Assessing the potential of solubility trapping in unconfined aquifers for subsurface carbon storage

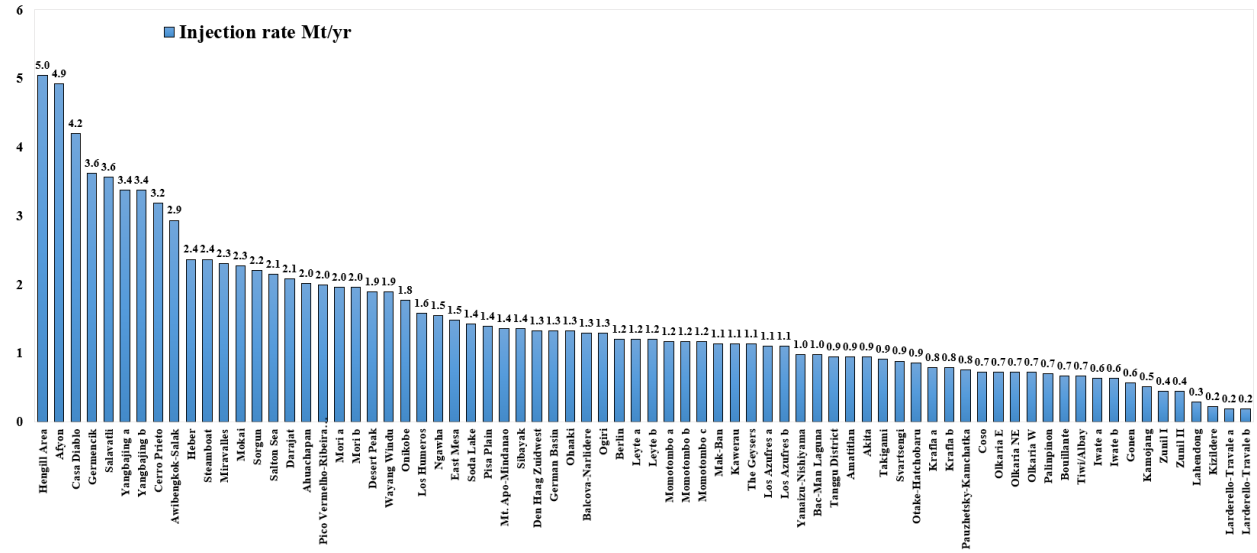
Mouadh Addassi[a*], Abdirizak Omar[a], Hussein Hoteit[a], Abdulkader M. Afifi[a], Serguey Arkadakskiy[b], Zeyad T. Ahmed[b], Noushad Kunnummal[b], Sigurdur R. Gislason[c], Eric H. Oelkers[d]

[a] King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia.
[b] Environmental Protection, Saudi Arabian Oil Company, Dhahran, Saudi Arabia
[c] Institute of Earth Sciences, University of Iceland, Sturlugötur 7, 102 Reykjavík, Iceland
[d] Géosciences Environnement Toulouse (GET), CNRS UMR 5563, France.

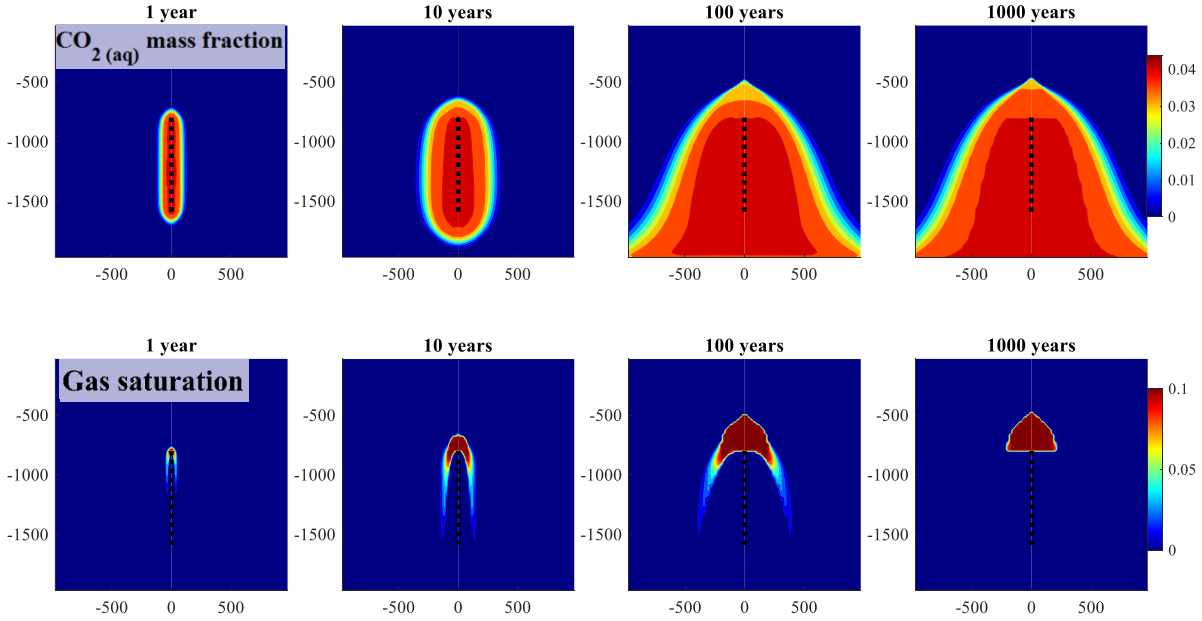
* Corresponding author email address: mouadh.addassi@kaust.edu.sa

SUPPLEMENTARY INFORMATION

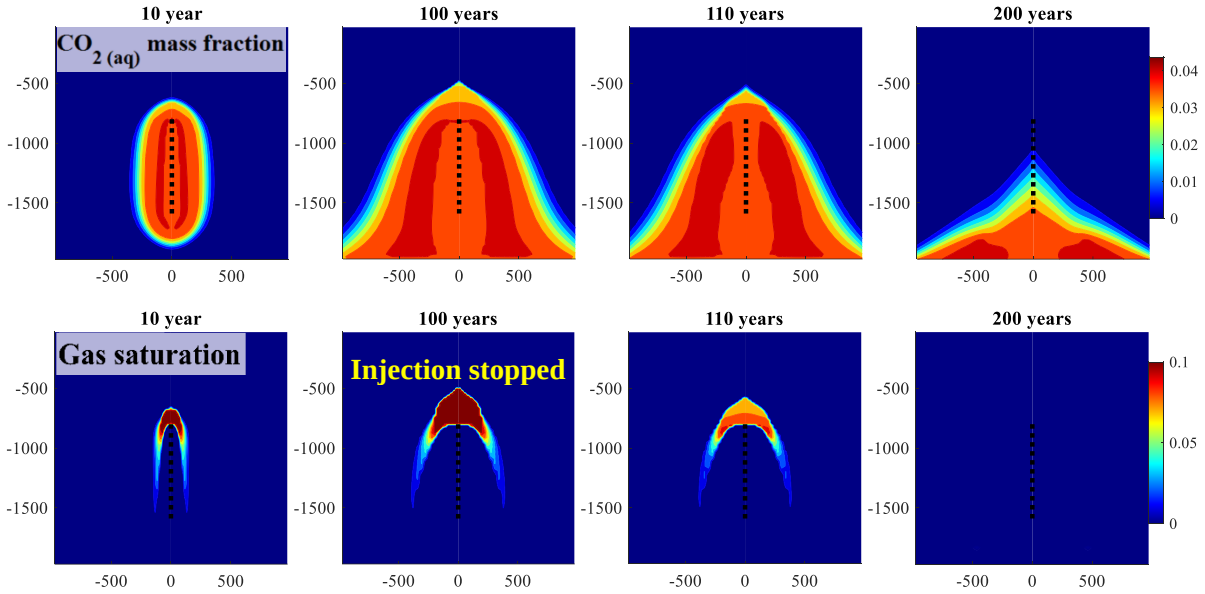
S1. Averaged annual re-injection rates per well for various geothermal projects. The rate per well was calculated from the total injection rate and the number of wells. Data collected by Hoteit et al. [42].



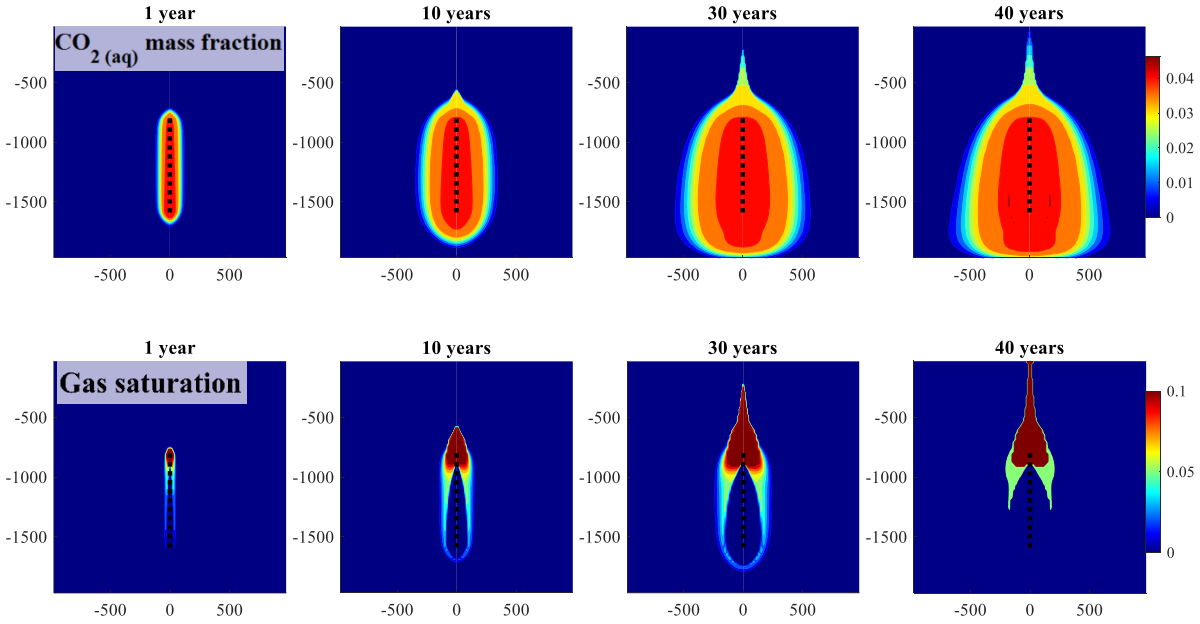
S2. Calculated CO_2 concentrations in the subsurface liquid and exsolved CO_2 mass fraction in the pore fluids after 1, 10, 100 and 1000 years of carbonated water injection. The results shown are for the 'reference system'. This system has a 30 ˚C/km gradient, a constant salinity of 35,000 ppm, equal to that of seawater, and water injection temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of the CO_2 concentration in the liquid phase whereas the lower plots show 2D cross sections of the CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



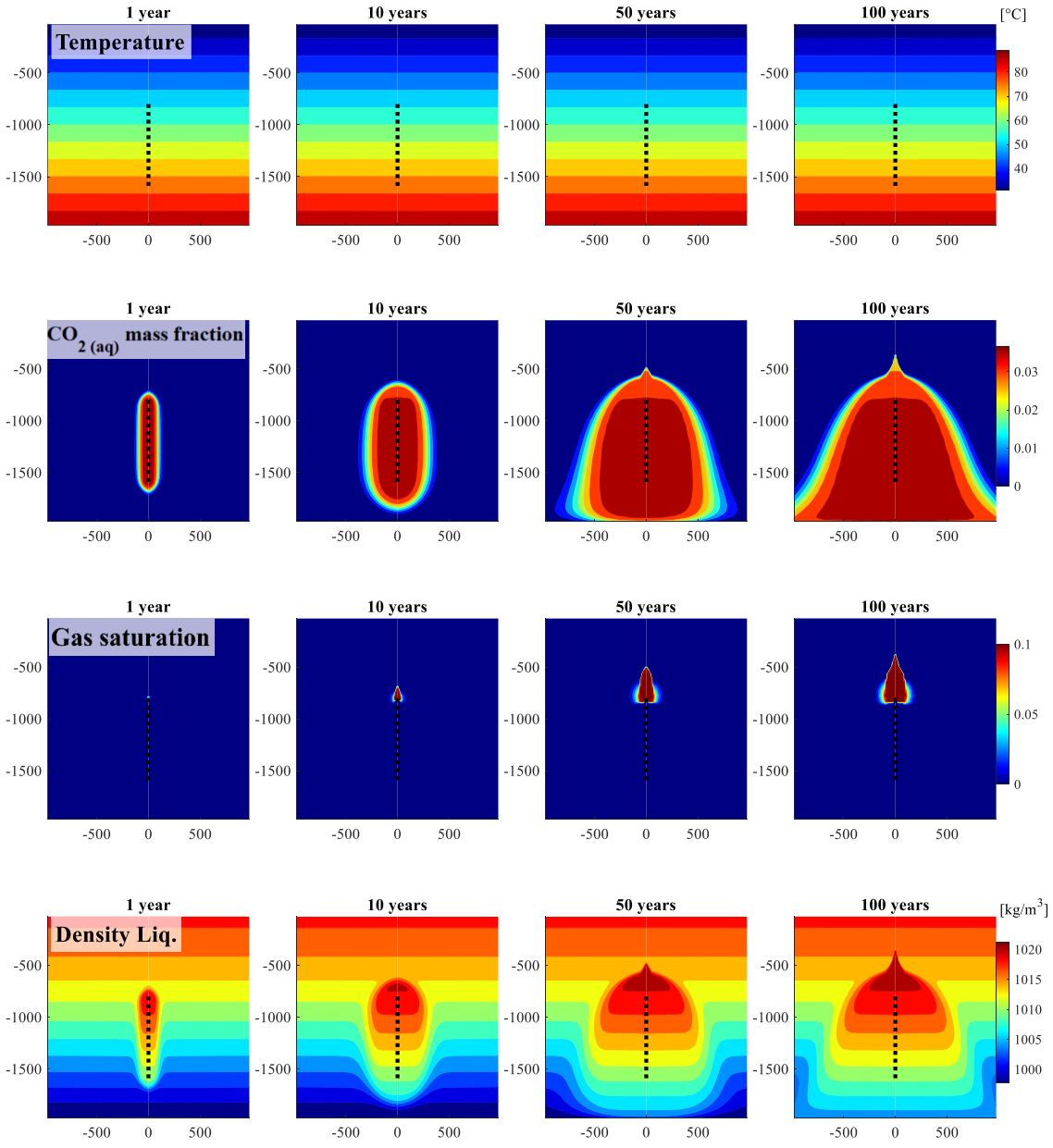
S3. Calculated CO_2 concentrations in the subsurface liquid and exsolved CO_2 mass fraction in the pore fluids 10, 100 years of carbonated water injection and 10 and 100 years after the end of the injection. The results shown are for the 'reference system'. This system has a 30 ˚C/km gradient, a constant salinity of 35,000 ppm, equal to that of seawater, and water injection temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of the CO_2 concentration in the liquid phase whereas the lower plots show 2D cross sections of the CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



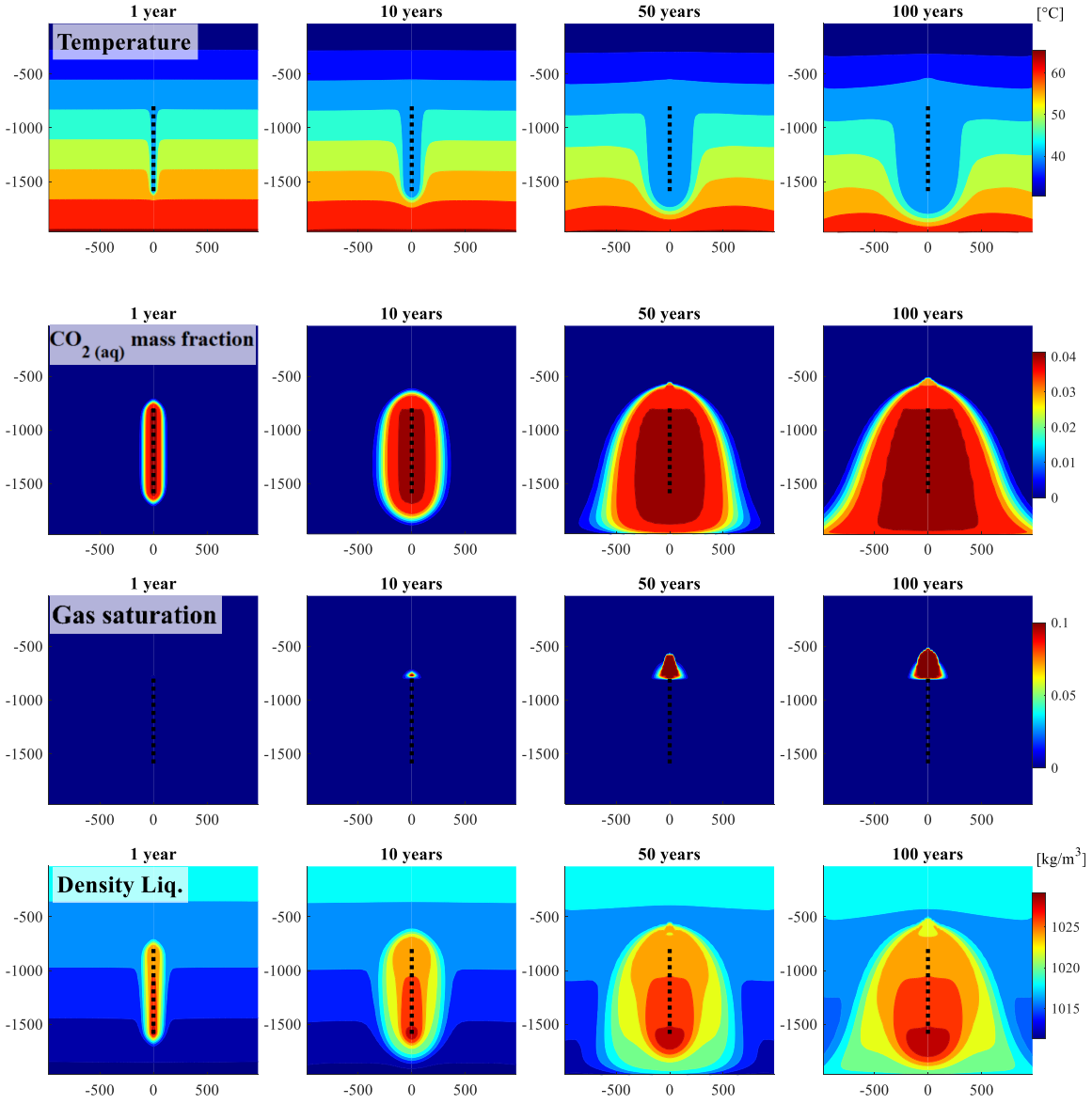
S4. Calculated CO_2 concentrations in the subsurface liquid and exsolved CO_2 mass fraction in the pore fluids after 1, 10, 30 and 40 years of carbonated water injection. The results shown are for the 'reference system'. This system has a 30 ˚C/km gradient, a constant salinity of 35,000 ppm, equal to that of seawater, and water injection temperature of 40 ˚C. The water to CO_2 injection mass ratio is 24:1. The upper plots show the 2D cross sections of the CO_2 concentration in the liquid phase whereas the lower plots show 2D cross sections of the CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone. Exsolved CO_2 reaches the surface after approximately 40 years of carbonate water injection.



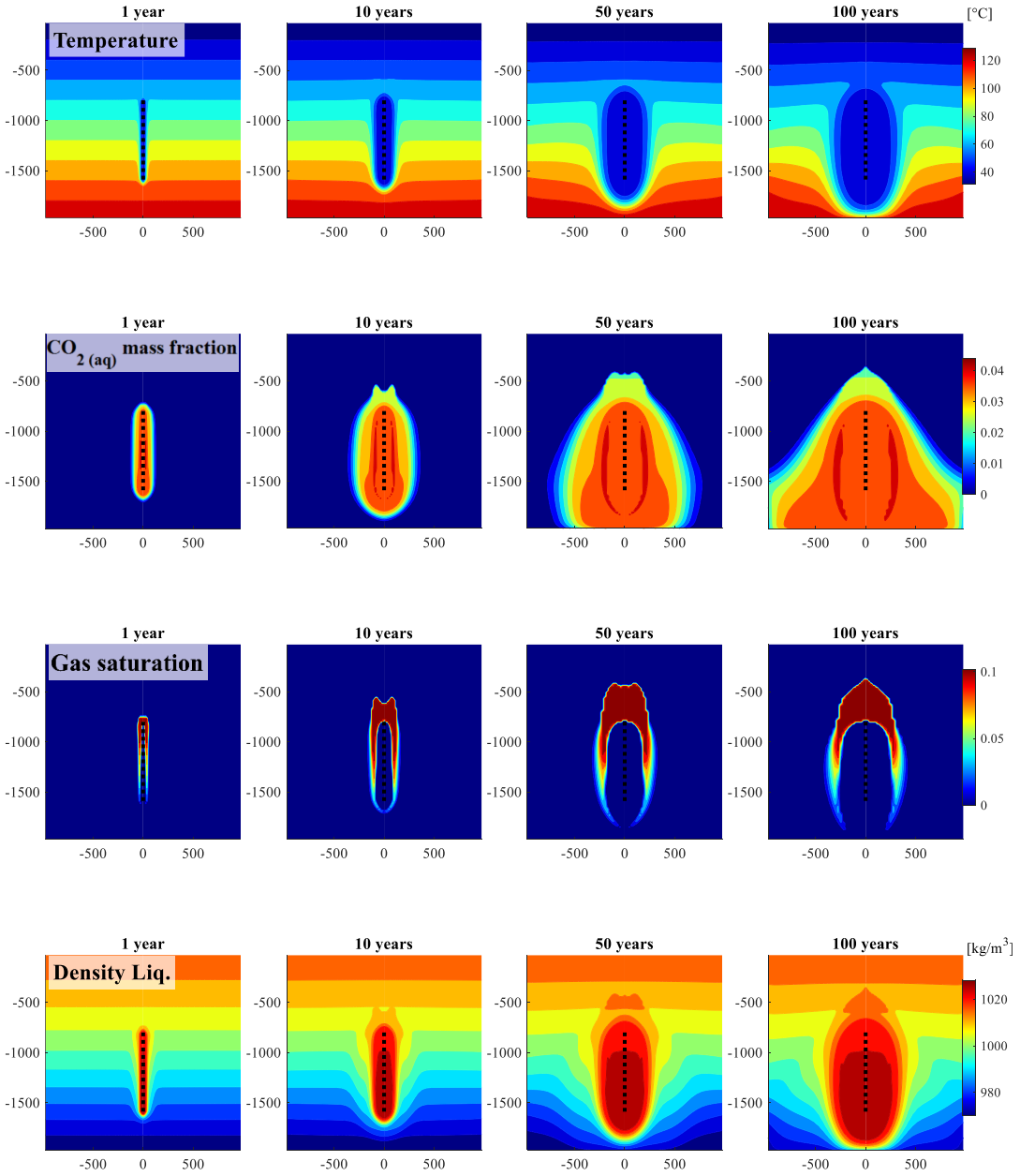
S5. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 1, 10, 50 and 100 years of carbonated water injection. The results shown are for the 'isothermal system'. This system has a 30 ˚C/km gradient, a constant salinity of 35000 ppm, equal to that of seawater. We exclude the impact of water injection temperature in this example, assuming isothermal reservoir conditions. The water to CO_2 injection mass ratio needed to prevent exsolved CO_2 from reaching the surface is 28:1. The upper plots show the 2D cross sections of temperature, followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



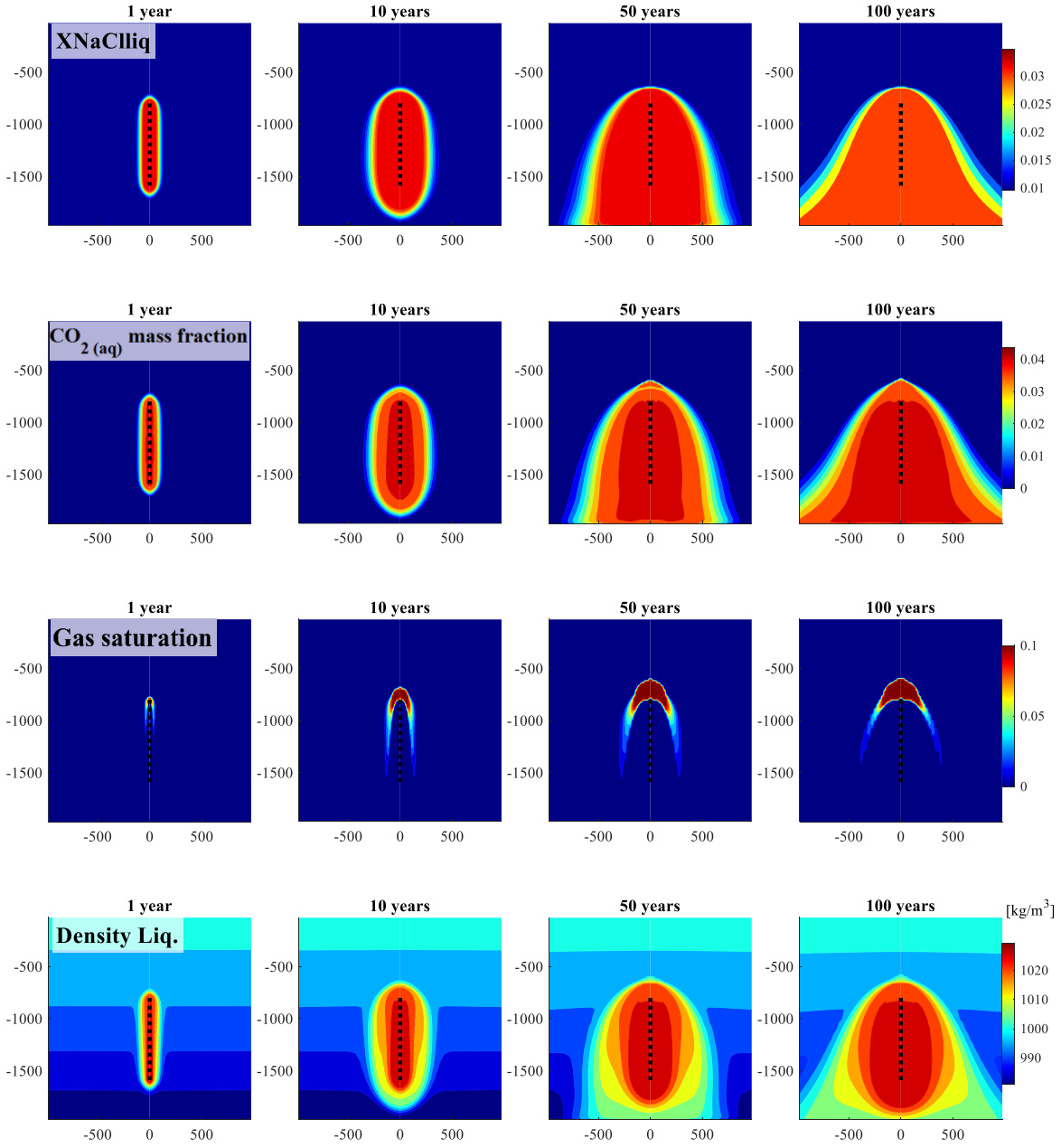
S6. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '18 ˚C/km temperature gradient system'. This system has a 18 ˚C/km gradient, a constant salinity of 35000 ppm, equal to that of seawater, and water injection temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of temperature, followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



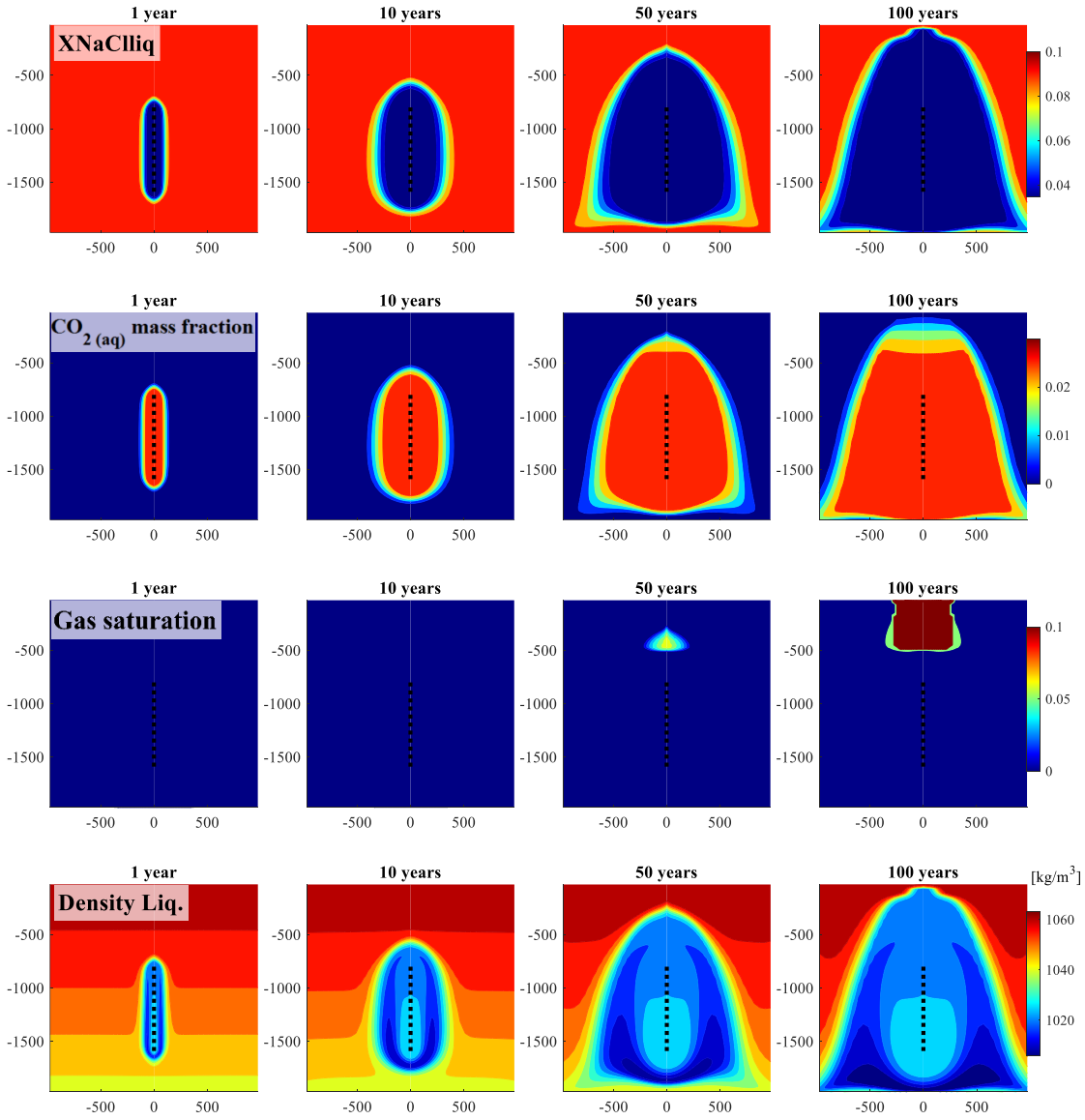
S7. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '50 ˚C/km temperature gradient system'. This system has a 50 ˚C/km gradient, a constant salinity of 35,000 ppm, equal to that of seawater, and water injection temperature of 40 ˚C. The water to CO_2 injection mass ratio is 26:1. The upper plots show the 2D cross sections of temperature, followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



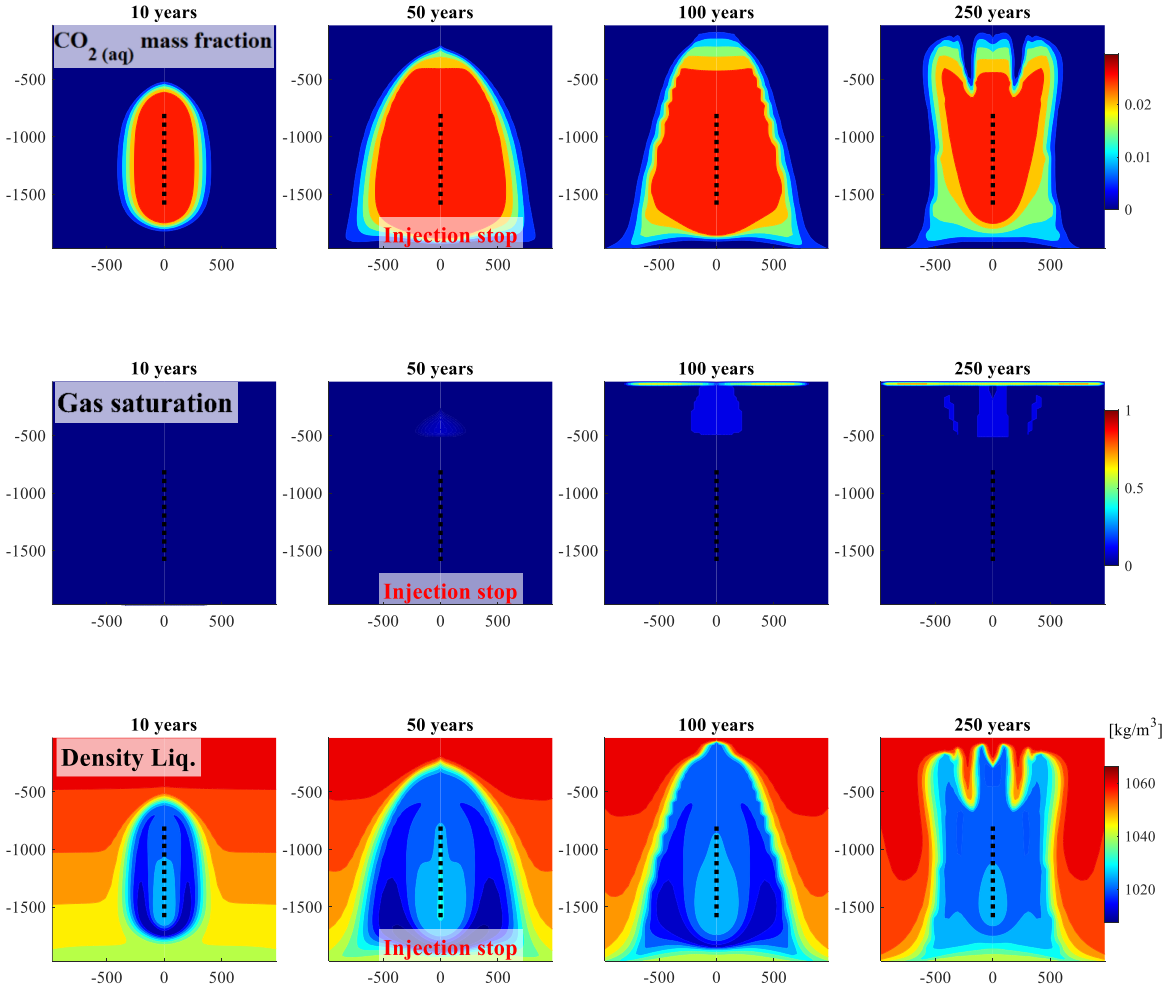
S8. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '10,000 ppm initial salinity system'. This system has a 30 ˚C/km gradient, a constant initial reservoir salinity of 10,000 ppm, injection water salinity of 35,000 ppm and temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of salinity (NaCl mass fraction in the liquid), followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



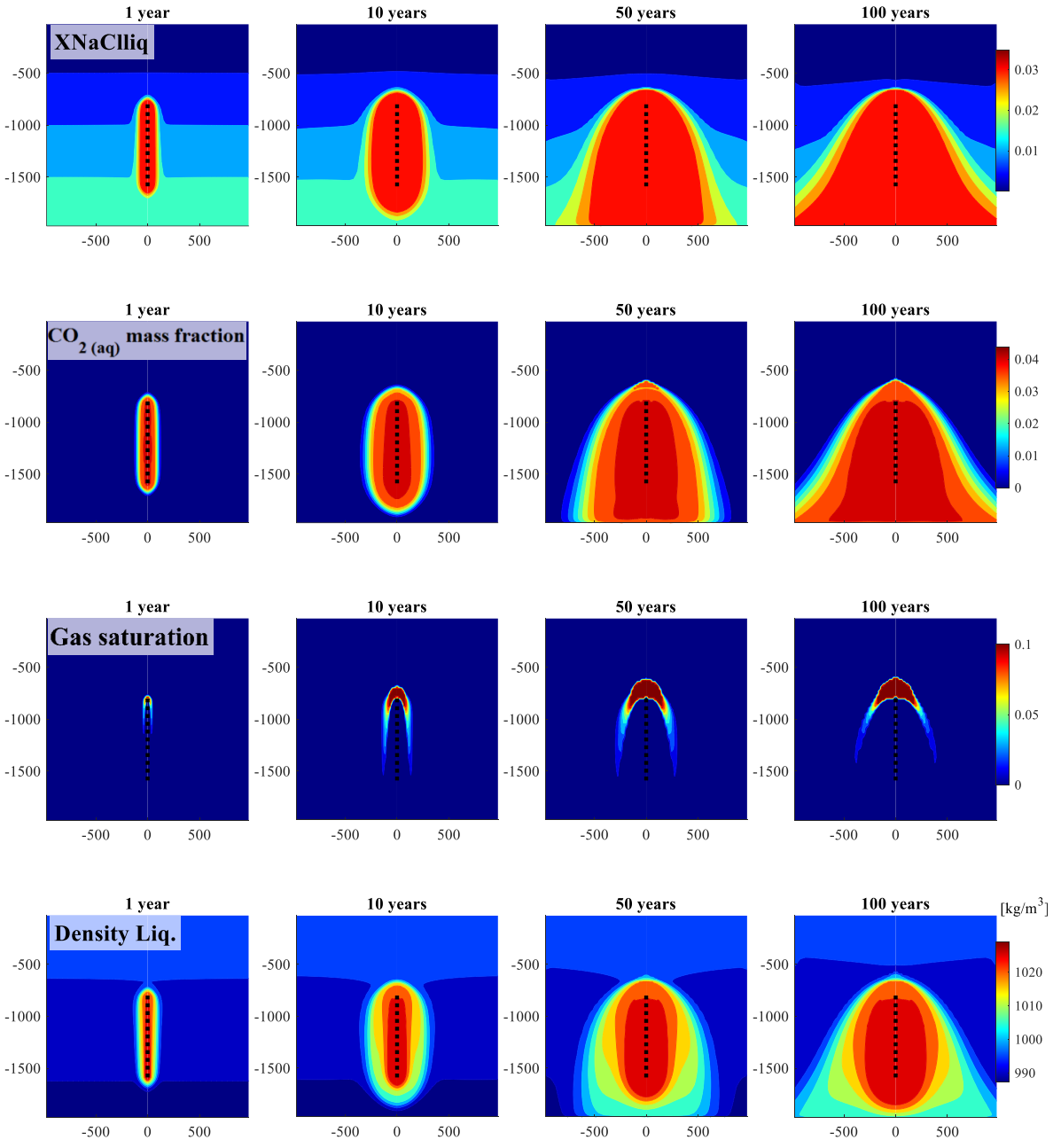
S9. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '100,000 ppm initial salinity system'. This system has a 30 ˚C/km gradient, a constant initial reservoir salinity of 100,000 ppm, injection water salinity of 35,000 ppm and temperature of 40 ˚C. The water to CO_2 injection mass ratio is 38:1. The upper plots show the 2D cross sections of salinity (NaCl mass fraction in the liquid), followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone. Results show that this injection would likely lead to CO_2 leakage.



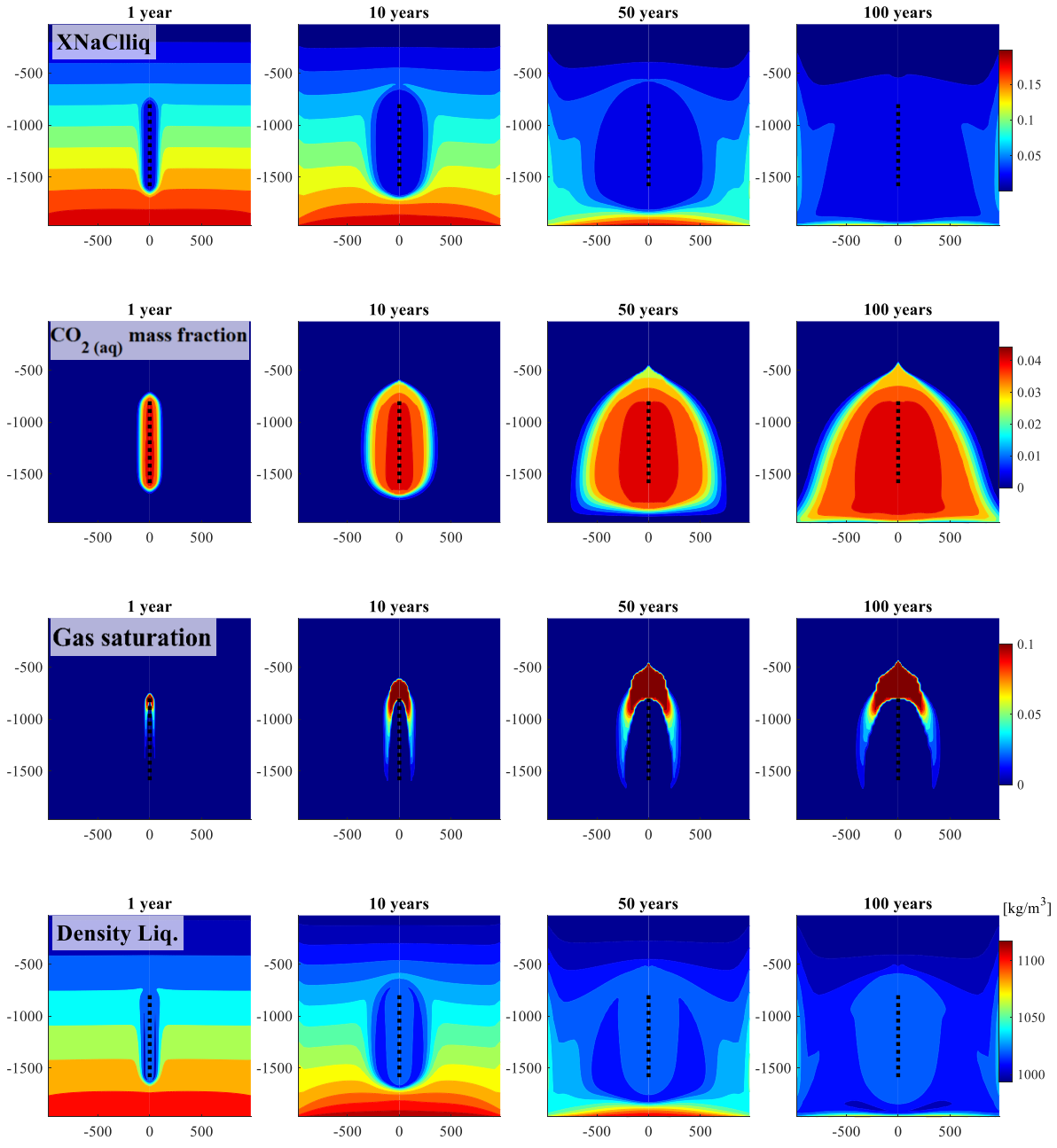
S10. Calculated CO_2 concentrations in the subsurface liquid exsolved CO_2 mass fraction in the pore fluids after 10, 50 years of carbonated water injection and 50 and 200 years after the end of the injection. The results shown are for the '100,000 ppm initial salinity system'. This system has a 30 °C/km gradient, a constant initial reservoir salinity of 100,000 ppm, injection water salinity of 35,000 ppm and temperature of 40 °C. The water to CO_2 injection mass ratio is 38:1. The upper plots show the 2D cross sections of CO_2 concentration in the liquid phase, followed by CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone. Results show that this injection would likely lead to CO_2 leakage.



S11. Calculated CO_2 concentrations in the subsurface liquid exsolved CO2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '10 ppm/m initial salinity gradient system'. This system has a 30 ˚C/km gradient, a 10 ppm/m initial reservoir salinity, injection water salinity of 35,000 ppm and temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of salinity (NaCl mass fraction in the liquid), followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



S12. Calculated CO_2 concentrations in the subsurface liquid exsolved CO2 mass fraction in the pore fluids after 1, 10, 100 and 100 years of carbonated water injection. The results shown are for the '100 ppm/m initial salinity gradient system'. This system has a 30 ˚C/km gradient, a 100 ppm/m initial reservoir salinity, injection water salinity of 35,000 ppm and temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of salinity (NaCl mass fraction in the liquid), followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.



S13. Calculated CO_2 concentrations in the subsurface liquid and gas after 10, 50, 100 years of carbonated water injection and 150 years after injection stop. The results shown are for the '100 ppm/m initial salinity gradient system'. This system has a 30 ˚C/km gradient, a 100 ppm/m initial reservoir salinity, injection water salinity of 35,000 ppm and temperature of 40 ˚C. The water to CO_2 injection mass ratio is 25:1. The upper plots show the 2D cross sections of salinity (NaCl mass fraction in the liquid), followed by the CO_2 concentration in the liquid phase, CO_2 gas saturation, which is the mass fraction of exsolved CO_2 in the pore fluids, whereas the lower plots show 2D cross sections of the density of the liquid phase at the indicated times. Color bars defining the range for each of the properties are displayed on right side. The dotted line marks the injection zone.