Measurements of groundwater chemistry |
| **B1.** Sheep Mountain, CO, USA (I) | Rural | Unknown | NA | Dynamic injection of drag-reduced brine followed by mud |
| **B2.** Paradox Basin, UT, USA (I) | Rural | Crystal Geyser: ~33 t $day^{-1}$ | NA | Measurements of atmospheric $CO_2$ concentrations |
| **B3.** Florina Basin, Greece (I) | Rural, small towns | Unknown | Death of one person | Leakage area closed off to people |

**Table 3** continued

| Site | Geographic setting/land use | Magnitude of surface $CO_2$ or $CH_4$ leakage | Consequences of release | Monitoring and remedial measures |
|---|---|---|---|---|
| **B4.** Torre Alfina geothermal field, Italy (I) | Rural | ~25,000 t | NA | Cementation of exploration well; borehole installation to focus subsurface gas flow and vent $CO_2$ at height in atmosphere; atmospheric $CO_2$ concentration monitoring |
| **B5.** Travale geothermal field, Italy (I) | Rural | Unknown | NA | Well allowed to discharge fluid, monitoring of fluid temperature, pressure, and chemistry |
| **B6.** Yaggy gas storage facility, KA, USA | Small town | Unknown | Gas explosions, two people killed, buildings damaged | Geophysical monitoring, wells plugged |
| **B7.** Leroy gas storage facility, WY, USA | Rural | ~$1.8 \times 10^7$ $m^3$ | NA | Tracer tests, decreased injection pressures |
| **B8.** Kingfisher, OK, USA | Rural | Unknown | NA | Geophysical, geochemical monitoring. Well plugged. |

*NA* not analysed

model for $CO_2$ or $CH_4$ accumulation, for example, the reservoir, reservoir depth (if known), and capping rocks. Column 4 in Tables 1 and 2 describes the event triggering the leakage of $CO_2$ or $CH_4$ from the reservoir. Columns 5 and 6 give the processes by which the $CO_2$ or $CH_4$ was emitted at the surface, including the pathway(s) for leakage and the style of surface emission. References for each of the leakage analogues are given in Appendices A and B (online supplementary material).

## Common FEPs

As shown in Tables 1 and 2, several key similarities exist between the FEPs of different natural and industrial cases of $CO_2$ or $CH_4$ leakage. First, the sources of $CO_2$ in natural accumulations are most commonly thermal decomposition of carbonate-rich sedimentary rocks and/or degassing of magma bodies at depth (analogues A1–A5, A7–A13, B1–B5). Second, $CO_2$ from these sources often accumulates in highly fractured and/or porous rocks (e.g., sandstones, limestones) under low-permeability cap rocks (analogues A1–A6, A12, A13, B1–B5). The cap rocks may be low-permeability rock units (e.g., shale and siltstone) or a zone of hydrothermal alteration.

In the case of natural $CO_2$ leakage, once the $CO_2$ leaks from the storage reservoir, fault and/or fracture zones are the primary pathways for $CO_2$ migration to the surface (analogues A1–A9, A12, A13). These high-permeability zones may be pre-existing, or be created/enhanced due to seismic activity associated with, for example, fluid migration and pore-fluid pressurization. In the case of $CO_2$ or $CH_4$ leakage associated with industrial activity, the event triggering the release is commonly a well blowout, related to injection/withdrawal practices or a defect in a well (analogues B1–B8). Also, the pathway for $CO_2$ or $CH_4$ migration to the surface is usually the well bore and/or fractures that have formed around the well bore.

## Differing FEPs

There are several key differences between the FEPs of the various examples of $CO_2$ or $CH_4$ leakage (Tables 1, 2). The depth of the $CO_2$ or $CH_4$ source and the reservoir(s) in which the $CO_2$ accumulates or is injected varies widely from <1 km (e.g., analogues B3–B7) to multiple km (e.g., analogues A1, B1, B8). At an individual site, $CO_2$ may accumulate in a single reservoir (e.g., analogues A1, A4–A6, B4), or within multiple

vertically stacked and/or horizontally compartmentalized reservoirs (analogues A12, A13, B2, B3, B5). Cap rocks and/or low-permeability fault zones can serve to separate multiple $CO_2$ reservoirs at a given site.

Some examples of natural $CO_2$ leakage have been correlated with specific triggering events, such as seismic activity or magmatic fluid injection (analogues A1, A3, A7, A10, A11), while other events have not been correlated with such events. However, the lack of correlation in the latter cases may be due to the absence of observations or data collection at the time of the leakage event. Where a trigger event was identified, it was commonly an event that caused geomechanical damage to cap rocks sealing the $CO_2$ reservoir.

Finally, the style of natural $CO_2$ leakage at the surface varies widely between different sites, as well as within individual sites. Surface releases occur in the form of diffuse gas emission over large land areas, focused vent emissions, eruptive emissions, degassing through surface water bodies, and/or release with spring discharge (analogues A1–A6, A8, A9, A10–A12). In rare cases, the $CO_2$ release may have been a self-enhancing or eruptive process (analogues A7, A10). In the case of $CO_2$ or $CH_4$ leakage associated with well failures, the gas may be emitted at the surface in a focused form, free flowing or geysering from the well and/or diffusely through soils, water pools, or fractures around the well site (analogues B1–B8).

## Additional considerations

The magnitude and consequences of $CO_2$ or $CH_4$ leakage events, as well as the type and success of strategies that were implemented to monitor and/or remediate the leakage, are important additional considerations that should be taken into account in risk assessment associated with geologic carbon sequestration. Table 3 and Appendices A and B (online supplementary material) detail these aspects for the natural and industrial leakage analogues, showing that the magnitude of the surface $CO_2$ or $CH_4$ release varies widely between different cases and does not necessarily depend on the style of the release. For example, the magnitude of diffuse $CO_2$ emissions from soils varies greatly between different, as well as within, individual sites. At sites where groundwater chemistry was monitored, chemical changes were sometimes observed related to $CO_2$ leakage (e.g., analogues A1, A3, A11, A12) and resulting groundwater acidification and interaction with host rocks along flow paths. However, groundwaters remained potable in most cases.

In many of the leakage examples, $CO_2$ was monitored in the near-surface environment within and around $CO_2$ leakage areas, often on a regular basis (analogues A1–A6, A8–A12, B2, B4). Monitoring strategies include measurements of soil $CO_2$ flux using accumulation chamber or eddy covariance methods and soil, atmospheric, or vent gas $CO_2$ concentration using gas analyser or chromatography techniques. Controlled degassing of $CO_2$-rich lakes has also been carried out to mitigate $CO_2$ buildup (analogues A10). In many cases, public education programs were implemented to advise people visiting or living near the $CO_2$ release areas of potential health, safety, and environmental hazards (e.g., analogues A1–A3, A6, A10). Zoning bylaws have also been established in some cases to control development near high $CO_2$ emission areas (e.g., analogues A3, A6). The hazard to human health was small in most examples of surface $CO_2$ releases; this could be attributed in part to public education and $CO_2$ monitoring programs.

## Conclusions and lessons learned

Leakage of $CO_2$ has occurred naturally from geologic reservoirs in numerous volcanic, geothermal, and sedimentary basin settings. In addition, $CO_2$ and $CH_4$ have been released from industrial reservoirs as a result of well defects and/or injection/withdrawal processes. These systems serve as natural and industrial analogues for the potential release of $CO_2$ from geologic storage reservoirs and provide important information about the key FEPs associated with releases, as well as the health, safety, and environmental consequences of releases and monitoring and mitigation efforts that can be applied. While the detailed characteristics of $CO_2$ or $CH_4$ leakage are unique to each case, five general FEPs were identified based on analysis of a range of natural and industrial analogues for $CO_2$ and $CH_4$ leakage, from which lessons can be learned and should be applied to risk assessment associated with geologic carbon storage:

1. Carbon dioxide can both accumulate beneath, and be released from, primary and secondary reservoirs with capping units located at a wide range of depths. Both primary and secondary reservoir entrapments for $CO_2$ should therefore be properly characterized at potential geologic carbon sequestration sites.
2. Many natural releases of $CO_2$ have been correlated with a specific event that has triggered the release, such as magmatic or seismic activity. The potential

for processes that could cause geomechanical damage to sealing cap rocks and trigger the release of $CO_2$ from a storage reservoir should be evaluated.

3. Unsealed fault and fracture zones can act as fast and direct conduits for $CO_2$ flow from depth to the surface. Risk assessment should therefore emphasize determining the potential for and nature of $CO_2$ migration along these structures.
4. Wells that are improperly constructed or abandoned, and become structurally unsound over time, have the potential to rapidly release large quantities of $CO_2$ to the atmosphere. One focus of risk assessment should therefore be an evaluation of the potential for both active and abandoned wells at storage sites to transport $CO_2$ to the surface, particularly in depleted oil or gas reservoir systems, where wells are abundant.
5. The style of $CO_2$ release at the surface varies widely between and within different leakage sites. In rare circumstances, the release of $CO_2$ can be a self-enhancing and/or eruptive process; this possibility should be assessed in the case of $CO_2$ leakage from storage reservoirs.

Furthermore, analysis of natural and industrial analogues has demonstrated two important points related to human health and safety and groundwater quality. First, the hazard to human health was small in most examples of $CO_2$ leakage**.** This could result from implementing public education and $CO_2$ monitoring programs; these ''remedial'' programs should therefore be employed to minimize potential health, safety, and environmental effects associated with $CO_2$ leakage. Second, while changes in groundwater chemistry can be related to $CO_2$ leakage caused by acidification and interaction with host rocks along flow paths, waters remained potable in many cases. Groundwaters should be monitored for changes in chemistry that could result from $CO_2$ leakage from storage sites.

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