CO_2 long-term future after injection

The CO_2, once injected, can undergo changes depending on the nature of the storage formation. This makes the security of the storage even greater. These changes are from free-phase CO_2 to CO_2 dissolved in water to CO_2 forming minerals over thousands of years. These changes are described as trapping mechanisms.

Trapping Mechanisms

The four basic mechanisms which hold the CO_2 in place are stratigraphical/structural, residual, solubility, and mineral trapping. Where the CO_2 is injected into horizontal or gently dipping reservoirs, or into saline formations, it can remain in the reservoir moving very slowly for a long time until eventually it is trapped by residual, solubility or mineral trapping. This is referred to as hydrodynamic trapping.

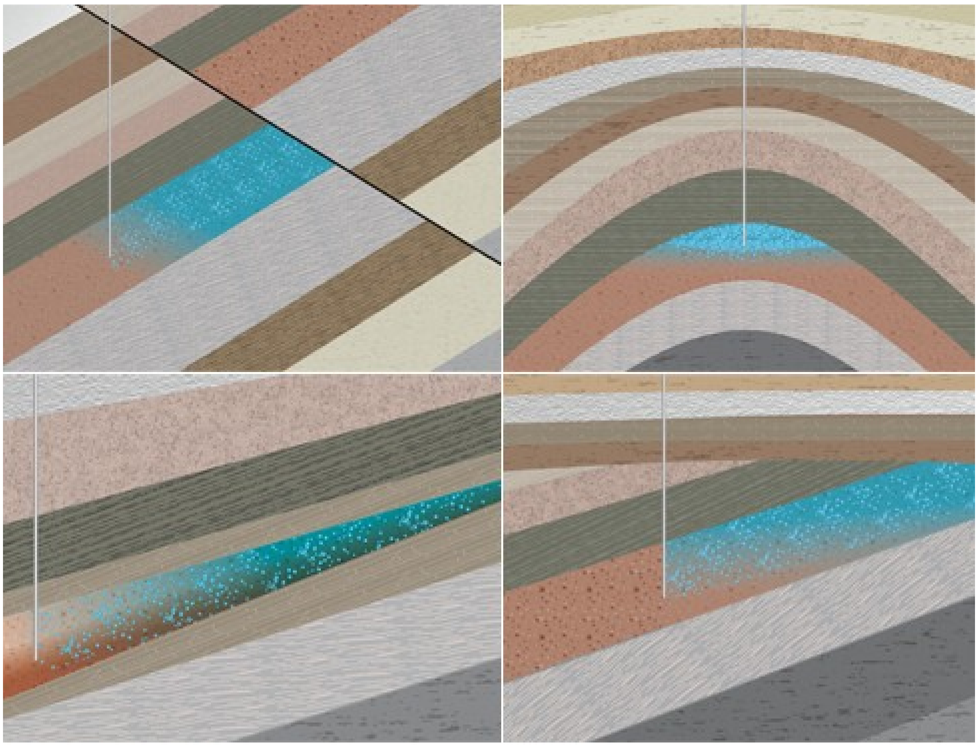
Structural/Stratigraphical Trapping

This type of trapping involves a physical trap. In a structural trap, the CO_2 is trapped at the top of an anticline, or in a tilted fault block. It is kept from further upward movement by the sealing rock (or caprock). There are a variety of geometrical arrangements of reservoir rock/sealing rock pairs. If the geometry of the subsurface does not contain faults or folds, the trapping is stratigraphical. Sometimes a change in rock type within the storage layer will create a closed stratigraphical trap.

When CO_2 is injected, it is not dissolved in formation water. It is said to be free-phase or immiscible. As it is supercritical, it is less dense than the formation water and so it rises upwards. Small bumps in the seal will behave like anticlines and trap the CO_2 until it spills out and continues migrating through the reservoir rock.

The CO_2 will remain trapped by the seal unless the height of the layer of CO_2 creates a capillary pressure that would enable it to enter the seal. Scientists calculate this height based on the pore radius of the sealing rock and the relative densities and surface tensions of CO_2 and water to determine the safe rate of injection into the reservoir.

Where the reservoir has closed structural trapping, it is likely that much of the CO_2 remains in supercritical, free-phase state in the storage reservoir, while the rest is trapped by other mechanisms.



Depth >800m

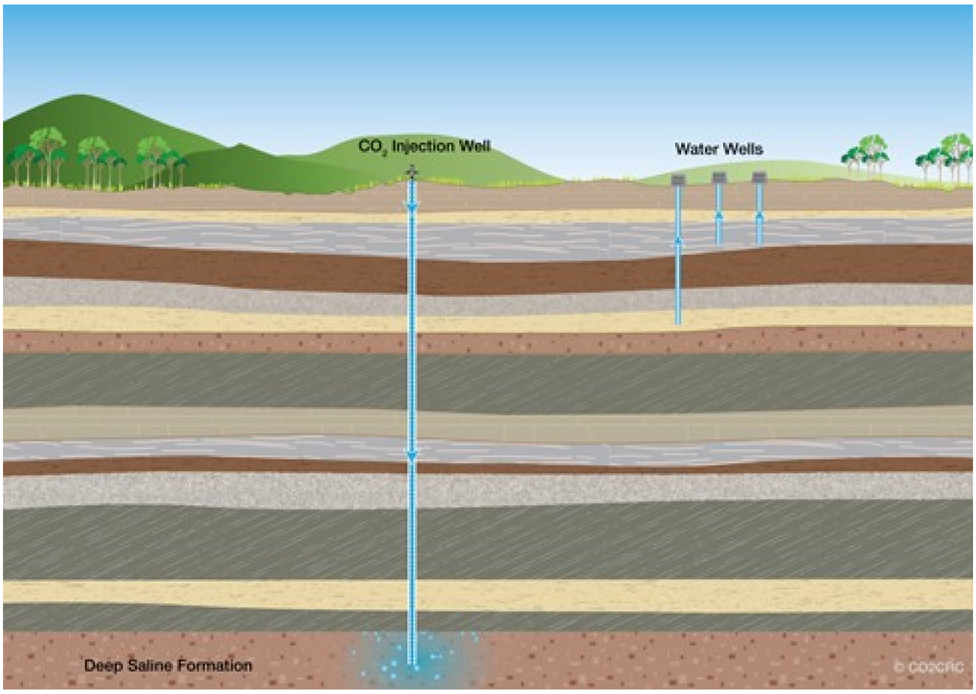
Clockwise from top left: fault trapping; anticline or stratigraphic trapping; facies change trapping; and unconformity trapping.

Hydrodynamic trapping

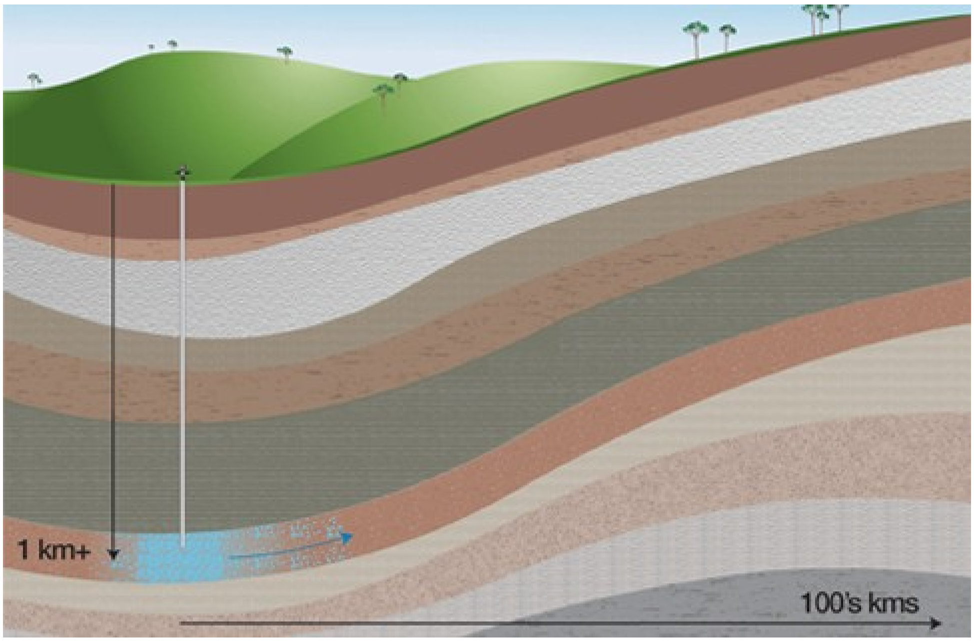
Saline formations generally have low flow velocities (of the order of cm/year). CO_2 that remains free-phase migrates upwards through permeable pathways in the rock. Because CO_2 is less viscous than the formation water (CO_2 is 15-20 times less viscous than brine at 1000m) it moves by a process called viscous fingering. Some CO_2 is dissolved in the formation water (see solubility). The dissolved CO_2 migrates with the formation water. The relationship between the dissolved CO_2 and the free-phase CO_2determines how far the CO_2 will migrate before all of the CO_2 is eventually trapped residually or in solution.

Factors that have a substantial influence on the length of the migration pathway include:

- stratigraphic heterogeneities (eg siltstones, shales and coals in the reservoir rock)
- geochemical reactions
- temperature



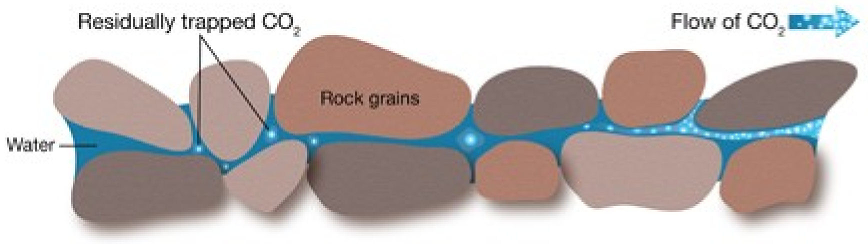
Rock formations for geologic storage, such as deep saline formations, would be much deeper than any usable groundwater and separated from that groundwater by thick barriers of impervious rock. These formations generally already proved their effectiveness by keeping highly-salty saline water separate from usable groundwater for millions of years.



Aquifer trapping

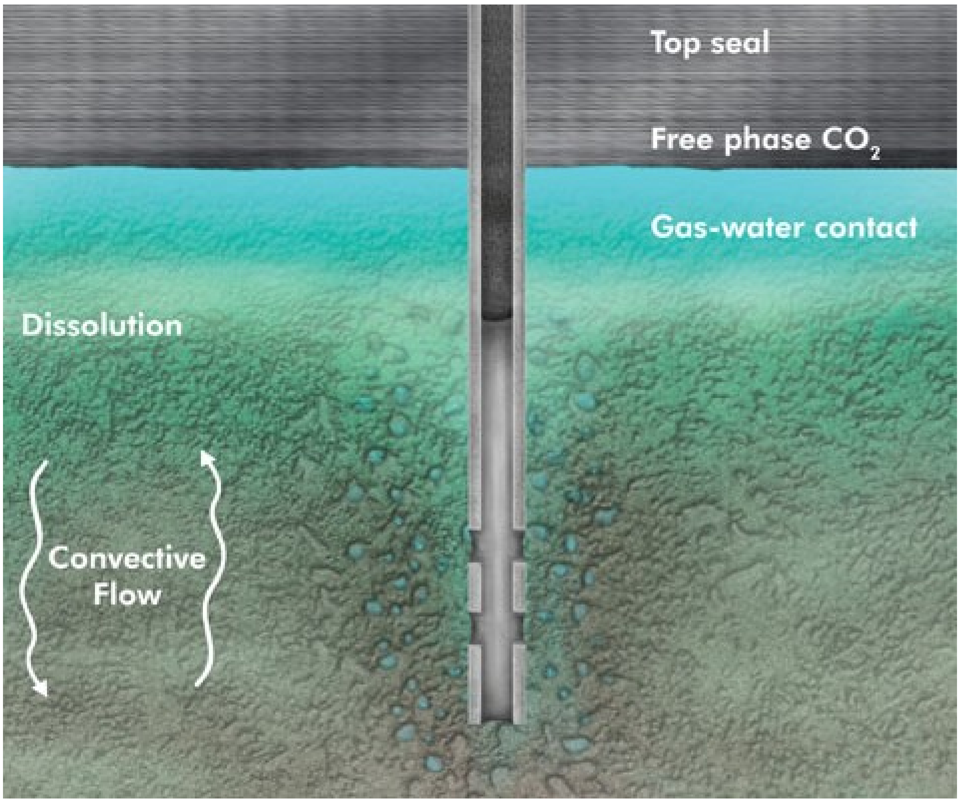
Residual Trapping

When free-phase CO_2 migrates, it forms a plume. At the tail of this plume, the concentration of the CO_2 falls below a certain level. It becomes trapped by capillary pressure from the water in the pore spaces between the rock and stops flowing. Over time, this residually trapped CO_2 can dissolve into the formation water.



Solubility Trapping

The solubility of CO_2 in water increases with increasing pressure and decreases with increasing temperature and increasing water salinity. As some CO_2 dissolves in water, the water becomes denser, and begins to sink downwards. This allows the CO_2 to become more dispersed in the water, and over time, the amount of CO_2 dissolved in the water can increase. If the reservoir formation is thin, the extent to which mixing occurs through a convective flow is limited.



CO_2 dispersion in reservoir after injection has stopped. Note the capillary trapping around the injection well.

Aqueous CO_2 can form carbonic acid, a weak acid, in the reaction

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

Mineral Trapping

When dissolved CO_2 reacts with the reservoir rock, carbonate minerals can form and precipitate, trapping CO_2 in the most stable form. While there is some reaction in the early years of storage, the time line for this trapping mechanism is over thousands of years. The potential for reaction to form these minerals depends on the composition of the reservoir rock (eg the presence of aluminosilicates), the temperature and pressure of the rock, the chemical composition of the water, the water/rock contact area and the rate of fluid flow through the rock. Mineral trapping is the most secure stage of CO_2 trapping.

One mineral which can be formed is calcite (calcium carbonate) in the following reaction:

$$CaAl_2Si_2O_8 + H_2O + CO_2 \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$$

anorthite calcite kaolinite

A typical mineral reaction that occurs in the natural accumulations of CO_2 in the Otway basin is that of iron-rich chlorite forming kaolinite and siderite. The reaction below shows the formation of siderite:

$Fe_4MgAl_2Si_3O_{10}(OH)_8$ (iron-rich chlorite) + $10H^+ \rightarrow 4Fe^{2+} Mg^{2+} + Al_2Si_2O_5(OH)_4$

(kaolinite) + $SiO_{2(aq)} + 7H_2O$

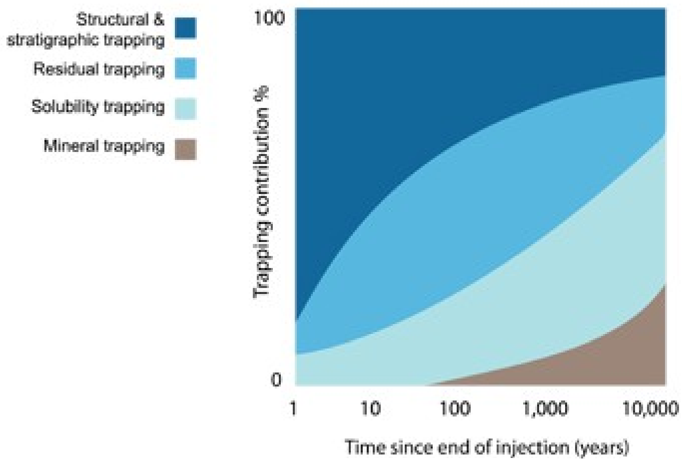
$4Fe^{2+} + Mg^{2+} + 5HCO_3^- \rightarrow 5Fe_{0.8}Mg_{0.2}CO_3$ (siderite) + $5H^+$

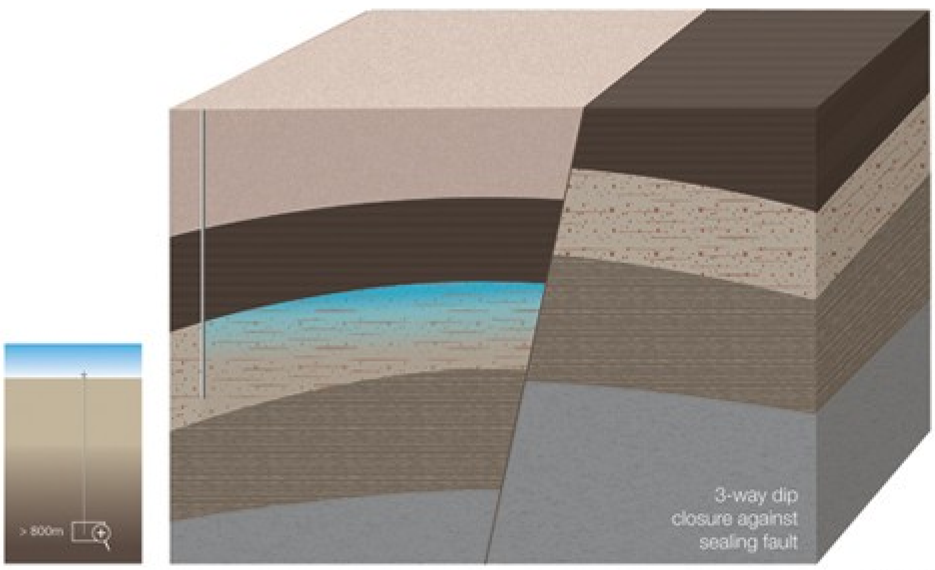
Storage mechanism over time

The way in which the CO_2 is injected and flows through the storage reservoir, together with the time the CO_2 remains in storage, determines the relative proportion of the trapping mechanism over time. In turn, the movement of CO_2 in the reservoir depends on the structure of the reservoir and the composition of the storage rocks and formation waters.

A mix of trapping mechanisms

CO_2 is injected into a thick saline formation of iron/magnesium-rich rock. The formation has a sealing fault on one side. After the CO_2 is injected it moves quickly away from the injection well. Some CO_2 remains free-phase, trapped by the rock structure. Small irregularities in the rock formation increase the migration pathway and residual trapping increasingly comes into play. Over time, significant amounts of CO_2 will dissolve into the formation brine and eventually, mineral trapping will occur.





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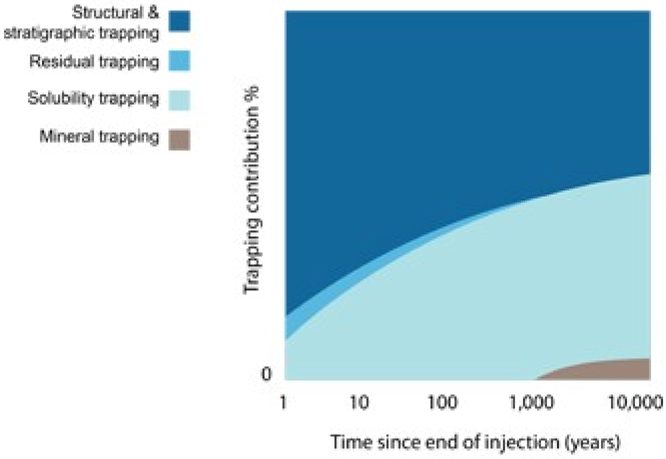
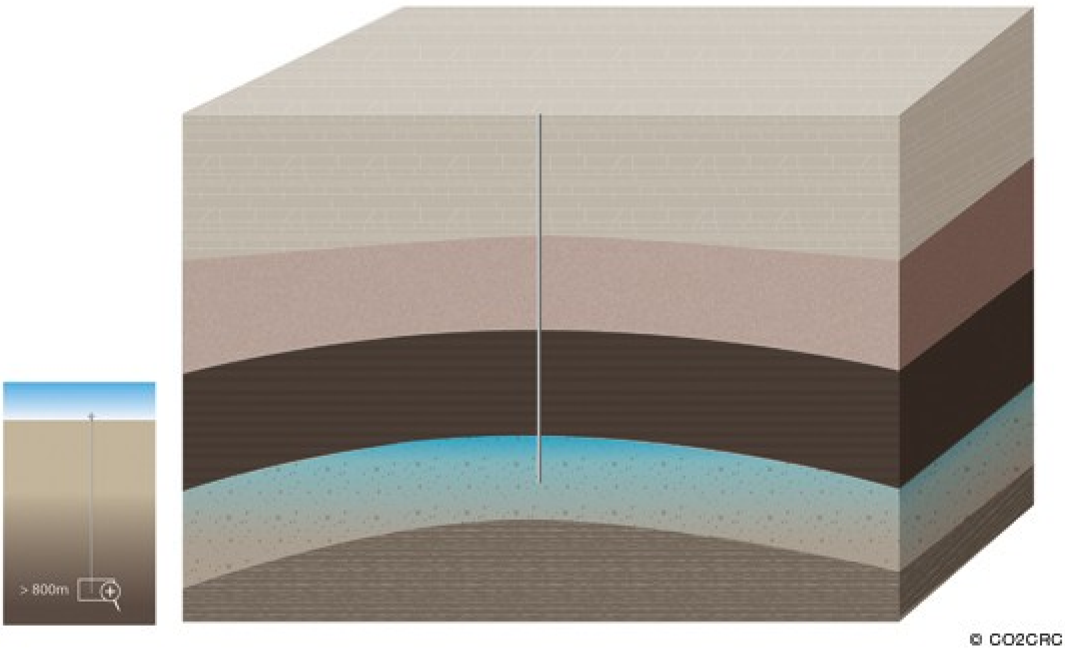
Structural trapping dominates

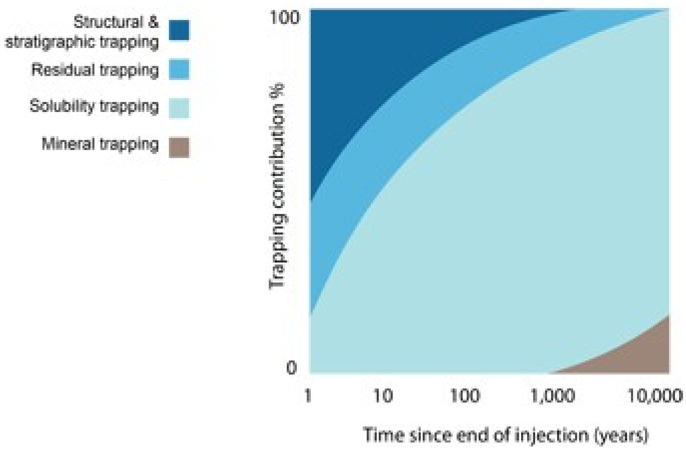
CO_2 is injected into a thin, silica sand reservoir which is a structural trap. The CO_2 moves to the top of the reservior, not reacting with the quartz sand and with minor residual trapping. Most of the CO_2 will remain free-phase, with some dissolving into the formation brine over time.

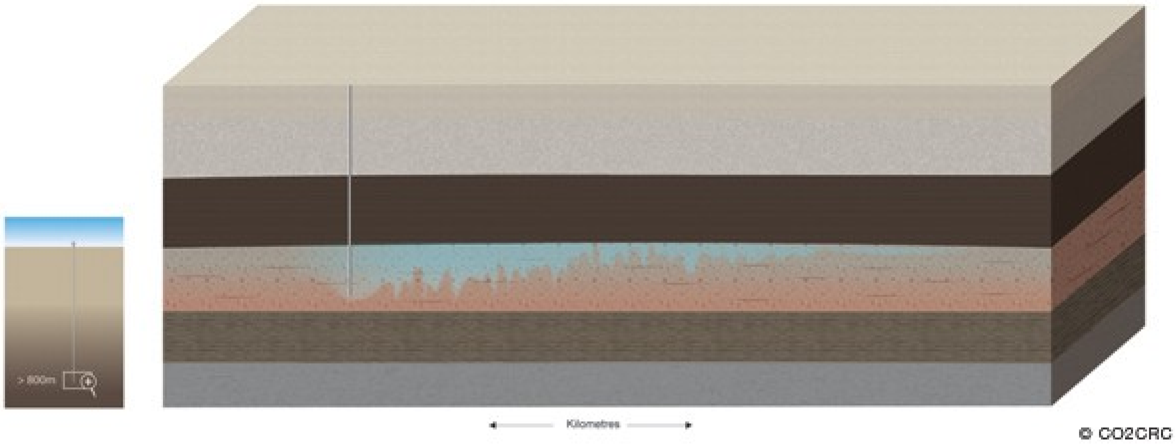




Solubility trapping dominates

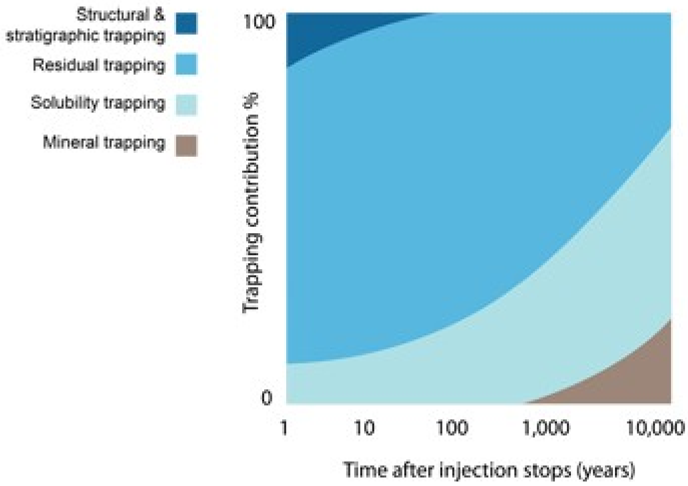
CO_2 is injected into an extensive saline formation of highly permeable rocks. The CO_2 will move easily upwards and spread out below the cap rock, eventually dissolving into the formation brine. There will be minor residual trapping.

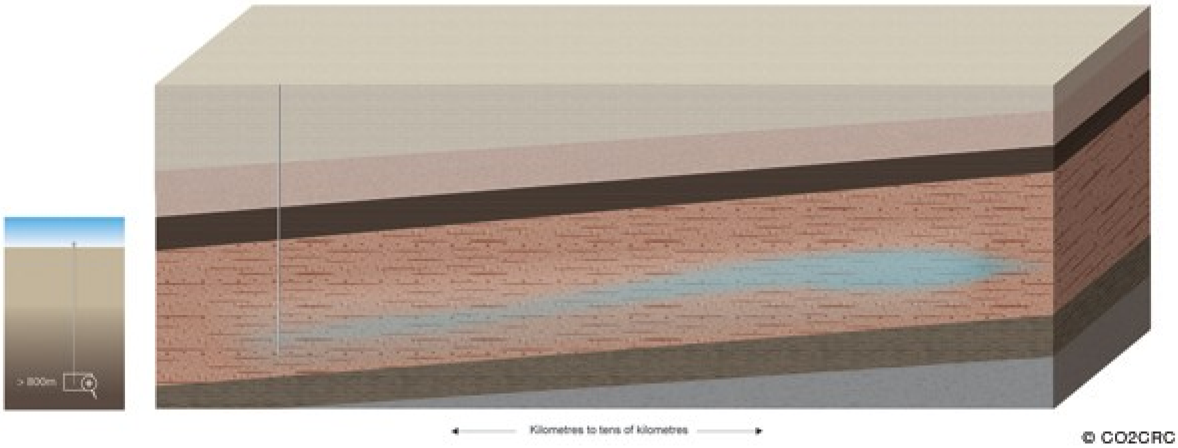




Residual trapping dominates

CO_2 is injected into a thick, heterogeneous saline formation of rock with mixed pore sizes and low vertical permeability. The CO_2 is prevented from moving directly upwards by "shelves" of very low permeability rock, providing a form of structural trapping within the reservoir. It moves slowly with the formation water, contacting a large number of rock pores in which it becomes residually trapped. The residually trapped CO_2 eventually dissolves in the formation water.




> 800m
Kilometres to tens of kilometres
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