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Large releases from CO_2 storage reservoirs: analogs, scenarios, and modeling needs

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Abstract

While the purpose of geologic storage 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. In this paper, we evaluate the potential for such CO_2 discharges based on the analysis of natural analogs, where large releases of gas have been observed. We are particularly interested in circumstances that could generate sudden, possibly self-enhancing release events. The probability for such events may be low, but the circumstances under which they occur and the potential consequences need to be evaluated in order to design appropriate site-selection and risk-management strategies. Numerical modeling of hypothetical test cases is suggested to determine critical conditions for large CO_2 releases, to evaluate whether such conditions may be possible at designated storage sites, and, if applicable, to evaluate the potential impacts of such events as well as design appropriate mitigation strategies.

Keywords: CO_2, storage, natural analogs, faults

Introduction

Large amounts of CO_2 would need to be injected into deep geological formations if geological sequestration is chosen as a viable option for reducing greenhouse gas emissions to the atmosphere. The extent of injected CO_2 plumes would be on the order of 100's of km^2, making it likely that caprock imperfections are encountered allowing some CO_2 to escape from the intended storage formation. At typical temperature and pressure conditions, CO_2 is less dense than water, and therefore is buoyant in most subsurface environments. Thus, leaking CO_2 would have the tendency to migrate upwards into the shallow subsurface and ultimately to the atmosphere. Discharge at the land surface is not necessarily a 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. Large-magnitude releases of gas (e.g., CO_2, natural gas) from depth to the near-surface environment that have occurred in natural settings can serve as analogs for the potential release of CO_2 from geologic storage sites. Analysis of these analogs provides important insight into the features, events, and processes associated with the CO_2 release, as well as the needs for further evaluation and modeling analysis.

Methodology and Results

Various natural analogs 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 [1]. Table 1 gives a summary of these natural analogs and their key characteristics. Industrial analogs, which may include well blowouts during drilling of new wells or leakage along existing wells with insufficient plugs, have not been evaluated in this paper. While the large number of abandoned wells is a major concern for storage of CO_2 in depleted or near-depleted oil and gas reservoirs [2], they may be of smaller importance for deep saline formations, simply because deep wells are much less abundant.

Table 1.   Summary of natural 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	Seismic activity and reservoir pressurization	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 releases with several sudden large releases also occurring, possibly triggered by seismic activity	Faults and fractures	1995 and 1999 events Fast, diffuse, vent, 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 (limnic)
Laacher See, Germany	Magmatic	NA	Seasonal lake overturn and mixing	NA	Diffusive 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 (upper unit at 300 m depth)., capped by silts and clays.	No specific release event captured	Slow leakage along rock discontinui-ties	Springs, gas seeps

While detailed information on geologic models of natural CO_2 accumulation or migration pathways is often unavailable, a few general conclusions can be drawn from the analog summary in Table 1 with respect to the risk assessment of geologic storage of CO_2.

1. Unsealed faults and fracture zones are the main pathways for gas migration in most natural analogs 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. During upward migration, CO_2 is affected by transitions from super- to sub-critical conditions, 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 decline. A series of hypothetical, yet realistic scenarios with fast CO_2 pathways should be modeled, while capturing as much "thermodynamics" as possible (see Section "CO_2 Migration Along a Fault"). 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 may be beneficial in that they prevent or retard upward migration (e.g., attenuation of CO_2 in multi-layer systems; energy losses through adiabatic cooling), while others may enhance CO_2 upflow (e.g., stress-induced increases in fault permeability; reduced phase interference).

2. Many natural releases of CO_2 have been correlated with a specific event that has triggered the release, such as seismic activity leading to geomechanical damage in sealing caprocks (e.g., hydraulic fracturing, fault slip and reactivation). The potential for processes to cause such damage and trigger the release of CO_2 from a storage reservoir should be evaluated with appropriate geomechanical modeling tools (see Section "Geomechanical Failure Analysis in a Multi-Layer System").

3. CO_2 can both accumulate beneath and be released from primary (deep) and secondary (shallow) reservoirs with caprock units located at a wide range of depths. In general, a sequence of caprock units above the intended storage formation would be a desirable feature for a geological sequestration site, because it provides additional barriers for leaking CO_2. However, when considering the possibility of large, sudden discharges at the land surface, accumulation of CO_2 in a secondary formation in the shallow subsurface could actually have detrimental effects. Consider for example a shallow anticlinal structure with a low-permeability caprock, where CO_2 leaking from depth would slowly accumulate. If the accumulated CO_2 would then be released, as triggered, for example, by sudden geomechanical damage of the sealing caprock, the pathway to the land surface might be too short to allow for significant mitigation or retardation of the plume. CO_2 present as a separate gas phase would move upward by buoyancy forces and pressure differences (Figure 1a). CO_2 dissolved in water would be subject to rapid degassing following depressurization, which could result in fast-rising expanding bubbles (Figure 1b). The potential for shallow CO_2 accumulation should be considered in site evaluation efforts and, if applicable, the possible release of CO_2 from such secondary accumulation should be evaluated in numerical modeling studies.
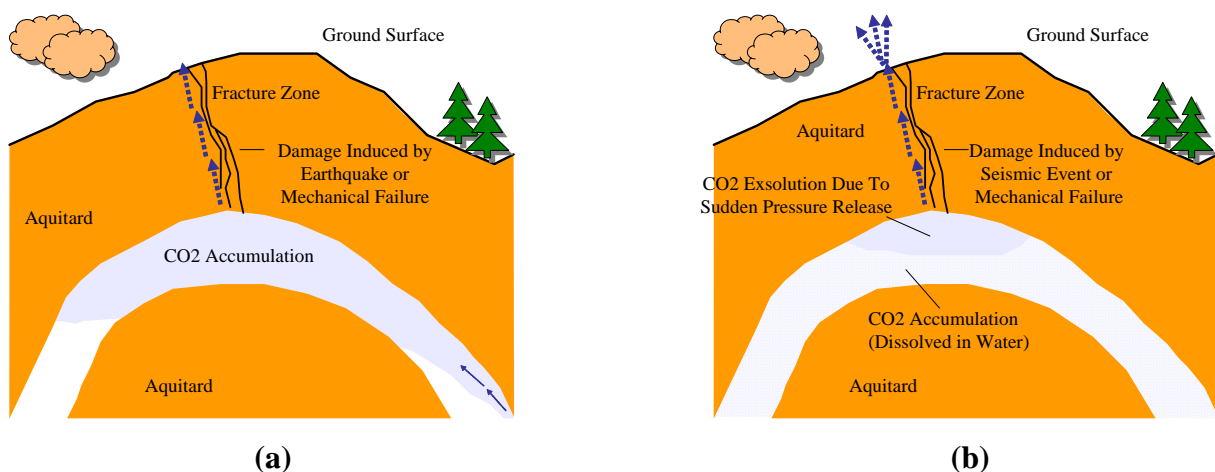

Figure 1. Sudden CO_2 leakage from secondary accumulation in shallow reservoirs. (a) CO_2 accumulates as a separate phase. (b) CO_2 is dissolved in water. A fracture or fault zone may develop as a result of geomechanical damage or in response to seismic activity.

4. There is rather inconclusive evidence from natural analogs that CO_2 presence could lead to pneumatic eruptions, i.e., self-enhancing, violent CO_2 releases driven by high-pressure gas [3, 4, 5]. 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 and sudden release of a large CO_2 volume pressurized in a shallow storage reservoir. It is not clear at present whether such pneumatic eruptions are physically possible under thermodynamic and hydrogeologic conditions representative of CO_2 injection sites. A thorough evaluation of the possibility of such high-energy discharges would be useful for demonstrating the technical feasibility of storing CO_2 in geologic reservoirs, and achieving public acceptance of the technology [5]. Numerical simulators that can handle the complex processes involved in pneumatic eruptions need to be developed for that purpose, and numerical modeling studies should be conducted covering a wide range of realistic to extreme scenarios, with the goal of gaining assurance that high-energy-eruptive releases are not possible.

Simulation Examples

Here we briefly summarize results of numerical simulation studies as examples of the type of scenario modeling needed to further our understanding of CO_2 storage and its related risks. The first example is on CO_2 leakage along a continuous fault zone from depth to surface. The focus is here on capturing the complex thermodynamics in detail to see whether self-limiting and self-enhancing features would tend to slow or accelerate the upward migration of CO_2. The second example involves geomechanical modeling to determine the potential for fault reactivation and hydraulic fracturing in a multi-layered reservoir-caprock system.

<u>CO_2 Migration along a Fault</u>

Figure 2 shows a schematic model of a fault zone, along with simulation results for CO_2 discharge through this fault. The fault initially contains water in a normal geothermal gradient of 30 °C/km with a land surface temperature of 15 °C, in hydrostatic equilibrium. CO_2 discharge is initiated by injecting CO_2 at an overpressure of approximately 10 bar in a portion of the fault at 710 m depth. The numerical simulation includes two- and three-phase flow of an aqueous phase and liquid and gaseous CO_2 phases in the fault, as well as conductive heat transfer with the wall rocks that are assumed impermeable [5, 6].
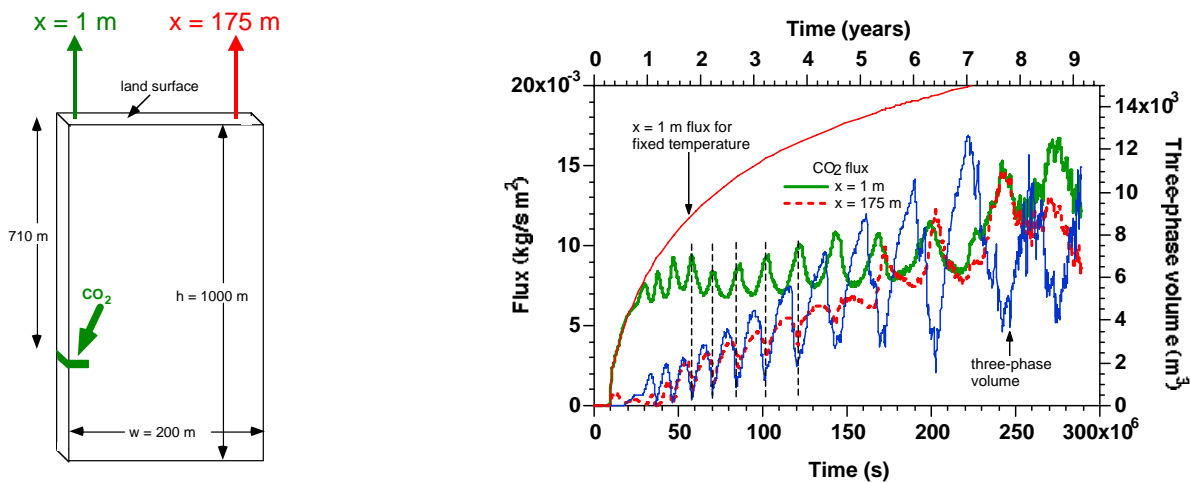

Figure 2. CO_2 leakage along a fault zone [5, 6]. A schematic model of a fault zone is shown on the left. The right panel gives temporal variation of CO_2 leakage fluxes at two different positions at the land surface. Total flow system volume with three-phase conditions is also shown.

4

Strong cooling occurs due to the Joule-Thomson effect as rising CO_2 expands. Additional temperature decline is evident when liquid CO_2 boils into gas. The simulations show persistent flow cycling with increasing and decreasing leakage rates at the land surface after a period of initial growth. Monotonic behavior is observed when flow-system temperatures are held constant at their initial values. The cyclic behavior is explained in terms of varying fluid phase composition, due to heat transfer limitations, giving rise to an interplay between self-enhancing and self-limiting features. Overall, the cyclic leakage rates are consistently smaller than those obtained from the fixed-temperature simulation, showing that Joule-Thompson cooling and other thermodynamic effects generate an overall slowing of CO_2 migration.

Geomechanical Failure Analysis in a Multi-Layer System

In a hypothetical multi-layer system, CO_2 is injected for 30 years in a 200-meter thick permeable saline water formation located at 1600 meters depth (Figure 3). Several layers of caprock as well as water-bearing formations are located above the intended injection unit, all of which are intersected by a permeable fault zone. During injection, CO_2 migrates laterally and upwards in the intended storage formation, driven by injection pressure and buoyancy forces. When the plume encounters the fault zone intersecting the containing caprock unit, a considerable amount of CO_2 migrates upwards, spreads laterally into the upper overlying zones, and may cause considerable fluid pressure increase there. Based on the changes in effective stresses, the potential for fault slip and fracturing are calculated [7].
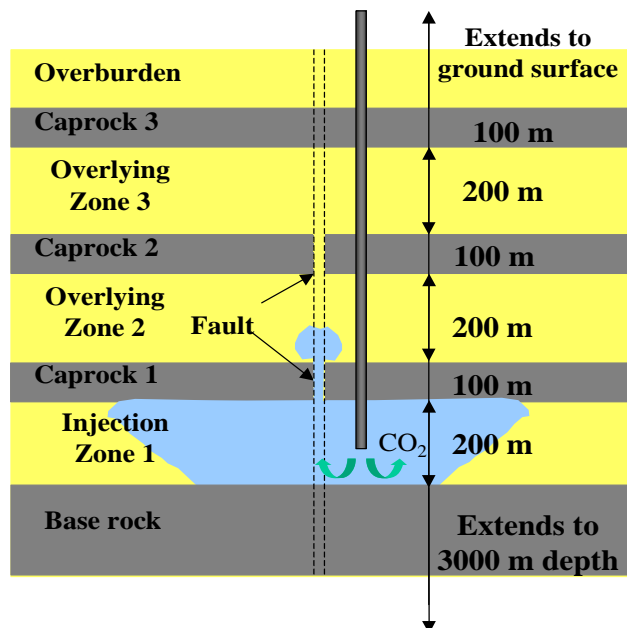

Figure 3.   Model geometry for simulation of CO_2 injection into a multilayered reservoir-caprock system

Figure 4 presents the potential for fault slip and hydraulic fracturing for two different initial stress regimes—a compressional stress regime (horizontal stress larger than vertical) and an extensional stress regime (horizontal stress smaller than vertical). Results are given in terms of pressure margins to the onset of shear slip or fracturing. A positive pressure margin in Figure 4 implies that the local fluid pressure may be above the critical pressure for onset of geomechanical damage. Dark contours indicate areas of the highest potential for onset of shear slip. Results suggest that, once leakage of CO_2 occurs, the potential for fault reactivation and fracturing could be larger in the overlying units than in the intended storage unit, a result of the smaller initial stresses in shallower units. Significant differences are observed between the compressional and extensional stress regimes. In the case of a compressional stress regime (Figure 4a), the shear slip is most likely to be initiated in subhorizontal fractures at the interface between the permeable formation layers and the overlying caprock unit. In the case of an extensional stress regime (Figure 4b), the shear slip is likely to occur in subvertical fractures in the uppermost aquifer and in the overburden. An extensional stress regime may also allow for hydraulic fracturing at the bottom of the uppermost caprock unit. Our analysis thus demonstrates that for evaluation of the maximum sustainable CO_2-injection pressure, it is essential to have a good estimate of the three-dimensional *in situ* stress field.
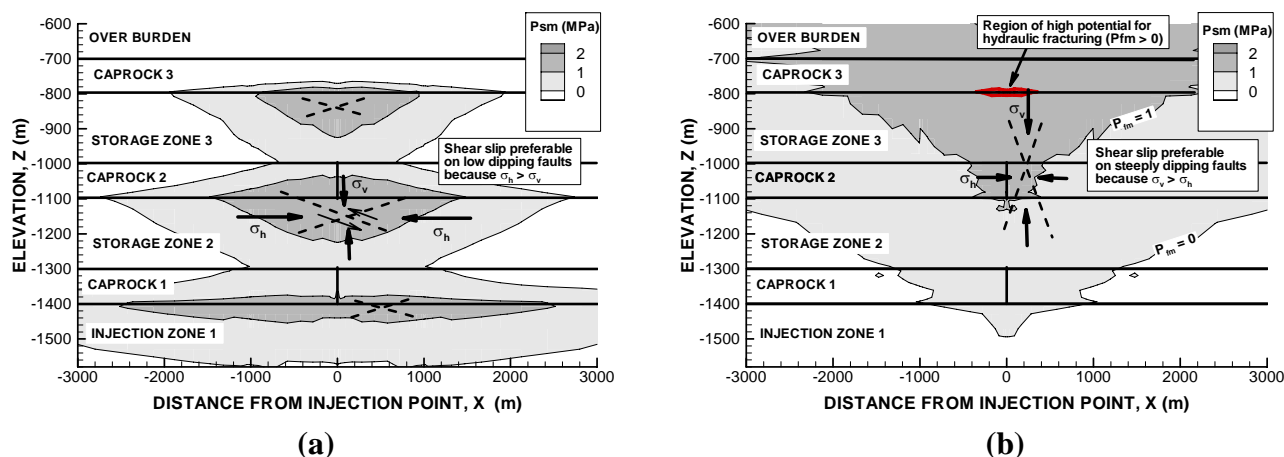
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Figure 4. Calculated pressure margin for shear slip under (a) compressional stress regime and (b) extensional stress regime. The one and only location for hydraulic fracturing is also indicated in (b).

Conclusions

Natural analogs 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. We have discussed areas where further numerical analyses on hypothetical, yet realistic scenarios would be beneficial, and have presented example simulations.

Acknowledgment

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