Supplementary Materials

Mass distribution in Bravo Dome

Using the available geophysical and geochemical data at Bravo Dome, Sathaye et al. (2014) estimated that 1.3±0.25 Gt CO₂ is currently (in 1981) stored at the reservoir, where 22% of the CO₂ has been dissolved into brine. Using the reservoir model, the mass distribution of pre-production (1981) and dissolved CO₂ were estimated in all six compartments of Bravo Dome (figure 1). In this paper, we mainly focused on the two main compartments (A and B), which contained 78% of the CO₂ in 1981. Moreover, 89% of the CO₂ dissolution occurred in these two compartments.

Pressure drop due to erosional unloading

Rebound of the saturated porous medium due to reduction of the vertical stress leads to drop in the pore pressure. This process is mathematically analyzed by writing the mass balance equations for the porous media. The governing equations of this mechanism was thoroughly explained by Neuzil and Pollock (1983). The pressure drop due to erosional unloading can be calculated by solving the following:

\[
\frac{\partial p'}{\partial t} = D \frac{\partial^2 p'}{\partial z^2} + \rho_b g \bar{m}
\]

\[
D = \frac{k}{\mu T S_s}
\]

\[
p' = p_h - p_p
\]

where, \( p' \) is the excess of hydrostatic pressure \( [MT^{-2}L^{-1}] \), \( p_p \) is the pore pressure, \( p_h \) is the hydrostatic pressure, \( t \) is time \( [T] \), \( z \) is vertical position \( [L] \), \( \rho_b \) is the soil bulk density \( [ML^{-3}] \), \( g \) is acceleration of gravity \( [LT^{-2}] \), \( \bar{m} \) is erosion rate \( [LT^{-1}] \), \( D \) is hydraulic diffusivity \( [L^2T^{-1}] \), \( k \) is the porous media permeability \( [L^2] \), \( \mu_f \) is the fluid viscosity \( [ML^{-1}T^{-1}] \), and \( S_s \) is specific storage \( [L^{-1}] \).

Here, we estimated the significance of pressure drop due to erosional unloading for a range of possible values for Bravo Dome (figure 2). Figure 2a shows the effect of soil bulk density and erosion rates on the pressure drop. After the CO₂ emplacement, the erosion rate in this area was 3-19 m/Myrs, and we assumed that the removed material was saturated soil with a density between 2700 and 3200 kg/m³. We also assumed an extreme case of very low hydraulic diffusivity \( (D = 10^{-11} m^2/s) \).

Figure 2b displayed the effects of hydraulic diffusivity and various erosion rates on the pressure drop. Figure 2c shows the pore pressures in Bravo Dome after 1.5 myrs of unloading going on for the limits of possible erosion rates in Bravo Dome. Our results indicate that erosional unloading reduces the pore pressures by 0.1-0.9 MPa, which associated with 2-13% of pressure drop in Bravo Dome.

FIG. 1: CO₂ mass distribution in Bravo Dome. a, Pre-production mass distribution (1981) b, Distribution of dissolved mass into brine c, Compartmentalized pre-production mass distribution (1981) d, Compartmentalized distribution of dissolved mass into brine.
Aquathermal depressuring

Erosional unloading also leads to a reduction of the subsurface temperature. In isolated systems with constant volume, such as the Bravo Dome compartments, a reduction in temperature decreases the fluid pressure. This pressure drop can be estimated if the length of eroded soil and geothermal gradient are known. Assuming a constant erosion rate, the maximum length of removed soil is given by $\Delta z = \bar{m} \Delta t$, where $\Delta t$ is the duration of erosion.

Since the emplacement of CO$_2$ into Bravo Dome 1.2-1.5 Myrs ago, the maximum erosion rate in this area was 19 m/Myrs. Hence, the maximum length of removed soil due to erosion is 22.8-28.5 m. The maximum temperature drop due to erosional unloading is given by $\Delta T_{erosion} = \frac{\partial T}{\partial z} \Delta z$, where $\frac{\partial T}{\partial z}$ is the geothermal gradient. Bottom hole temperature data indicates that the geothermal gradient in Bravo Dome is in the range of 20-33 °C/km (figure 3). Therefore, the $\Delta T_{erosion}$ is 0.6-1 °C. Using the current density of 60 kg/m$^3$, the calculated change in temperature due to erosional unloading associated with 0.02-0.1 MPa of pressure drop, which is less than 1% of the observed under-pressure at Bravo Dome and was correctly neglected.

We calculated the maximum amount of CO$_2$ that can be stored in Bravo Dome before the reservoir gets to hydrostatic pressure. Here, we again focused only on the two main compartments, and used Peng-Robinson equation of state. We assumed volume and temperature remains constant during the injection. So, the increase in mass and consequently density only leads to an increase in pressure. Therefore, this calculation gives an upper bound for the capacity of the Bravo Dome. The results are shown in figure 4 and indicate that compartments A and B together can store up to 6.5-9 GtCO$_2$.

Bravo Dome capacity

FIG. 2: Contribution of erosion on pressure drop in Bravo Dome. a, Effects of soil bulk density and erosion rate on pressure drop with constant hydraulic diffusivity of $10^{-11}$ m$^2$/s. b, Effects of hydraulic diffusivity and erosion rate on pressure drop with constant soil bulk density of 3300 kg/m$^3$. c, Pore pressures in Bravo Dome after 1.5 Ma of unloading with two extreme case of erosion rates.

FIG. 3: Histogram of geothermal gradient at Bravo Dome.

FIG. 4: Compartments A and B 2 storage capacity. The storage capacity is the amount of mass that can be inject into the reservoir before it gets to the hydrostatic condition. Peng-Robinson equation of state has been used and these results assume isothermal condition and constant volume for each compartment. The inserted PT-diagram shows the density changes due to the injection of mass into the reservoir while the volume remains constant.

References

