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Evaluating Potential for Large Releases from CO₂ Storage Reservoirs: Analogues, Scenarios, and Modeling Needs

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Introduction

While the purpose of geologic storage of CO₂ in deep saline formations is to trap greenhouse gases underground, the potential exists for CO₂ 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 CO₂ 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 CO₂ were to occur at the land surface, especially where CO₂ could accumulate. In this paper, we develop possible scenarios for large CO₂ 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 CO₂ have been evaluated, placing emphasis on the geologic model for CO₂ accumulation, processes leading to the releases of CO₂, 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 CO₂.

1. Large releases often originate from natural CO₂ plumes that have risen from depth and accumulated under low-permeability caprock. This suggests that the possibility of large CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ discharge. It is thus mandatory to be able to predict qualitatively and quantitatively the fast upward flow of CO₂ 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, CO₂ is affected by transitions from super- to sub-critical conditions, by phase changes between liquid and gaseous CO₂, phase partitioning between water-rich and CO₂-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 CO₂ 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 CO₂ 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 CO₂ upflow (e.g., through stress-induced increases in fault permeability; reduced phase interference with water as CO₂ saturation increases).
3. There is rather inconclusive evidence from natural analogues that CO₂ presence could lead to pneumatic eruptions, i.e., self-enhancing, violent CO₂ 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 CO₂ volume pressurized in a secondary storage reservoir. A self-enhancing, possibly eruptive escape of CO₂ 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. CO₂ present as a separate gas phase would move upward by buoyancy forces and pressure differences. CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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.

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Table 1 Summary of natural analogs with large releases of CO₂

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