Evaluating Potential for Large Releases from CO_2 Storage Reservoirs: Analogues, Scenarios, and Modeling Needs

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Introduction

While the purpose of geologic storage of CO_2 in deep saline formations is to trap greenhouse gases underground, the potential exists for CO_2 to escape from the target reservoir, migrate upward along permeable pathways, and discharge at the land surface. Such discharge is not necessarily a serious concern, as CO_2 is a naturally abundant and relatively benign gas in low concentrations. However, there is a potential risk to health, safety and environment (HSE) in the event that large localized fluxes of CO_2 were to occur at the land surface, especially where CO_2 could accumulate. In this paper, we develop possible scenarios for large CO_2 fluxes based on the analysis of natural analogues, where large releases of gas have been observed. We are particularly interested in scenarios which could generate sudden, possibly self-enhancing, or even eruptive release events. The probability for such events may be low, but the circumstances under which they might occur and potential consequences need to be evaluated in order to design appropriate site selection and risk management strategies. Numerical modeling of hypothetical test cases is needed to determine critical conditions for such events, to evaluate whether such conditions may be possible at designated storage sites, and, if applicable, to evaluate the potential HSE impacts of such events and design appropriate mitigation strategies.

Methodology and Results

Various natural analogues with large releases of CO_2 have been evaluated, placing emphasis on the geologic model for CO_2 accumulation, processes leading to the releases of CO_2, pathways for migration, and type of release at the surface. Table 1 gives a summary of these analogues and their characteristics. While detailed information on geologic models of accumulation or on migration pathways is often unavailable, a few general conclusions can be drawn with respect to release scenarios and modeling studies important for the risk assessment of geologic storage of CO_2.

1. Large releases often originate from natural CO_2 plumes that have risen from depth and accumulated under low-permeability caprock. This suggests that the possibility of large CO_2 discharges at the land surface is not necessarily linked to fast release from the primary storage formation. In fact, the length of the flow pathway from depth and various mitigating effects make such a scenario rather unlikely. Conditions more conducive to a large, sudden release would involve accumulation of slowly leaking CO_2 in a secondary formation closer to the land surface. Suitable conditions could be provided by an anticlinal

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structure with a good caprock, where CO_2 can accumulate until it reaches a spillpoint. It is thus important to consider the potential for secondary storage reservoirs in a site evaluation and, if applicable, to determine the accumulation and possible release of CO_2 from such secondary reservoirs in numerical modeling studies.

2. Faults and fracture zones are the main pathways for gas migration in most natural analogues with large CO_2 discharge. It is thus mandatory to be able to predict qualitatively and quantitatively the fast upward flow of CO_2 in high-permeability zones that may extend from depth to surface. It is possible that such pathways are generated during or after injection by disruptive events related to geomechanical failures or seismic activity. During upward migration, CO_2 is affected by transitions from super- to sub-critical conditions, by phase changes between liquid and gaseous CO_2, phase partitioning between water-rich and CO_2-rich phases, and adiabatic cooling as a result of pressure loss. Modeling such behavior is a complex task. Only recently has a multiphase flow simulator been developed that handles the entire range of such thermodynamic conditions, but application so far has been limited to simple test cases (Pruess, 2004). A series of hypothetical, yet realistic scenarios with fast CO_2 pathways should be modeled, while capturing as much "thermodynamics" as possible. Such studies would serve to gain a better understanding of the fluid flow and heat transfer processes that would accompany CO_2 migration away from the primary storage reservoir, towards shallow depths and ultimately to the land surface. Some of these processes are beneficial in that they prevent or retard upward migration (e.g., through attenuation in multi-layer systems; energy losses through adiabatic cooling), others may enhance CO_2 upflow (e.g., through stress-induced increases in fault permeability; reduced phase interference with water as CO_2 saturation increases).

3. There is rather inconclusive evidence from natural analogues that CO_2 presence could lead to pneumatic eruptions, i.e., self-enhancing, violent CO_2 releases driven by high-pressure gas (Giggenbach et al., 1991; Benson et al., 2002). As opposed to the well-understood hydrothermal eruptions, where depressurization of a hot water reservoir may cause buoyant runaway of steam, pneumatic eruptions would not require substantial contributions of thermal energy. Pneumatic eruptions would be particularly harmful if occurring close to the land surface, which requires the accumulation of a large CO_2 volume pressurized in a secondary storage reservoir. A self-enhancing, possibly eruptive escape of CO_2 could be initiated by a sudden pressure loss in combination with the opening of a permeable pathway, as triggered, for example, by a seismic event, pressure-induced fracturing, or the drilling of a water-well into the reservoir. CO_2 present as a separate gas phase would move upward by buoyancy forces and pressure differences. CO_2 dissolved in water would be subject to rapid degassing following depressurization, which could result in an eruption of rising, expanding bubbles. It is not clear at present whether such pneumatic eruptions are possible under thermodynamic and hydrogeologic conditions representative of CO_2 injection sites. Numerical modeling studies covering a wide range of realistic to extreme scenarios could help determine the risks and consequences of pneumatic eruptions, and could evaluate whether such events are possible for designated storage sites.

Conclusions

Natural analogues with significant CO_2 discharges at the land surface have been evaluated to identify case scenarios and related modeling needs in support of risk assessment for geological storage of CO_2. The focus is on conditions that could generate large, possibly self-enhancing, or even eruptive release events. We discuss three areas where further numerical analyses would be beneficial, and will present some example simulations.

References

Benson S.M., R. Hepple, J. Apps, C.F. Tsang, and Lippmann, M., 2002, Lessons learned from natural and industrial analogs for storage of carbon dioxide in deep geological formations. Lawrence Berkeley National Laboratory Report LBNL-51170, Berkeley CA, 2002.

Giggenbach W.F., Y. Sano, and H.U. Schmincke, 1991. CO2-rich Gases from Lakes Nyos and Monoun, Cameroon; Lacher See, Germany; Dieng, Indonesia, and Mt. Gambier, Australia – Variations on a Common Theme. J. Volcanol. Geotherm. Res., Vol. 45, pp. 311 - 323.

Pruess K., 2004: Numerical simulation of CO_2 leakage from a geologic disposal reservoir, including transitions from super to sub-critical conditions, and boiling of liquid CO_2. Soc. Pet. Eng. J., June 2004, pp. 237 - 248.

Table 1 Summary of natural analogs with large releases of CO_2

Site	**CO_2 Source**	**Geologic model for accumulation**	**Event triggering leakage**	**Pathway for leakage**	**Type of release**
Mammoth Mountain, CA USA	Magmatic + thermal decomposition of carbonates	Accumulation at ~2 km depth in porous/fractured rock under caprock	Dike injection and seismic activity	Faults and fractures	Fast, diffuse, vent, spring
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 release event captured	Faults and fractures	Diffuse and vent
Mátraderecske, Hungary	Geothermal/copper-zinc mineralization	CO_2 accumulates in karst water reservoir (~1 km depth)	No specific release event captured	Faults and fractures	Diffuse, vent, spring
Latera caldera, Italy	Thermal decomposition of carbonates	CO_2 accumulates in liquid-dominated, carbonate geothermal reservoir capped by hydrothermally altered volcanics	No specific release event captured	Faults and fractures	Diffuse, vent, spring
Albani Hills, Italy	Magmatic + thermal decomposition of carbonates	Deep pressurized reservoirs in structural highs of sedimentary bedrock	Slow leakage, plus sudden large releases possibly triggered by seismic activity	Faults and fractures	Fast, diffuse, vent, and spring/well
Dieng, Indonesia	Magmatic	Unknown	Volcanic, possibly “pneumatic” eruptions	Fissure	Eruptive

Rabaul, Papua New Guinea	Magmatic	Unknown	Unknown	Fractures	Fast, vent
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
Laacher See, Germany	Magmatic	NA	Seasonal lake overturn and mixing	NA	Diffuse and bubbling from lake surface, diffuse from lake shore
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 release event captured	Faults and fractures	Gas vents, springs
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 release event captured	Faults and fractures	Diffuse, gas seeps, springs
Florina Basin, Greece	Thermal decomposition of carbonates	Reservoirs are vertically stacked, limestone and sandstone units, capped by silts and clays.	No specific release event captured	Slow leakage along rock discontinuities	Springs, gas seeps