Enhanced Geothermal Systems (EGS): Comparing Water and CO_2 as Heat Transmission Fluids

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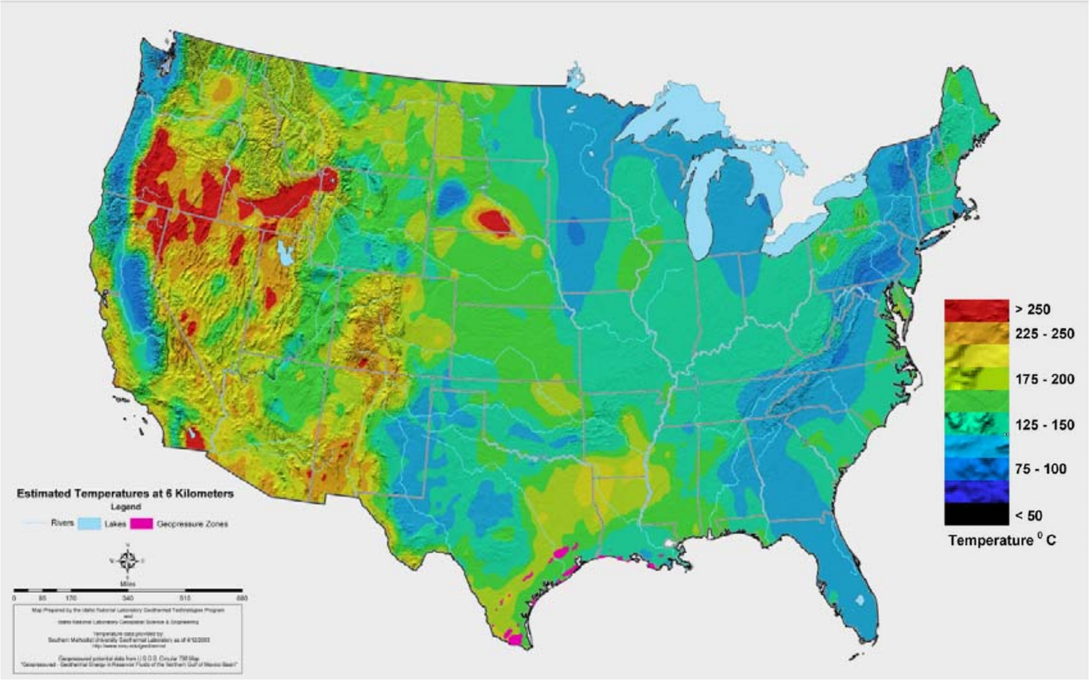
U.S. Geothermal Resources are Huge



Heat content in subsurface rocks to 6 km depth, relative to ambient temperature (Dave Blackwell, SMU)

- T > 200 ˚C: 296,000 EJ*
- T > 125 ˚C: 2,410,000 EJ

(* EJ = ExaJoule; 1 EJ = 10^{18} J)

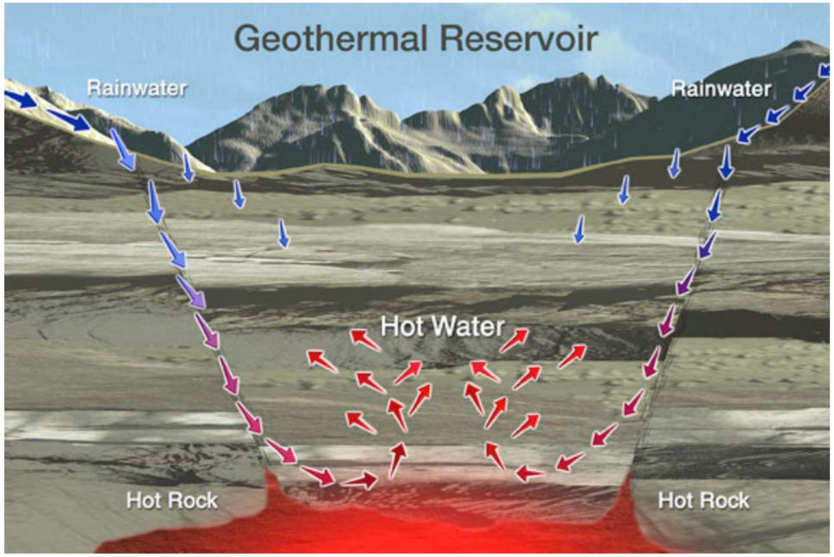
(Map c/o INL Geothermal Program)

Primary energy consumption in U.S. (2004)

- total primary energy consumption: ≈ 100 EJ
- total U.S. geothermal energy use: 0.31 EJ (≈ 0.3 % of primary)

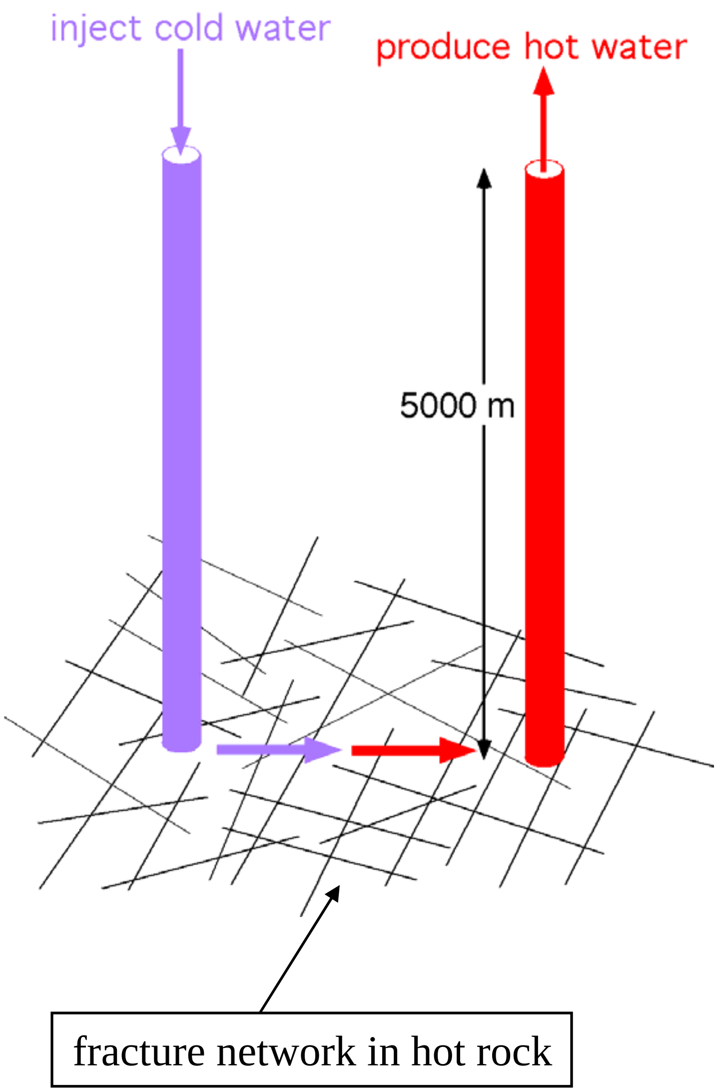
Why is Geothermal Energy Contribution so Small?

- Geothermal energy extraction is currently limited to hydrothermal systems (the “low-hanging fruit”).
- There is a vast store of geothermal heat that is difficult to recover (hot rocks lacking fluid and permeability).
- How can the essentially inexhaustible heat in deep geologic formations be tapped and transferred to the land surface for human use?



Source: Geothermal Education Office (GEO)
http://www.geothermal.marin.org/

Enhanced Geothermal Systems (EGS)



- Artificially create permeability through hydraulic and chemical stimulation.
- Transfer heat to the land surface by circulating water through a system of injection and production boreholes.
- Experimental projects in U.S., U.K., France, Japan, Australia, Sweden, Switzerland, Germany.
- EGS is currently not economically viable; the chief obstacles are:
  - dissolution and precipitation of rock minerals, that may cause anything from short-circuiting flows to formation plugging
  - large "parasitic" power requirements for keeping water circulating
  - water losses from the circulation system
  - inadequate reservoir size - heat transfer limitations
  - high cost of deep boreholes (≈ 5 km)

How about using CO_2 as Heat Transmission Fluid?

property	CO_2	water
chemistry	**poor solvent for rock minerals**	powerful solvent for rock minerals: lots of potential for dissolution and precipitation
fluid circulation in wellbores	**highly compressible and larger expansivity** **==> more buoyancy, lower parasitic power consumption**	low compressibility, modest expansivity ==> less buoyancy
ease of flow in reservoir	**lower viscosity**, lower density	higher viscosity, **higher density**
heat transmission	smaller specific heat	**larger specific heat**
fluid losses	**earn credits for storing greenhouse gases**	costly

Favorable properties are shown **bold-faced**.

EGS-CO_2 Issues

- Effectiveness of CO_2 as a heat transfer medium.
- Other processes induced by CO_2, that may affect feasibility and sustainability of EGS with CO_2 (chemical reactions, corrosion).
- Can we make an EGS-CO_2 reservoir? (Circulate CO_2 to remove the water.)
- Energy conversion system (binary plant w/ heat exchanger; directly using CO_2 on the turbines)
- Economics.
- Fluid lost = fluid stored?

General Makeup of a CO_2-Based EGS Reservoir

<u>Zone 1</u>

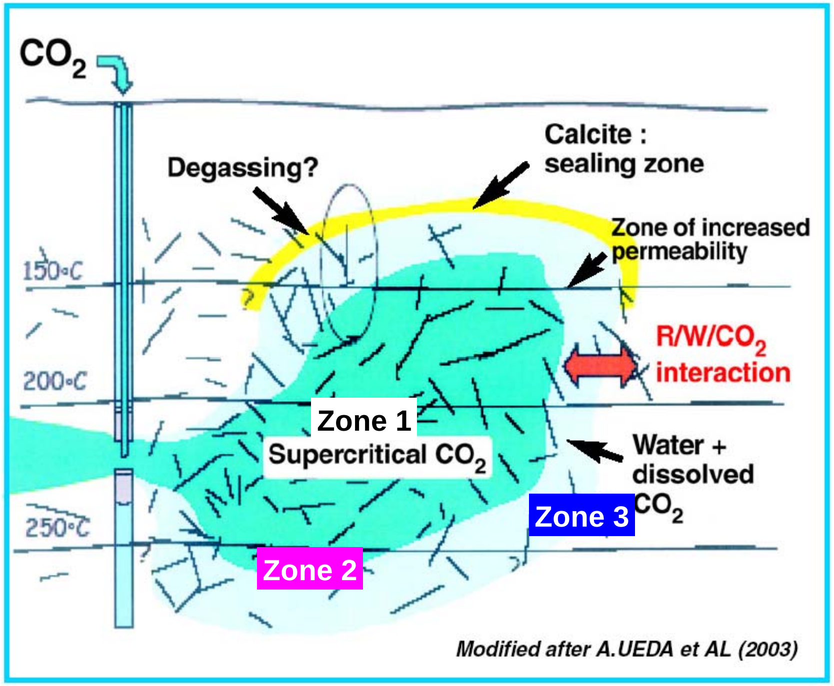
Central zone and core of EGS system, where most of the fluid circulation and heat extraction is taking place. This zone contains supercritical CO_2; all water has been removed by dissolution into the flowing CO_2.

<u>Zone 2</u>

An intermediate region with weaker fluid circulation and heat extraction, which contains a two-phase mixture of CO_2 and water.

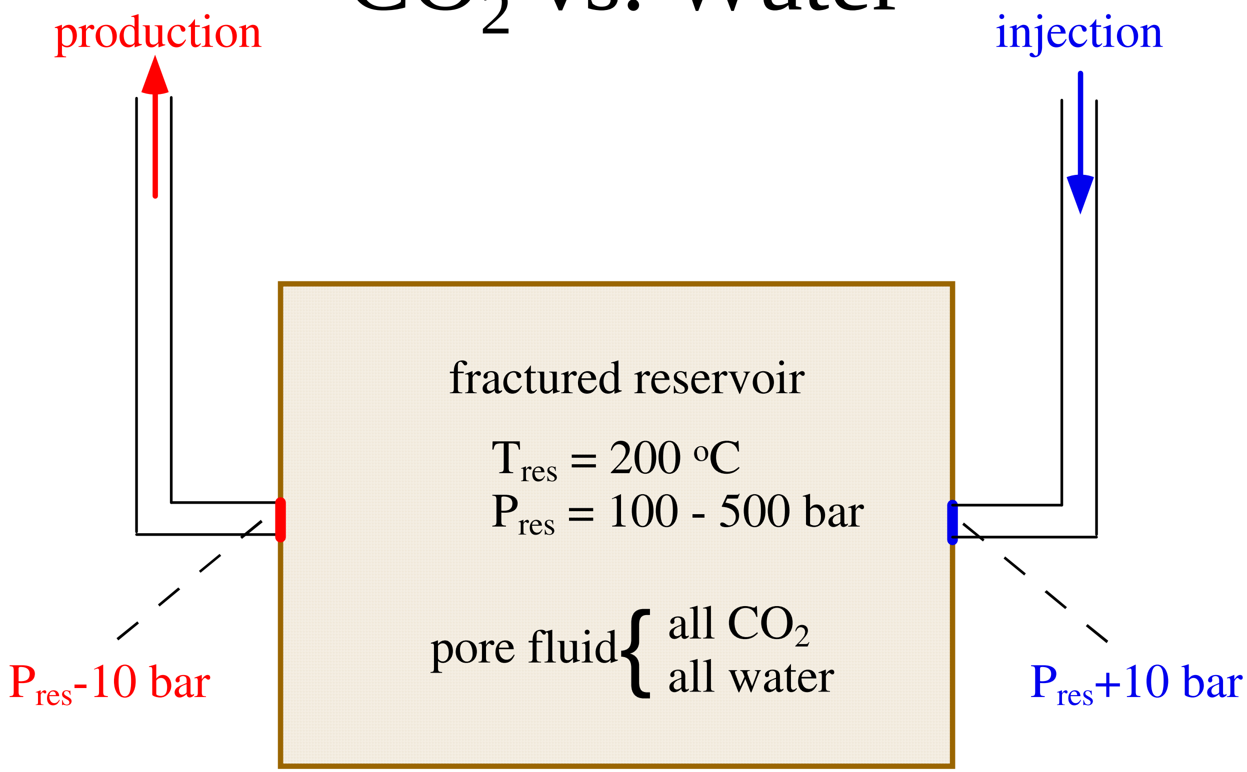
<u>Zone 3</u>

The outer region affected by EGS activities. The fluid is a single aqueous phase with dissolved CO_2.



(after Christian Fouillac et al., *Third Annual Conference on Carbon Capture and Sequestration*, Alexandria, VA, May 3-6, 2004)

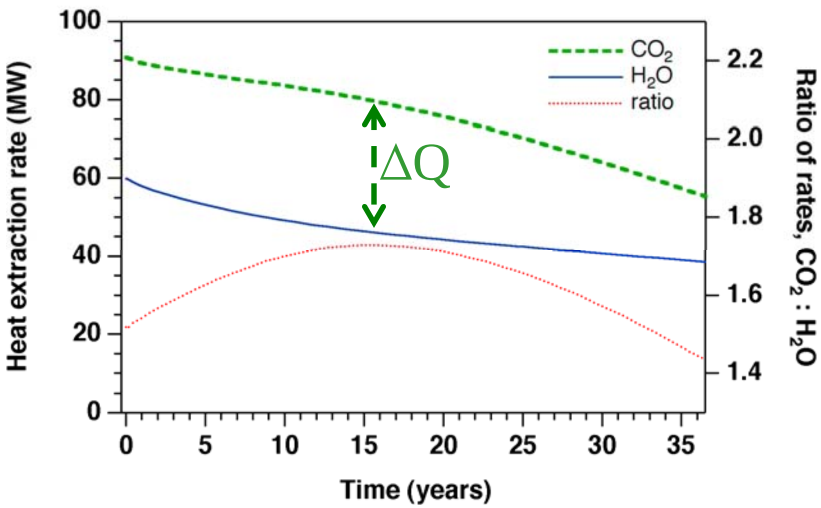
Comparing Operating Fluids for EGS: CO_2 vs. Water



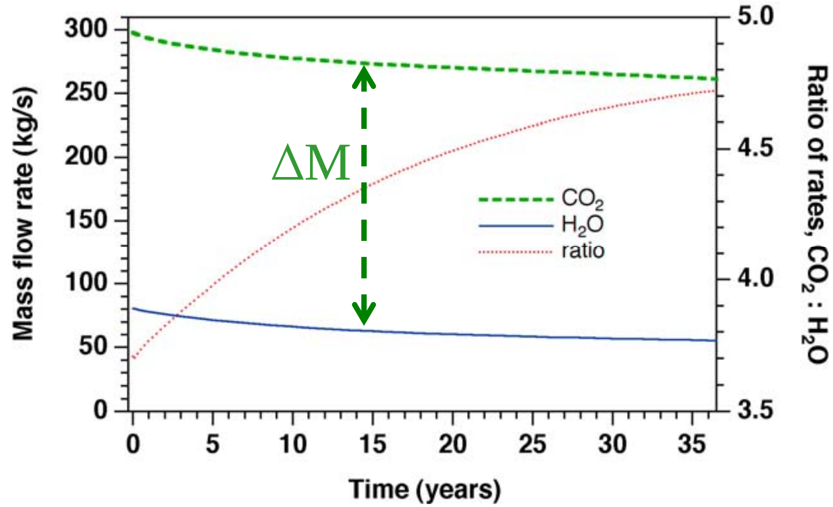
- monitor mass flow, heat extraction rates

Reference Case

T_{res} = 200 ˚C, P_{res} = 500 bar, T_{inj} = 20 ˚C

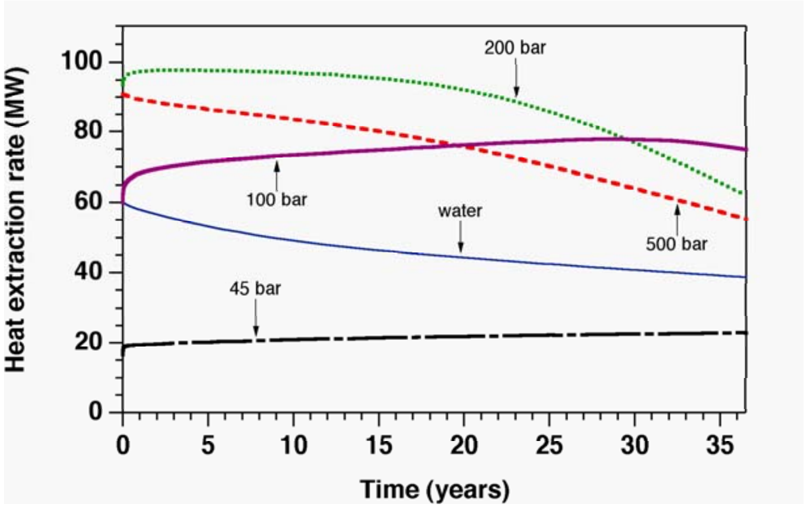


heat extraction

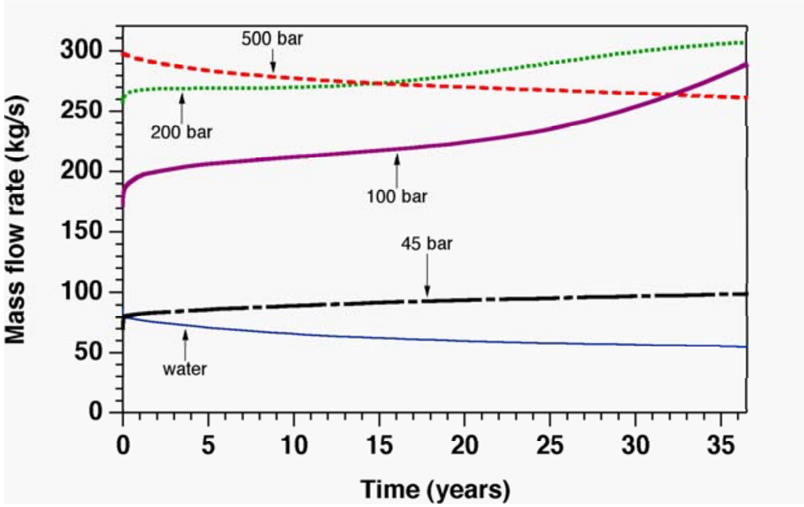


mass flow

Simulation Results for Different Reservoir Pressures at T = 200 ^{o}C



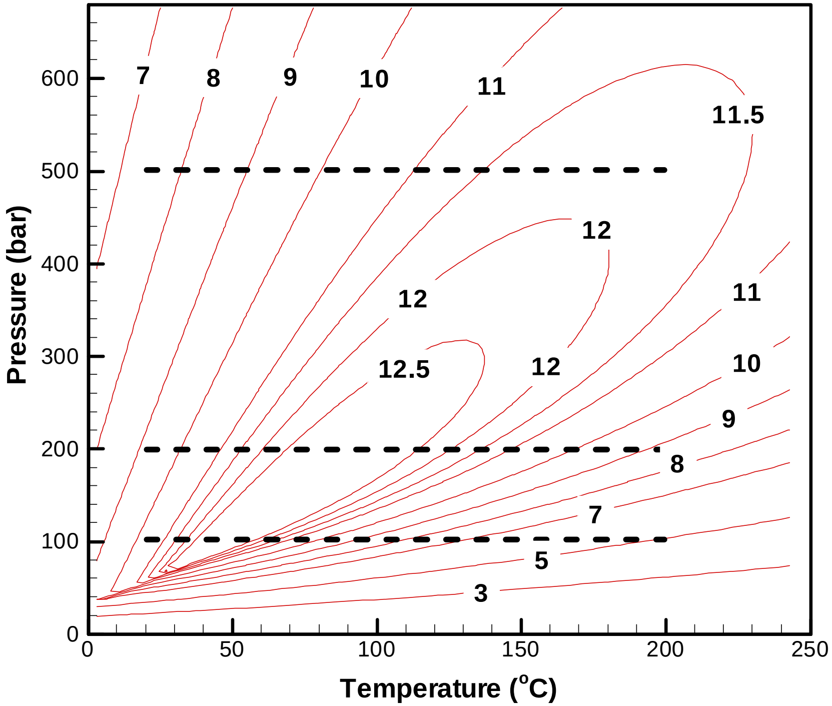
heat extraction



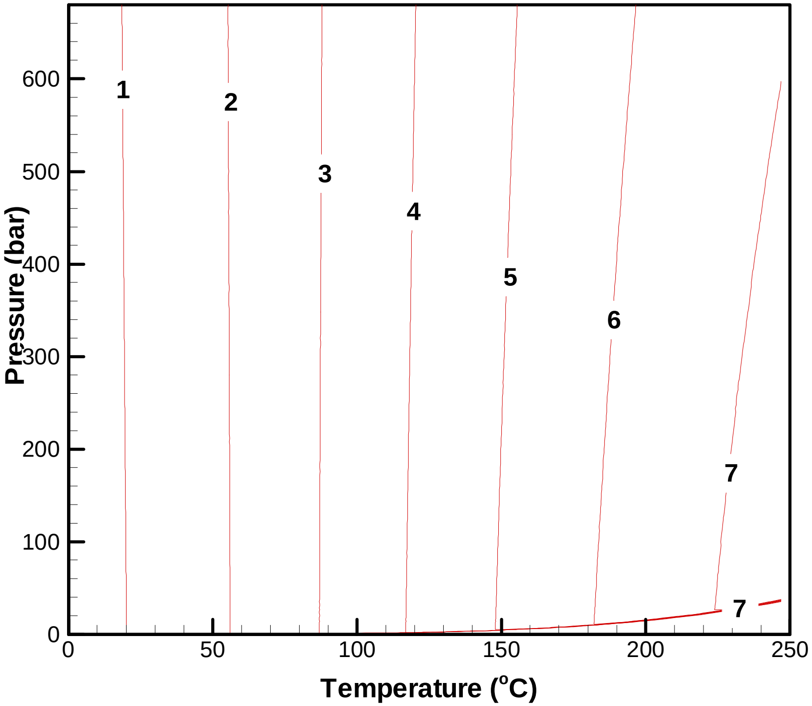
mass flow

Fluid Mobility

(density:viscosity; units of 10^6 s/m^2)

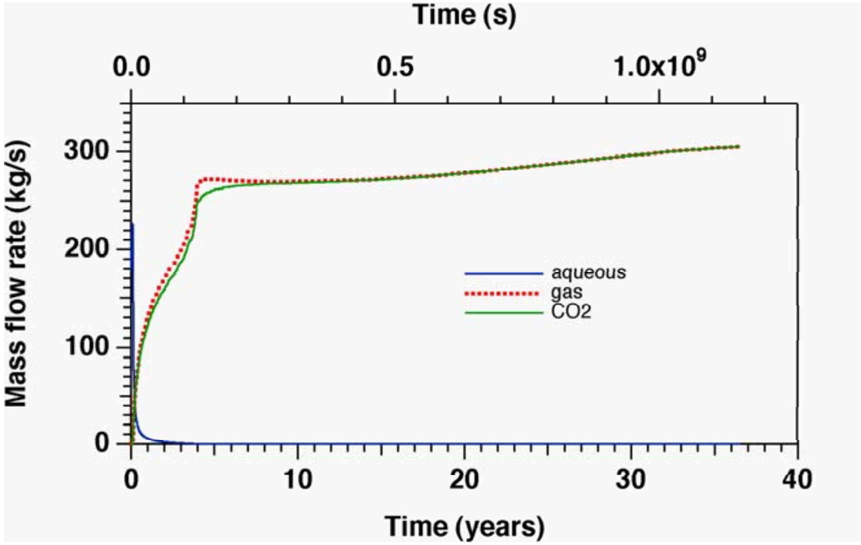


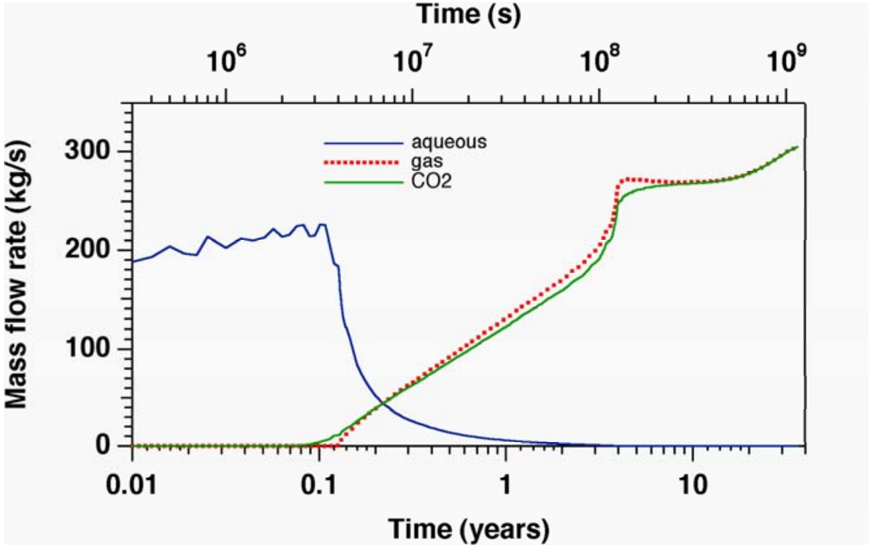
CO_2



water

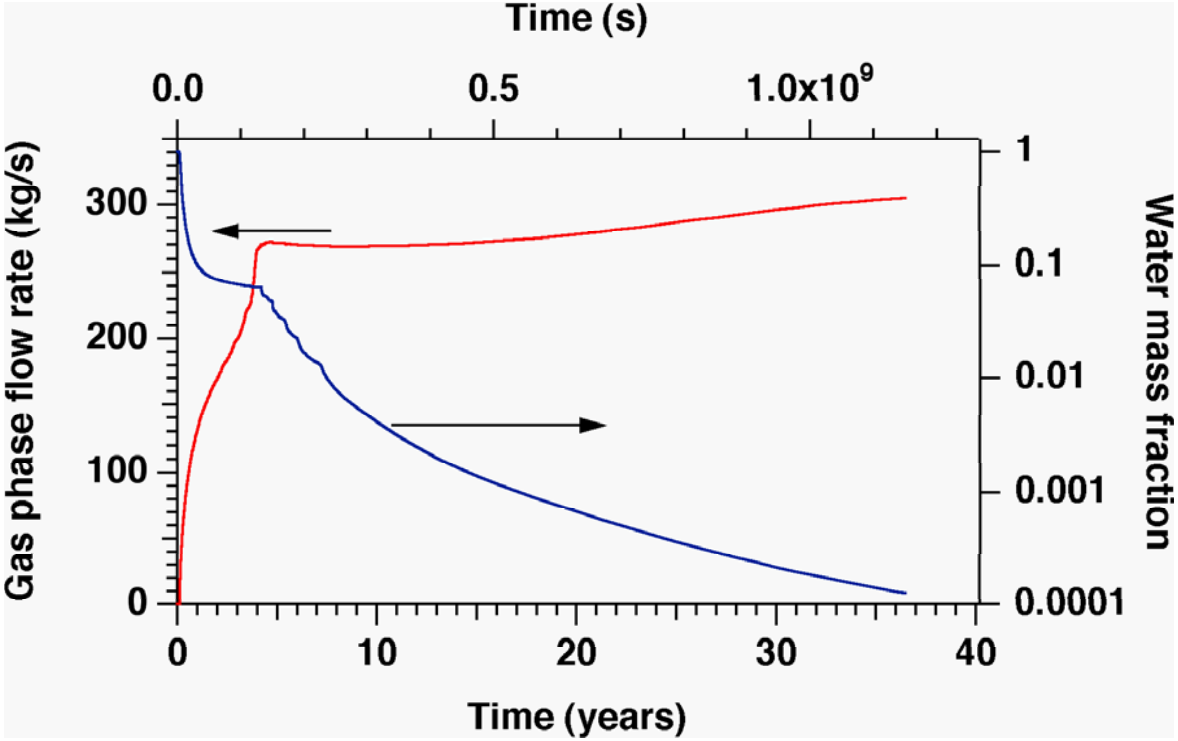
Injecting CO_2 into an Aqueous System





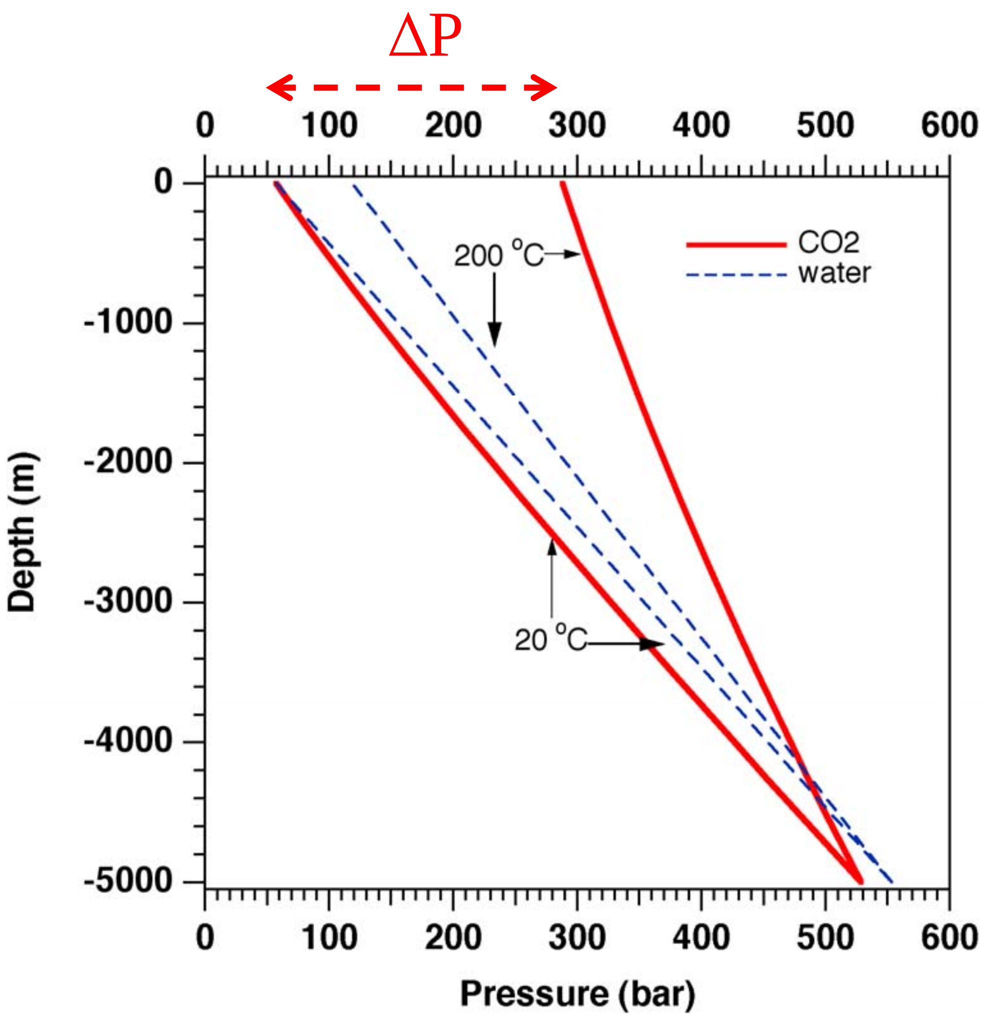
- At early time (≤ 0.1 year), produce single-phase water
- This is followed by a two-phase water-CO_2 mixture (0.1 - 2.5 yr)
- Total production rate during two-phase period is low due to phase interference
- Subsequently produce a single supercritical CO_2-rich phase with dissolved water

Rate and Composition of Produced CO_2



- Water is removed from fracture network fairly rapidly (about 4.4 % remaining after 5 years)
- The low-permeability rock matrix provides a long-term source of water, with almost half of initial inventory remaining after 36.5 years

Wellbore Flow: CO_2 vs. Water



Pressure difference between production and injection well

CO_2: 288.1 - 57.4 = 230.7 bar

water: 118.6 - 57.4 = 61.2 bar

CO_2 generates much larger pressures in production well, facilitating fluid circulation.

CO_2 Storage Capacity

- Need a mass flow of approximately 20 tons of CO_2 per second, per GW electric power capacity.
- Expect a fluid loss rate of order 5%, or **1 ton per second of CO_2 per GW** of installed EGS capacity.
- This is equivalent to **CO_2 emissions from 3 GW** of coal-fired power generation.
- The MIT report (2006) projects 100 GW of EGS electric power by 2050.
- 100 GW of EGS with CO_2 would **store 3.2 Gt/yr** of CO_2, approximately **40 % of total current U.S. emissions**.

➢ CO_2 lost = CO_2 stored?

Massachusetts Institute of Technology

Power Generation from CO_2-Based EGS

- One option is **binary conversion** technology, using similar equipment as water-based systems.
- Alternatively, it may be possible to **directly feed the produced CO_2** to the turbines. This may be possible because supercritical CO_2 without admixed liquid water is not corrosive to metals.
- Direct expansion of CO_2 in the turbines would avoid otherwise inevitable and irreversible heat losses in a heat exchanger.
- However, the produced **CO_2 stream** will need to be **dried** before entering the turbines, to avoid condensation of liquid water during decompression and cooling.
- Clarify the relative merits and thermodynamic efficiencies of different options for power generation.
- Need to **balance and optimize tradeoffs** between power generation and CO_2 storage.

Path Forward*

- Fluid-rock reaction experiments with supercritical CO_2
- Laboratory flow experiments for water-CO_2 mixtures and pure anhydrous CO_2
- Modeling of fluid flow, heat transfer and rock-fluid interactions (chemical/mechanical)
- Design studies for a field pilot test of EGS with CO_2

*cooperation with BRGM - French geological survey

Concluding Remarks

- Water-based enhanced geothermal systems (EGS) face difficult hurdles to (1) achieve adequate heat extraction rates, and (2) maintain injectivity and heat extraction performance in the face of strong rock-fluid interactions.
- CO_2 has attractive properties as a heat transmission fluid for EGS.
  - **Heat extraction** rates when using CO_2 are estimated to be approximately 50 % larger than for water.
  - CO_2 is very favorable in terms of **wellbore hydraulics**.
  - Unavoidable **fluid losses** are costly for water, but could earn greenhouse gas storage credits when using CO_2.
- The fluid produced from an EGS operated with CO_2 will change from initially water (≈ 1 month), to a two-phase aqueous-CO_2 mixture (a few years), to $scCO_2$ with dissolved water of order 0.1 wt.-%.
- Use of CO_2 as heat transmission fluid for EGS looks promising and deserves more study (geochemistry/geomechanics!).
- We are aiming to develop the scientific basis for a field demonstration.

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Reactivity of Rocks for $scCO_2$

reactivity

low

high

Rock type	Characteristics
granite	➢ generally high in SiO_2, low in carbonates ➢ limited surface area and reactivity of mineral grains
sandstone	➢ may have carbonate cements
graywacke	➢ relatively low in carbonates
ignimbrite	➢ welded tuffs, lithophysal cavities
felsite	
non-welded tuff	➢ more reactive ➢ zeolitized by water
marine sediments	➢ can be high in carbonates
basalt	➢ amorphous, highly reactive