

# Natural and industrial analogues for leakage of CO<sub>2</sub> from storage reservoirs: identification of features, events, and processes and lessons learned

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Received: 16 August 2006 / Accepted: 16 August 2006 / Published online: 7 October 2006  
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**Abstract** Instances of gas leakage from naturally occurring CO<sub>2</sub> reservoirs and natural gas storage sites serve as analogues for the potential release of CO<sub>2</sub> 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<sub>2</sub> are correlated with a specific event that triggered the release; (3) unsealed fault and fracture zones may act as conduits for CO<sub>2</sub> flow from depth to the surface; (4) improperly constructed or abandoned wells can rapidly release large quantities of CO<sub>2</sub>; (5) the types of CO<sub>2</sub> 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<sub>2</sub> leakage, waters often remained potable. Lessons learned for risk assessment associated with geologic carbon sequestration are discussed.

**Keywords** CO<sub>2</sub> storage · Leakage · Natural analogue · Industrial analogue · FEP

## Introduction

The injection and storage of anthropogenic CO<sub>2</sub> in deep geologic formations is a potentially feasible strategy by which to reduce CO<sub>2</sub> 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<sub>2</sub> underground, CO<sub>2</sub> 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<sub>2</sub> leakage does not negate the net reduction of CO<sub>2</sub> emissions to the atmosphere, adverse health, safety, and environmental risks associated with elevated CO<sub>2</sub> concentrations must be evaluated, particularly if the release at the surface occurs quickly and/or is spatially focused. Cases of CO<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> injection and storage.

**Electronic supplementary material** Supplementary material is available in the online version of this article at <http://dx.doi.org/10.1007/s00254-006-0479-7> and is accessible for authorized users.

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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<sub>2</sub> storage sites. However, FEPs associated with geologic sequestration of CO<sub>2</sub>, in particular potential CO<sub>2</sub> leakage from storage sites, have not been identified from actual cases of leakage from natural CO<sub>2</sub> reservoirs. The purpose of this paper is to summarize and compare the FEPs of CO<sub>2</sub> leakage examples from natural geologic reservoirs and CH<sub>4</sub> from natural gas storage sites. To this end, a broad (although not exhaustive) set of natural and industrial analogues for CO<sub>2</sub> leakage is summarized (Appendices A and B; online supplementary material). In addition, several examples of CH<sub>4</sub> leakage associated with industrial processes are described. Based on this summary, the causes and consequences of CO<sub>2</sub> leakage resulting from natural and industrial processes are described, with particular emphasis on (a) the geologic model for CO<sub>2</sub> accumulation in the reservoir, (b) events leading to the leakage of the CO<sub>2</sub> from the reservoir, (c) pathways for CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> from geologic carbon sequestration sites and provide information on both the short and long-term causes and effects of CO<sub>2</sub> leakage. It should be noted, however, that in some environments the rates of CO<sub>2</sub> filling of natural geologic reservoirs may not be comparable to (i.e., may be lower than) CO<sub>2</sub> 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 geo-mechanical damage.

Leakage of CO<sub>2</sub> from geologic reservoirs resulting from industrial processes has occurred relatively infrequently. A limited number of examples of CO<sub>2</sub> and CH<sub>4</sub> leakage associated with exploration for or exploitation of geothermal, CO<sub>2</sub>, 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<sub>2</sub> from sequestration sites caused by human-related practices. Because most reported events of industrial CO<sub>2</sub> 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<sub>2</sub> leakage. Although the densities and solubilities of CH<sub>4</sub> and CO<sub>2</sub> are different, they have similar viscosities and behave as buoyant fluids. Furthermore, CO<sub>2</sub> injection rates into storage reservoirs will likely be comparable to CH<sub>4</sub> injection rates into natural gas storage sites. Thus, examples of CH<sub>4</sub> leakage from natural gas storage sites can serve as industrial analogues for CO<sub>2</sub> leakage.

Together, natural and industrial analogues for CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>4</sub> leakage related to industrial processes are given. Focus is placed on CO<sub>2</sub> 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<sub>2</sub> leakage and (2) a relatively large number of examples of natural CO<sub>2</sub> leakage events are reported in the literature.

To compare the key characteristics of CO<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> accumulation, the events leading to the leakage of CO<sub>2</sub> or CH<sub>4</sub> from the reservoir, and the processes by which the CO<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> in the accumulation, and the geologic

**Table 1** Summary of FEPs of natural leakage of CO<sub>2</sub> (see Appendix A for references)

Site	CO <sub>2</sub> source	Geologic model for accumulation	Event triggering leakage	Pathway for leakage	Type of surface leakage
<b>A1.</b> 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
<b>A2.</b> Solfatara, Italy	Magmatic + thermal decomposition of carbonates	Relatively shallow zone of fractured rock contains gas phase and overfiles aquifers, then magma body at several km depth	No specific leakage event captured	Faults and fractures	Diffuse and vent
<b>A3.</b> 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
<b>A4.</b> Clear Lake, CA, USA	Thermal decomposition of metasedimentary rocks, minor magmatic component	CO <sub>2</sub> derived from liquid-dominated geothermal reservoir hosted in marine metasedimentary rocks	No specific leakage event captured	Faults and fractures	Gas vents, springs
<b>A5.</b> Latera caldera, Italy	Thermal decomposition of carbonates, magmatic component	CO <sub>2</sub> accumulates in liquid-dominated, carbonate geothermal reservoir capped by hydrothermally altered volcanics	No specific leakage event captured	Faults and fractures	Diffuse, vent, spring
<b>A6.</b> Mátradereske, Hungary	Geothermal/copper-zinc mineralization	CO <sub>2</sub> accumulates in karst water reservoir (~1 km depth)	No specific leakage event captured	Faults and fractures	Diffuse, vent, spring
<b>A7.</b> Dieng, Indonesia	Magmatic	Unknown	Volcanic, possibly “pneumatic”, eruptions	Fissure	Eruptive, gas vents, springs
<b>A8.</b> Southern Negros, Philippines	Geothermal	Unknown	Unknown	Faults	Gas vents, springs, diffuse (kaipohans)
<b>A9.</b> Rabaul, Papua New Guinea	Magmatic	Unknown	Unknown	Fractures	Fast, vent
<b>A10.</b> 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)
<b>A11.</b> Laacher See, Germany	Magmatic	NA	Seasonal lake overturn and mixing	NA	Diffusive and bubbling from lake surface, diffuse from lake shore
<b>A12.</b> 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
<b>A13.</b> 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<sub>2</sub> or CH<sub>4</sub> (see Appendix B for references)

Site	CO <sub>2</sub> or CH <sub>4</sub> source	Geologic model for accumulation	Event triggering leakage	Pathway for leakage	Type of surface leakage
<b>B1.</b> 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 <sub>2</sub> gas from well, CO <sub>2</sub> leakage from fractures above drill site
<b>B2.</b> 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
<b>B3.</b> 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 <sub>2</sub> gas leakage from soils, water-filled pool formation around well
<b>B4.</b> Torre Alfina geothermal field, Italy	Geothermal	Geothermal reservoir with a gas CO <sub>2</sub> cap at ~660 m depth, capped by sequences of shales, marls, and limestones	Well blowout	Well	Free flowing CO <sub>2</sub> gas from well, diffuse emissions from ground around well
<b>B5.</b> 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
<b>B6.</b> 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
<b>B7.</b> 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
<b>B8.</b> 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<sub>2</sub> or CH<sub>4</sub> 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 <sub>2</sub> or CH <sub>4</sub> leakage	Consequences of release	Monitoring and remedial measures
<b>A1.</b> Mammoth Mountain, CA USA (N)	Recreational area (US national forest, ski resort)	~250 t day <sup>-1</sup> from 480,000 m <sup>2</sup> area	Formation of tree kill areas, one person with symptoms of asphyxiation, four people killed	Temporal and spatial monitoring of CO <sub>2</sub> concentrations and fluxes in tree kill areas; measurements of groundwater chemistry; public education
<b>A2.</b> Solfatarara, Italy (N)	Recreational area (private park/campground) surrounded by urban area	1,500 t day <sup>-1</sup> from 0.5 km <sup>2</sup> area	No vegetation in degassing area	Temporal and spatial monitoring of soil CO <sub>2</sub> fluxes, monitoring of heat release; monitoring of fumarole gas chemistry; seismic and deformation monitoring; public education
<b>A3.</b> Albani Hills, Italy (N)	Urban area	74 t day <sup>-1</sup> as surface gas emissions (61,000 m <sup>2</sup> area) and 506 t day <sup>-1</sup> as dissolved CO <sub>2</sub> in shallow ground water ~1 t day <sup>-1</sup>	High CO <sub>2</sub> concentrations in homes; deaths of livestock (1999 event); past human deaths Four people killed	Measurements of soil CO <sub>2</sub> fluxes and concentrations; monitoring groundwater chemistry; identification of residential areas at risk; development of zoning bylaws, and development of public education programs Measurements of soil and vent CO <sub>2</sub> fluxes and concentrations, mineral pool closed to public Soil gas concentration surveys, hazard mapping
<b>A4.</b> Clear Lake, CA, USA (N)	Rural	Unknown	Vegetation stress or kill	CO <sub>2</sub> detection and control devices installed in homes, demolition of homes with hazardous CO <sub>2</sub> levels, public education Vent gas chemical analysis
<b>A5.</b> Latera caldera, Italy (N)	Rural, small towns	Unknown	High CO <sub>2</sub> concentrations in homes, death of several people ~145 people killed, vegetation stress or kill	Vent and diffuse gas chemical analysis
<b>A6.</b> Mátraderecske, Hungary (N)	Rural area, village	Average CO <sub>2</sub> flux ~200–400 g m <sup>-2</sup> day <sup>-1</sup> (total degassing area unknown) Unknown	Three people killed, birds killed	NA
<b>A7.</b> Dieng, Indonesia (N)	Rural	Unknown	Loss of human (~1800 combined) and animal life (e.g., thousands of cattle), vegetation damage NA	Controlled lake degassing using pipes, monitoring of lake chemistry, public education
<b>A8.</b> Southern Negros, Philippines	Rural	Unknown	NA	Monitoring CO <sub>2</sub> fluxes and concentrations from lake surface and shore
<b>A9.</b> Rabaul, Papua New Guinea	Rural	Unknown	NA	Measurements of soil CO <sub>2</sub> fluxes; monitoring groundwater chemistry
<b>A10.</b> Lakes Monoun and Nyos, Camaroon (N)	Rural, villages	Nyos: 240,000 t CO <sub>2</sub> in eruptive event ~14 t day <sup>-1</sup>	NA	Measurements of groundwater chemistry
<b>A11.</b> Laacher Sec, Germany (N)	Rural	Soil CO <sub>2</sub> fluxes up to 100 g m <sup>-2</sup> day <sup>-1</sup> ; total emission rate unknown Unknown	NA	Dynamic injection of drag-reduced brine followed by mud
<b>A12.</b> Paradox Basin, UT, USA (N)	Rural	Unknown	NA	Measurements of atmospheric CO <sub>2</sub> concentrations
<b>A13.</b> Florina Basin, Greece (N)	Rural, small towns	Unknown	Death of one person	Leakage area closed off to people
<b>B1.</b> Sheep Mountain, CO, USA (I)	Rural	Unknown		
<b>B2.</b> Paradox Basin, UT, USA (I)	Rural	Crystal Geyser: ~33 t day <sup>-1</sup>		
<b>B3.</b> Florina Basin, Greece (I)	Rural, small towns	Unknown		

Table 3 continued

Site	Geographic setting/land use	Magnitude of surface CO <sub>2</sub> or CH <sub>4</sub> leakage	Consequences of release	Monitoring and remedial measures
<b>B4.</b> 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 <sub>2</sub> at height in atmosphere; atmospheric CO <sub>2</sub> concentration monitoring
<b>B5.</b> Travale geothermal field, Italy (I)	Rural	Unknown	NA	Well allowed to discharge fluid, monitoring of fluid temperature, pressure, and chemistry
<b>B6.</b> Yaggy gas storage facility, KA, USA	Small town	Unknown	Gas explosions, two people killed, buildings damaged	Geophysical monitoring, wells plugged
<b>B7.</b> Leroy gas storage facility, WY, USA	Rural	~1.8 × 10 <sup>7</sup> m <sup>3</sup>	NA	Tracer tests, decreased injection pressures
<b>B8.</b> Kingfisher, OK, USA	Rural	Unknown	NA	Geophysical, geochemical monitoring. Well plugged.

NA not analysed

model for CO<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> from the reservoir. Columns 5 and 6 give the processes by which the CO<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> leakage. First, the sources of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> leakage, once the CO<sub>2</sub> leaks from the storage reservoir, fault and/or fracture zones are the primary pathways for CO<sub>2</sub> 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<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> leakage (Tables 1, 2). The depth of the CO<sub>2</sub> or CH<sub>4</sub> source and the reservoir(s) in which the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> reservoirs at a given site.

Some examples of natural CO<sub>2</sub> 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<sub>2</sub> reservoir.

Finally, the style of natural CO<sub>2</sub> 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<sub>2</sub> release may have been a self-enhancing or eruptive process (analogues A7, A10). In the case of CO<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> 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<sub>2</sub> or CH<sub>4</sub> release varies widely between different cases and does not necessarily depend on the style of the release. For example, the magnitude of diffuse CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> was monitored in the near-surface environment within and around CO<sub>2</sub> leakage areas, often on a regular basis (analogues A1–A6, A8–A12, B2, B4). Monitoring strategies include measurements of soil CO<sub>2</sub> flux using accumulation chamber or eddy covariance methods and soil, atmospheric, or vent gas CO<sub>2</sub> concentration using gas analyser or chromatography techniques. Controlled degassing of CO<sub>2</sub>-rich lakes has also been carried out to mitigate CO<sub>2</sub> buildup (analogues A10). In many cases, public education programs were implemented to advise people visiting or living near the CO<sub>2</sub> 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<sub>2</sub> emission areas (e.g., analogues A3, A6). The hazard to human health was small in most examples of surface CO<sub>2</sub> releases; this could be attributed in part to public education and CO<sub>2</sub> monitoring programs.

### Conclusions and lessons learned

Leakage of CO<sub>2</sub> has occurred naturally from geologic reservoirs in numerous volcanic, geothermal, and sedimentary basin settings. In addition, CO<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> or CH<sub>4</sub> leakage are unique to each case, five general FEPs were identified based on analysis of a range of natural and industrial analogues for CO<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> should therefore be properly characterized at potential geologic carbon sequestration sites.
2. Many natural releases of CO<sub>2</sub> 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<sub>2</sub> from a storage reservoir should be evaluated.

3. Unsealed fault and fracture zones can act as fast and direct conduits for CO<sub>2</sub> flow from depth to the surface. Risk assessment should therefore emphasize determining the potential for and nature of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> to the surface, particularly in depleted oil or gas reservoir systems, where wells are abundant.
5. The style of CO<sub>2</sub> release at the surface varies widely between and within different leakage sites. In rare circumstances, the release of CO<sub>2</sub> can be a self-enhancing and/or eruptive process; this possibility should be assessed in the case of CO<sub>2</sub> 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<sub>2</sub> leakage. This could result from implementing public education and CO<sub>2</sub> monitoring programs; these “remedial” programs should therefore be employed to minimize potential health, safety, and environmental effects associated with CO<sub>2</sub> leakage. Second, while changes in groundwater chemistry can be related to CO<sub>2</sub> 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<sub>2</sub> leakage from storage sites.

**Acknowledgments** We are grateful to C.M. Oldenburg, S. Brennan, and an anonymous reviewer for constructive review of this manuscript. We thank the US Environmental Protection Agency, Office of Water and Office of Air and Radiation for funding this study under an Interagency Agreement with the US Department of Energy at the Lawrence Berkeley National Laboratory, Contract No. DE-AC02-05CH11231.

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