Sustainable Energy and Carbon Capture and Storage

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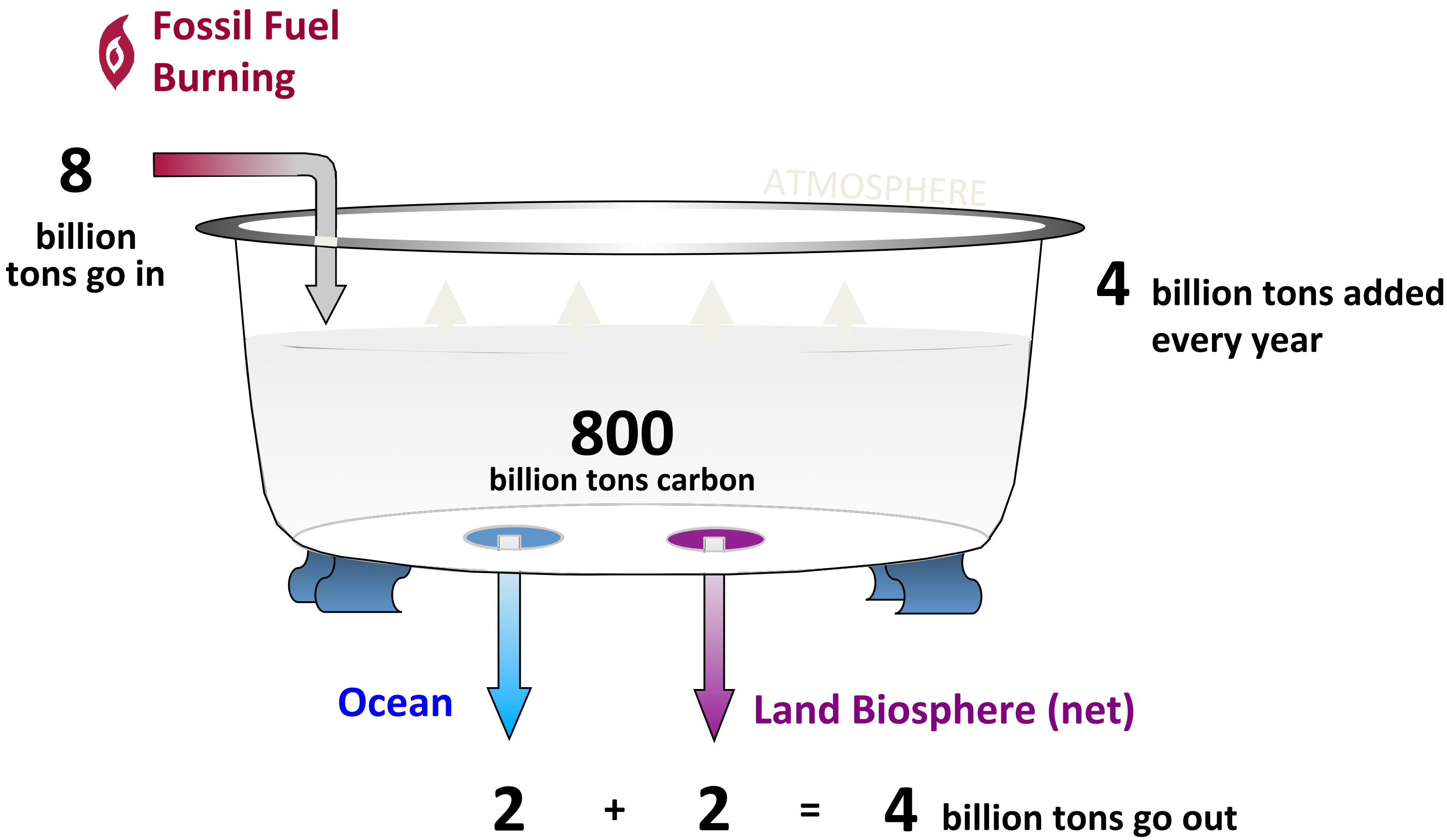
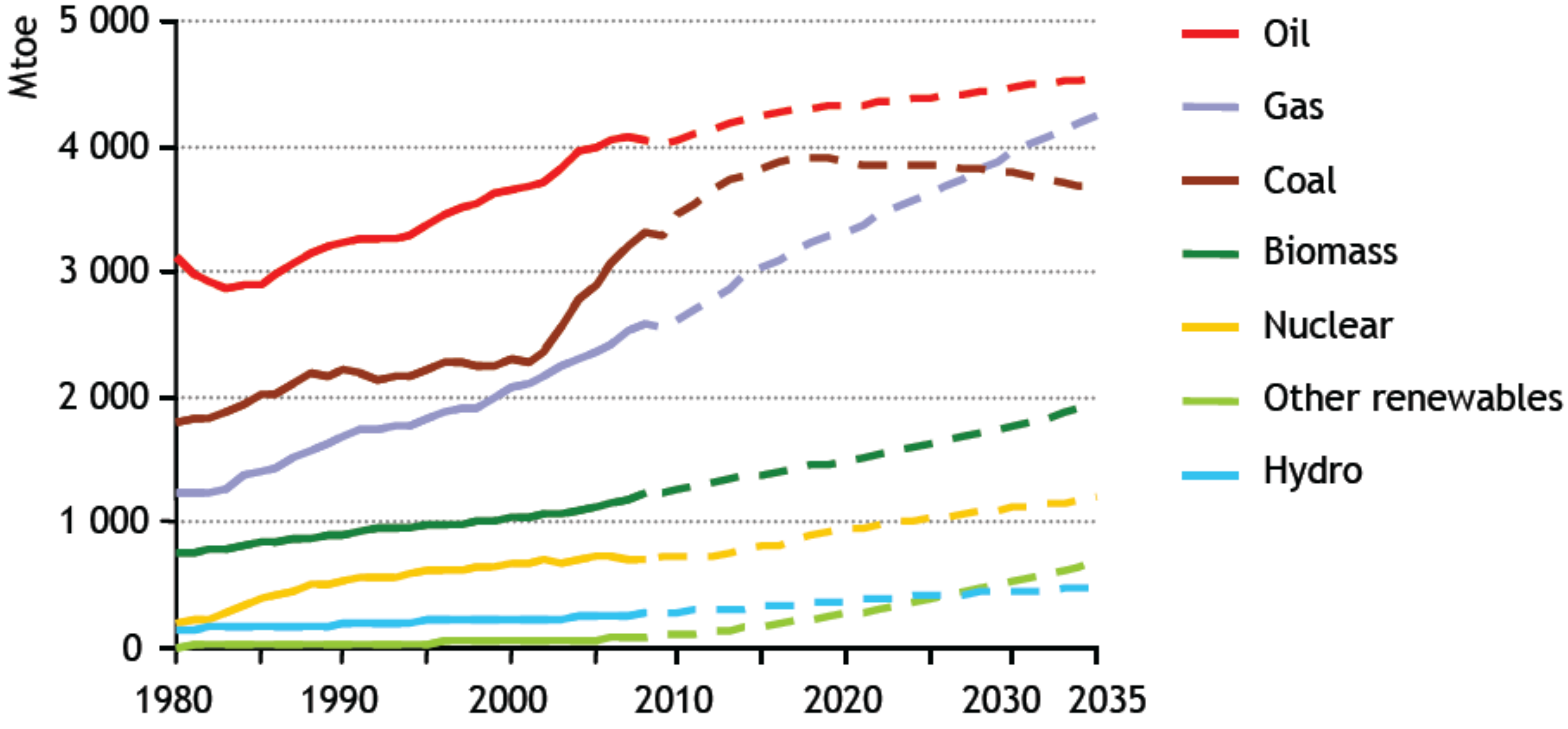
October 17, 2012

Simplified Carbon Balance

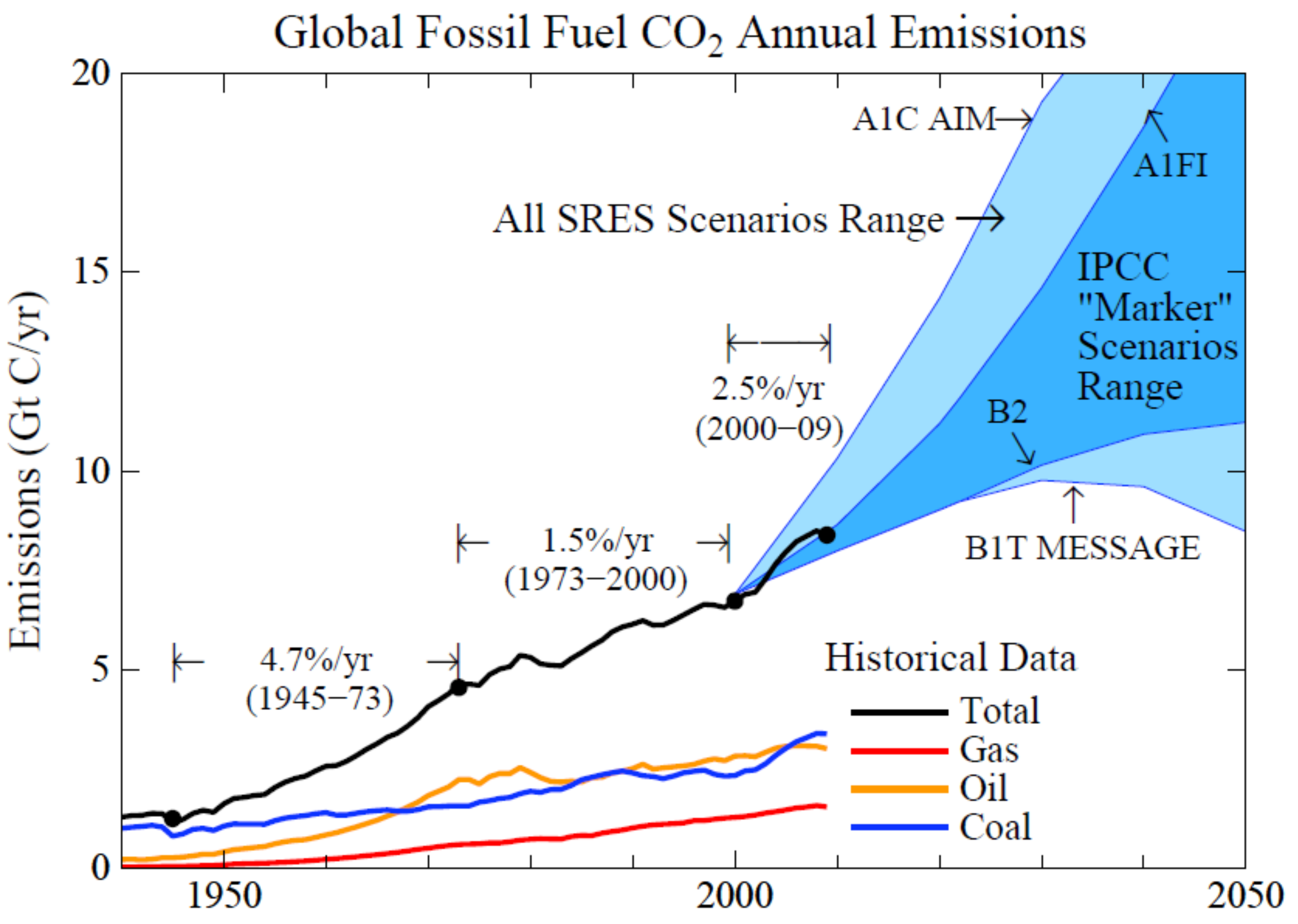


Source: Carbon Mitigation Initiative

World primary energy demand by fuel (IEA gas scenario)



World Energy Outlook – Special Report (2011)

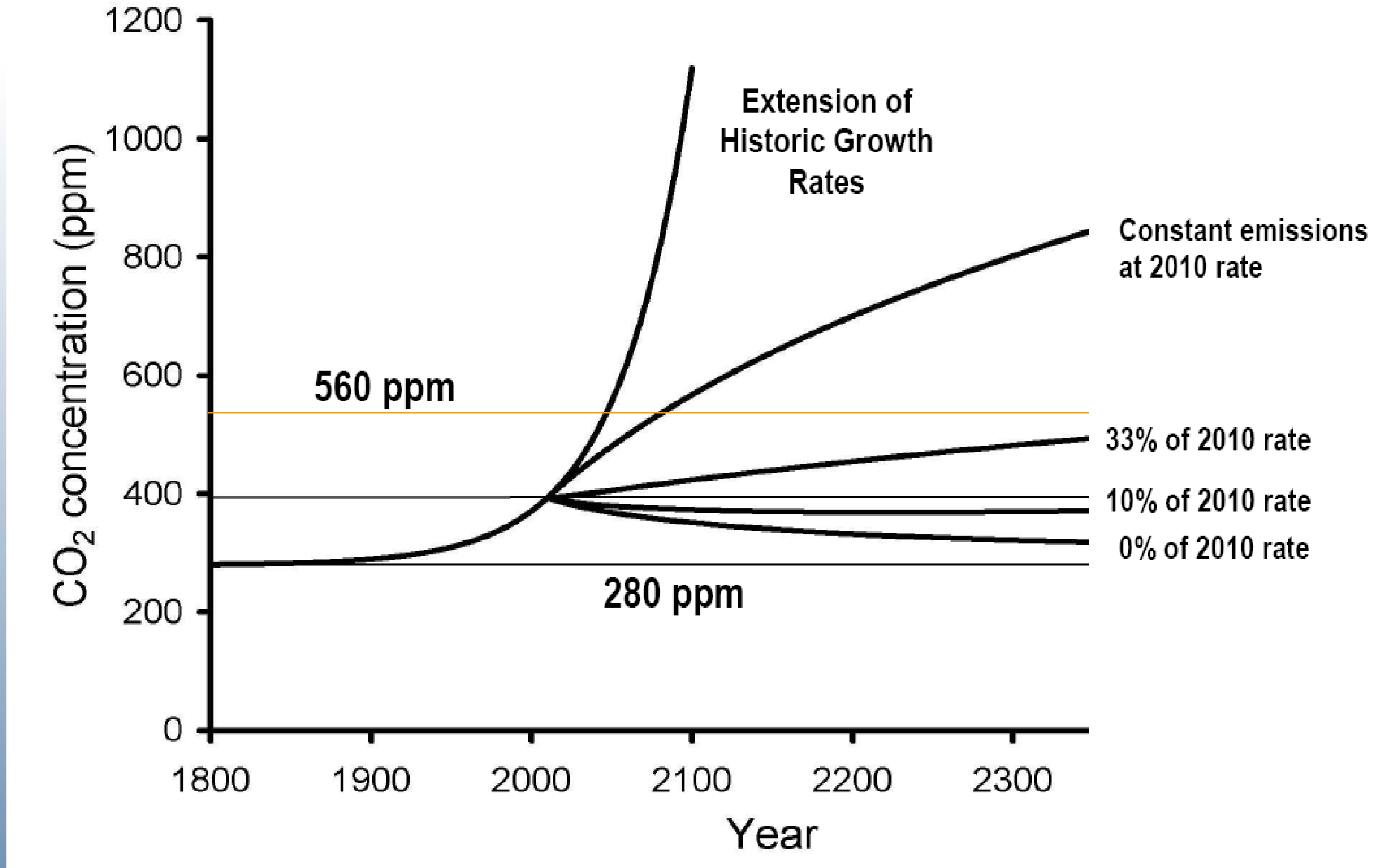


Global fossil fuel carbon dioxide emissions accelerated after Kyoto Protocol.

Date sources: Marland et al. (U.S. Dept. Energy, Oak Ridge and extended with BP Statistical Review of World Energy.)

Source: http://www.columbia.edu/~jeh1/presentations.shtml

Environmental Limits – not resources limited



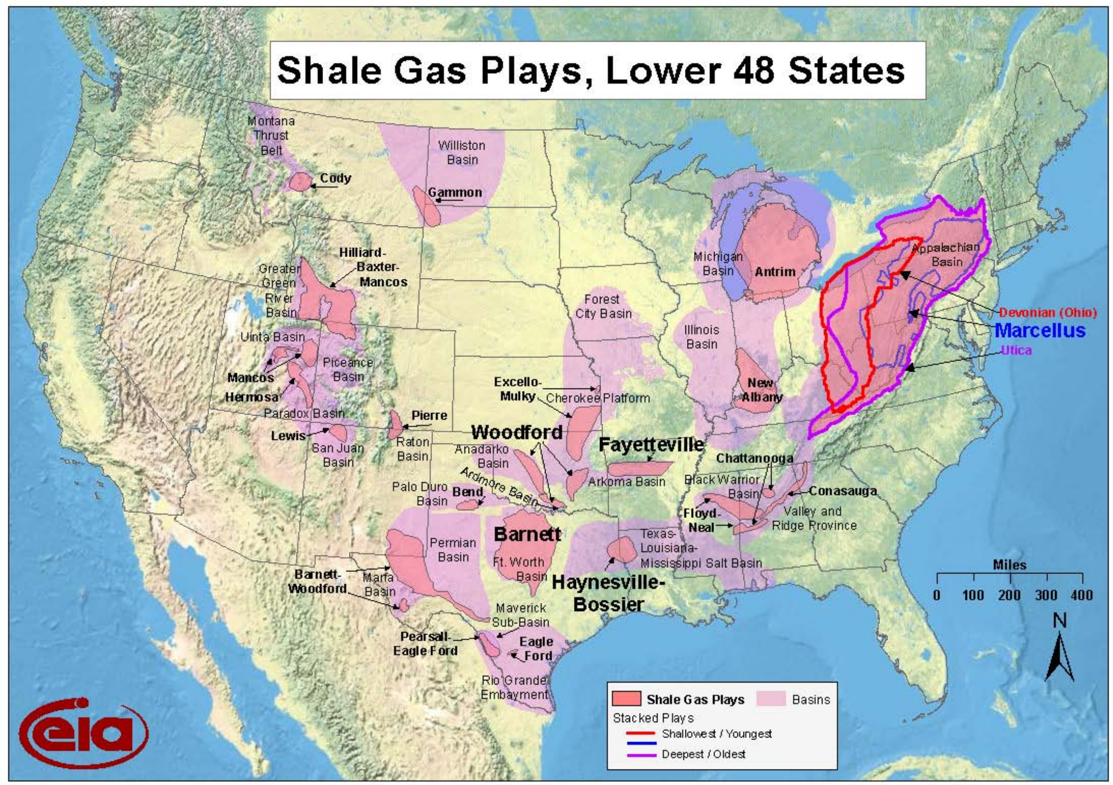
Stabilize atmospheric CO_2 concentration – not CO_2 emissions

The Big Three Energy Options

Fossil fuels are plentiful

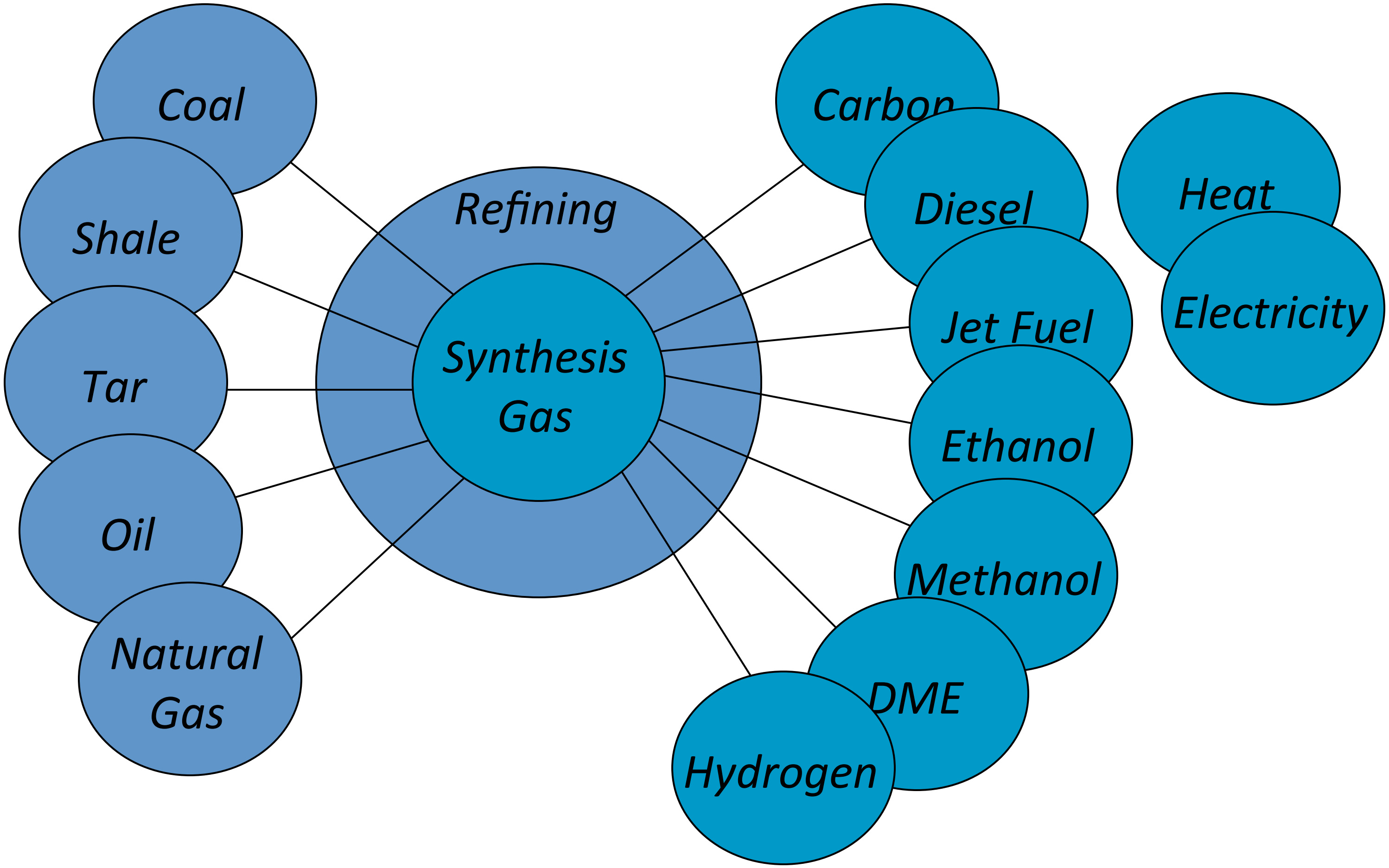
- Coal resources alone could be 3000 to 5000 Gt C
  - 400 Gt consumed since 1800
  - annual production of 8 Gt/yr of fossil carbon

- Natural gas reserves are growing rapidly
- Gas to liquid could support transportation sector



Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

Fossil fuels are fungible



Without carbon capture and storage fossil fuels will have to be phased out

Response Options

Reducing Emissions

- increasing efficiency
- change of fuel mix
- substitute renewable energy sources for fossil fuels
- nuclear
- **carbon capture and storage**

Increasing Carbon Sinks

- iron fertilization
- forestation/reforestation
- soil management
- enhanced weathering
- ocean sequestration

Net Zero Carbon Economy

CO_2 from concentrated sources

Capture from power plants, cement, steel, refineries, etc.

CO_2 extraction from air

Permanent & safe disposal

Geological Storage
Mineral carbonate disposal

Carbon Dioxide Capture

- Objective: Transform fossil fuel-based energy systems to CO_2 neutral systems by capturing CO_2 safely and cost effectively.
- Sources for capture: fossil fuel power plants, fuel processing plants, large-scale industrial processing plants and the atmosphere.
- CO_2 capture technology already in operation today in some large industrial plants (e.g. natural gas treatment plants, ammonia production).
- No applications of carbon capture in large (500 MW) power plants.
- No applications for transport sector.


• Air extraction can compensate for CO_2 emissions anywhere
Air Capture
Separate Sources from Sinks
▪Art courtesy Stonehaven CCS, Montreal
Prof. Klaus Lackner, Lenfest Center for Sustainable Energy

Sorbent: Anionic Exchange Resins

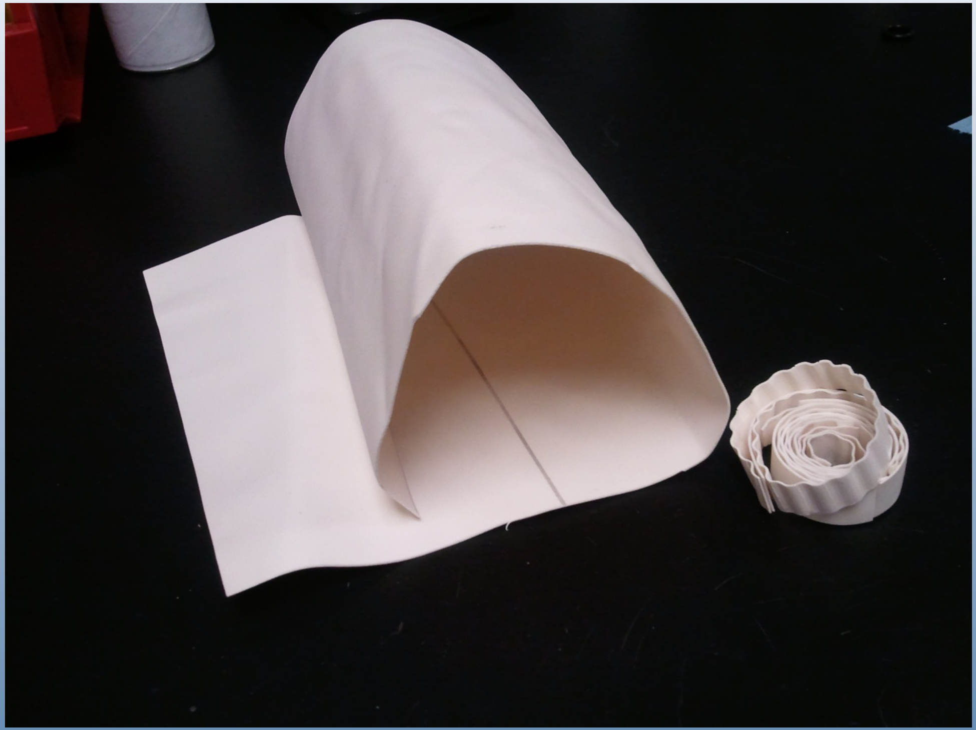
-> Moisture driven CO_2 swing

- Positive ions fixed to polymer matrix
  - Negative ions are free to move
  - Negative ions are hydroxides, OH^-
- Dry resin loads up to bicarbonate
  - $OH^- + CO_2 \rightarrow HCO_3^-$ (hydroxide → bicarbonate)
- Wet resin releases CO_2 to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$

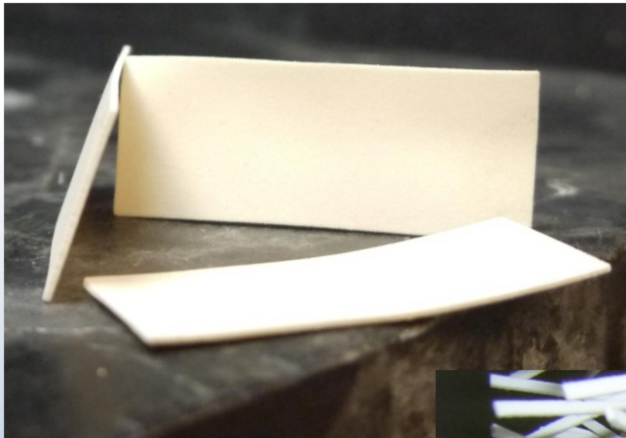
Membrane material

- Snowpure
  electrochemical membrane (1mm thick)
- Polypropylene matrix with embedded fine resin particles (25µm)
- Ammonium cations

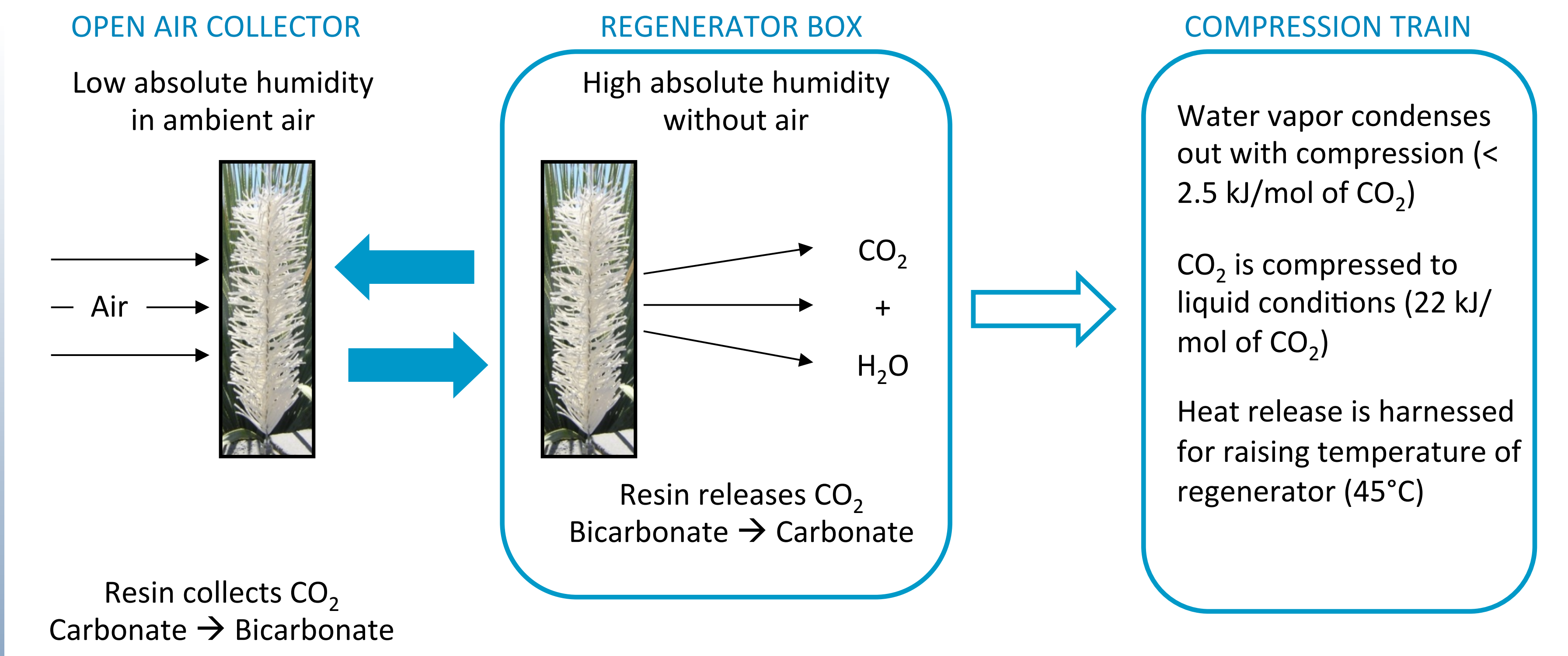
  Carbonate/bicarbonate form
- 1.7 mol/kg charge equivalent



Resin material



Novel Regenerator Chemistry – Moisture Swing Absorption

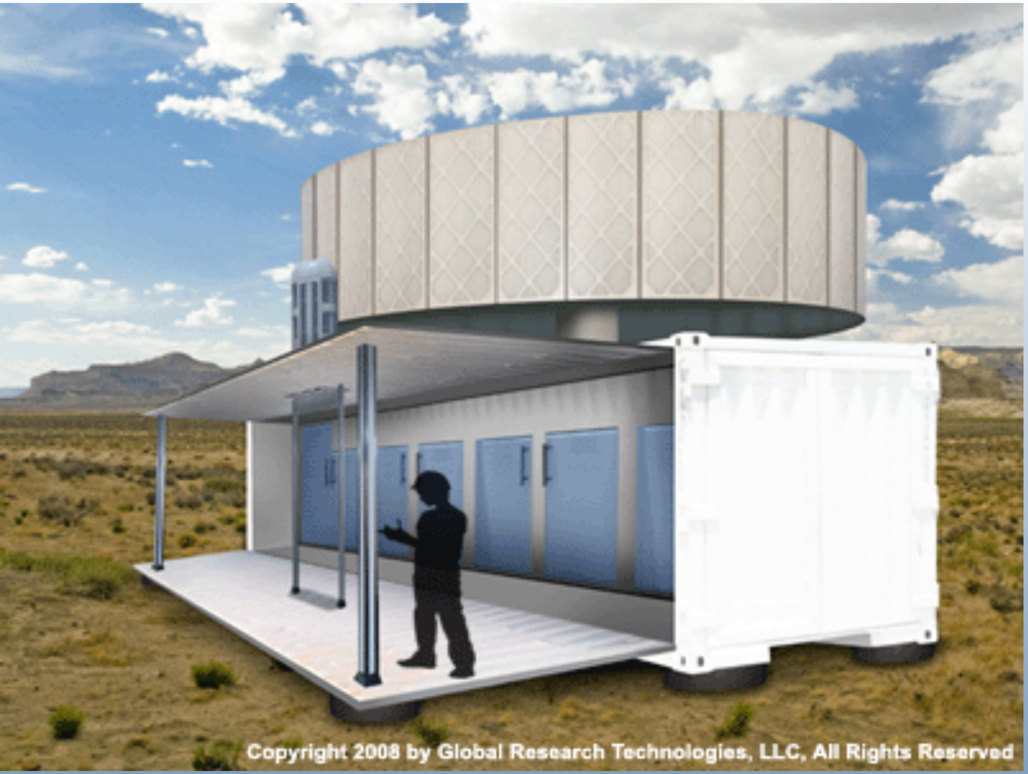


- Moisture swing consumes water and electric power
  - 50 kJ/mol of CO_2
  - 10 liter of saline water per kg of CO_2

Four steps in the moisture swing

- **Dry resin absorbs CO_2 from air**
  - Lowers free energy
- **Resin is wetted**
  - no free energy change in water transfer
  - water interaction with resin may change state
- **Wet resin releases CO_2 at higher pressure**
  - Total system lowers free energy
  - CO_2 has increased free energy (paid internally)
- **Resin dries**
  - Releases latent free energy available in the liquid water
  - This is the only source of free energy to drive the cycle

Setting the Scale for 1 ton/day

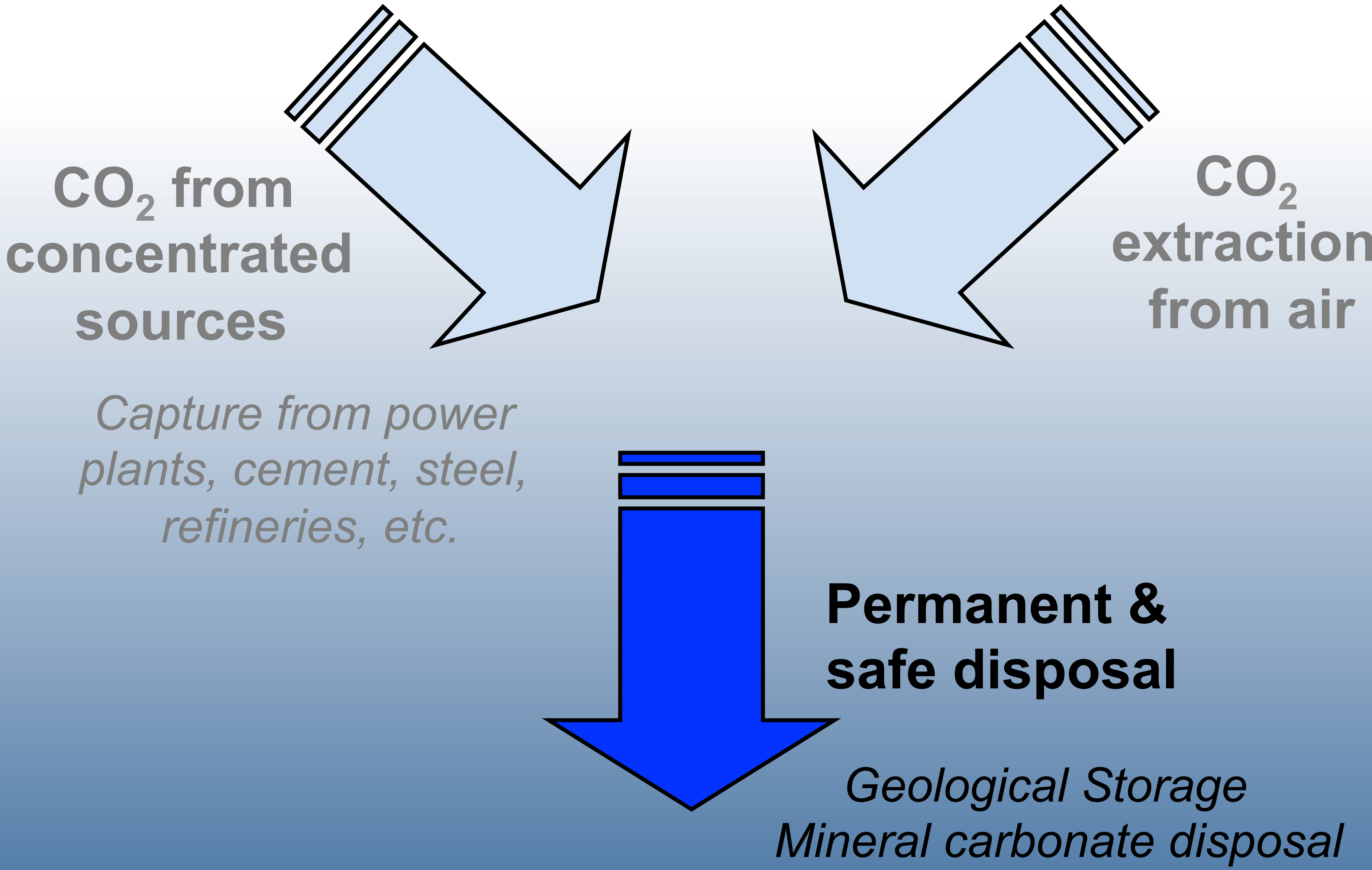


- 2 × 30 panels
  - 2.5m × 1m × 0.3m
- 2 × 2500 kg of resin
  - 10,000m^2 of surface
- 6 × Chambers
  - 4m^3 each
- One Container
  - 86m^3
  - can hold all panels

Mass Production and Cost

- 10 million units @ 1 ton per day
  - capture 3.6 Gt CO2 per year (12% of emissions)
  - require annual production of 1 million (10 year life)
- 100 million units would lower CO2 in the air
- Operating cost
  - inputs (power, water etc.) are low
  - maintenance is high
  - $120 per ton of CO_2

Net Zero Carbon Economy



The 3 Big Storage Options

Geologic

- Injection of CO_2 as a liquid or supercritical gas in permeable geological formations
- Demonstration Phase / Mature market (EOR)

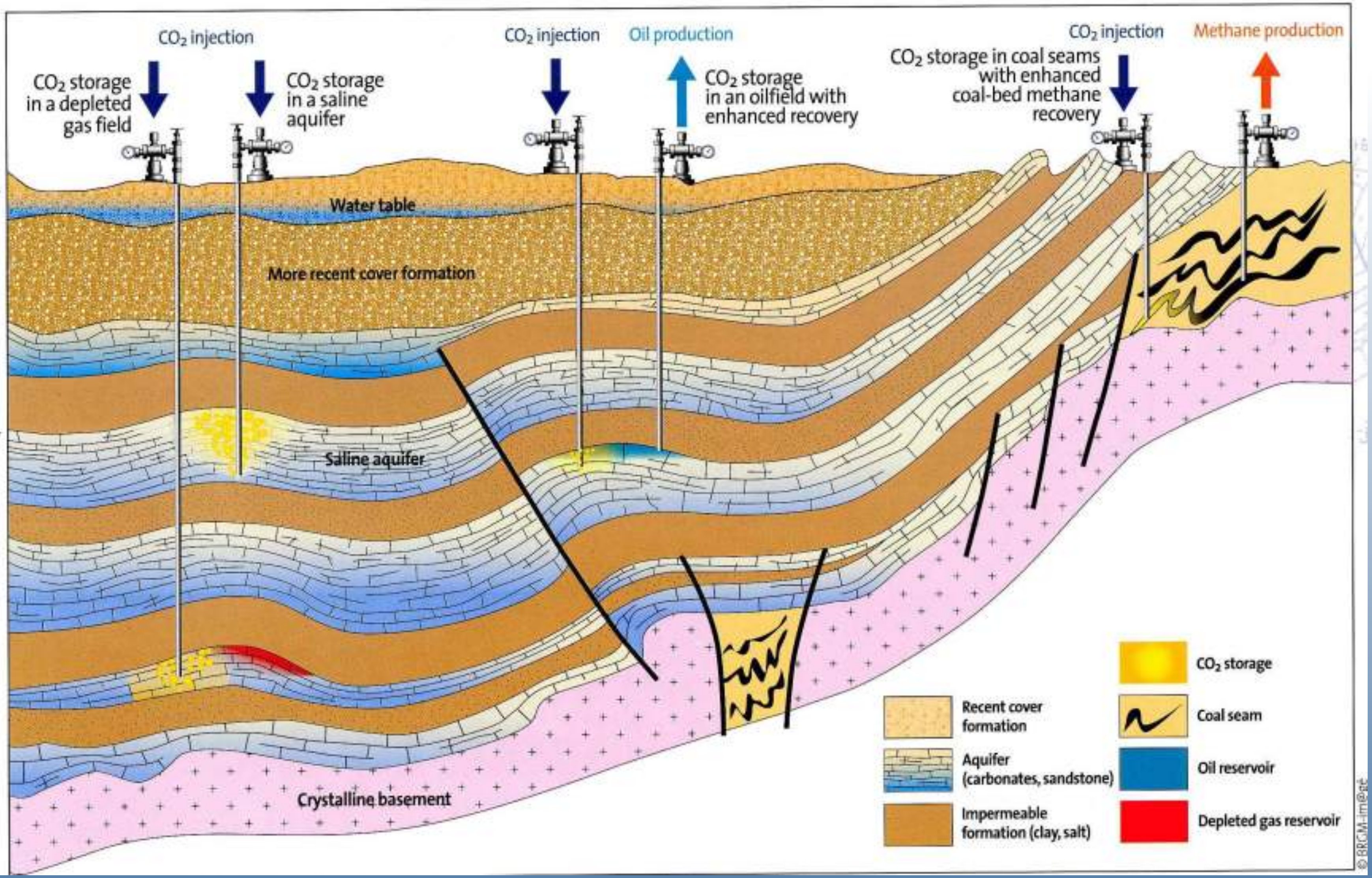
Ocean

- Injection of CO_2 as a liquid into the deep ocean (depths > 1,000 m)
- Research / Demonstration Phase

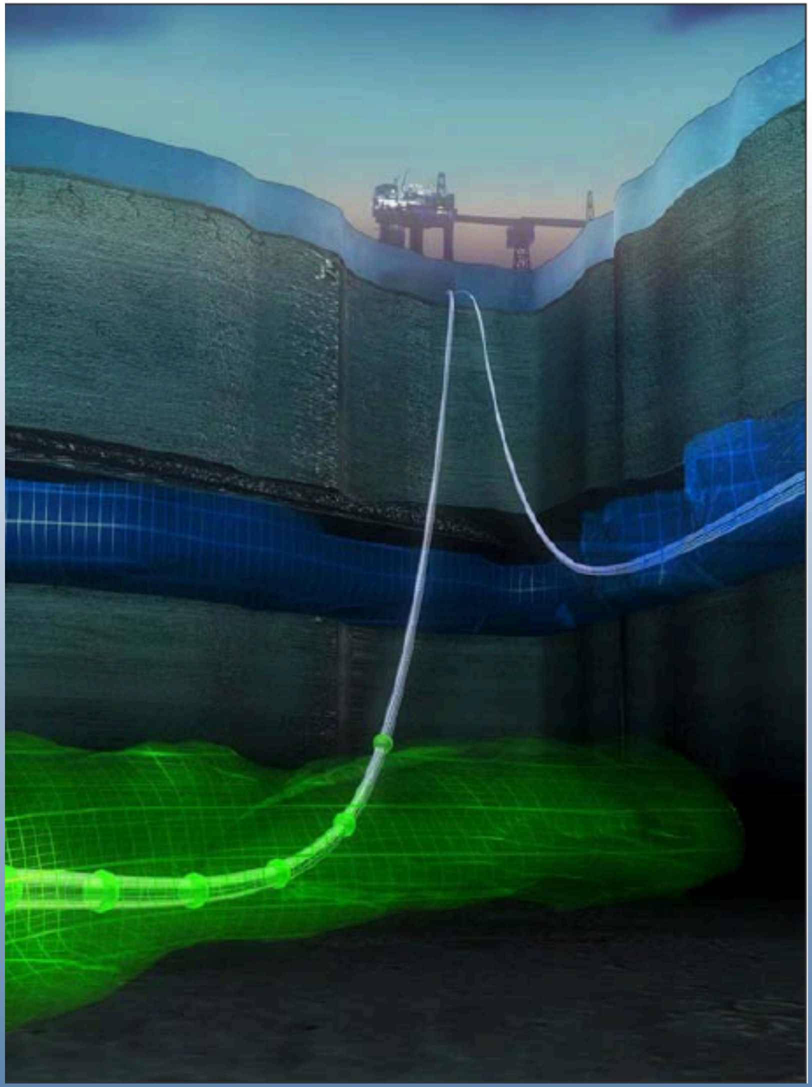
Mineral Carbonation

- Chemical reaction of CO_2 with metal oxide bearing materials to form chemically stable carbonates
- Research / Demonstration Phase

Geologic Storage Sites



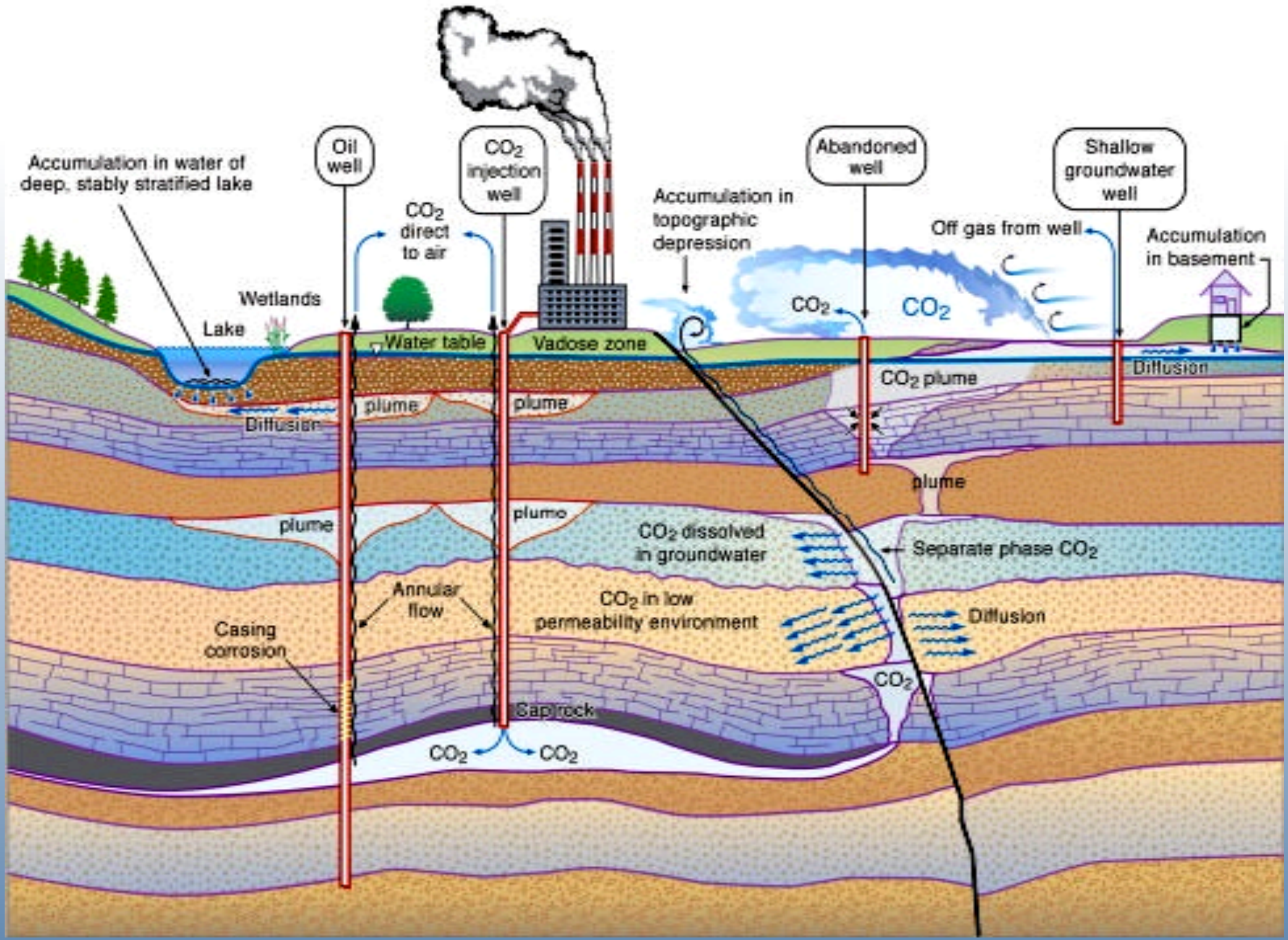
Sleipner CO_2 Project



- Natural gas from Sleipner West Field contains 9% CO_2
- CO_2 captured by amine process
- CO_2 injected offshore in Utsira Formation
- One injection well
- 12 million tons of CO_2 injected so far

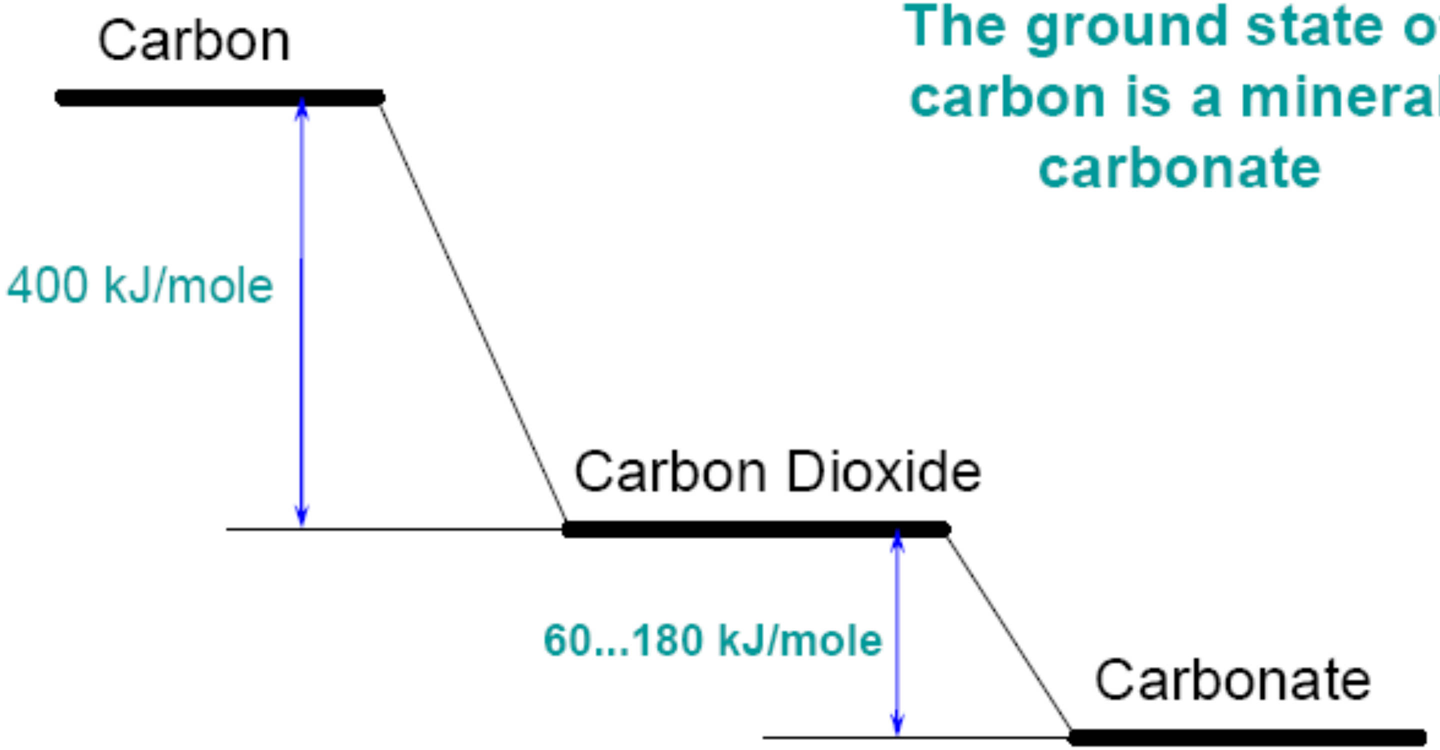
Source: Statoil

Earth is not a leak-proof container



Source: www.westcarb.org

The ground state of carbon is a mineral carbonate



But we also know…….

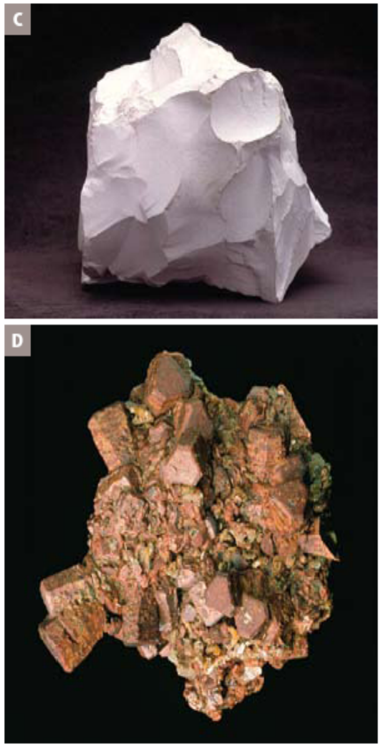
- rocks convert atmospheric CO_2 (dissolved in surface waters) to stable, inert carbonate minerals
- they do this surprisingly fast, and the process gives off energy
- we could speed up this process, taking advantage of natural energy sources

Permanent CO_2 storage via *in situ* mineral carbonation

basalt

$SiAl_{0.36}Ca_{0.30}Mg_{0.25}Fe_{0.17}O_{3.35}$

$+ CO_2 =$



peridotite

$SiAl_{0.08}Mg_{1.32}Fe_{0.14}O_{3.42}$

$+ CO_2 =$

Calcite
Magnesite
siderite

• **mineral carbonation requires combining CO_2 with metals (Ca^{2+}, Mg^{2+}, Fe^{2+})**

$$\underset{\text{Forsterite}}{Mg_2SiO_4} + 2CO_2 = \underset{\text{Magnesite}}{2MgCO_3} + \underset{\text{Quartz}}{SiO_2}$$

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + CO_2 + 2H_2O = \underset{\text{Calcite}}{CaCO_3} + \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4}$$

Potential Source Minerals

SOLID	CHEMICAL FORMULA	Tons required to sequester 1 ton of carbon
Wollastonite	$CaSiO_3$	9.68[a]
Forsterite	Mg_2SiO_4	5.86[b]
Serpentine/ chrysotile	$Mg_3Si_2O_5(OH)_4$	7.69[b]
Anorthite	$CaAl_2Si_2O_8$	23.1[a]
Basaltic glass	$Na_{0.08}\,K_{0.008}\,Fe(II)_{0.17}\,Mg_{0.28}\,Ca_{0.26}\,Al_{0.36}\,Fe(III)_{0.02}\,SiTi_{0.02}\,O_{3.45}$	8.76[c]

[a]as calcite, [b]as magnesite, [c]assuming all Ca, Mg, Fe are converted into calcite, magnesite and siderite

Source: Oelkers, Gislason, and Matter, Elements (2008)

Carbonate Phases for Potential CO_2 Storage

Mineral	Formula	Mass produced per ton C (ton)	Volume produced per ton C (m^3)
Calcite	$CaCO_3$	8.34	3.08
Magnesite	$MgCO_3$	7.02	2.36
Dawsonite	$NaAl(CO_3)(OH)_2$	12.00	4.95
Siderite	$FeCO_3$	9.65	2.49
Ankerite	$Ca(Fe,Mg)(CO_3)_2$	8.60	2.81

Source: Oelkers, Gislason, and Matter, Elements (2008)

In situ Mineral Carbonation in Basalt

Source: McGrail et al. 2006, JGR Vol. 111, B12201

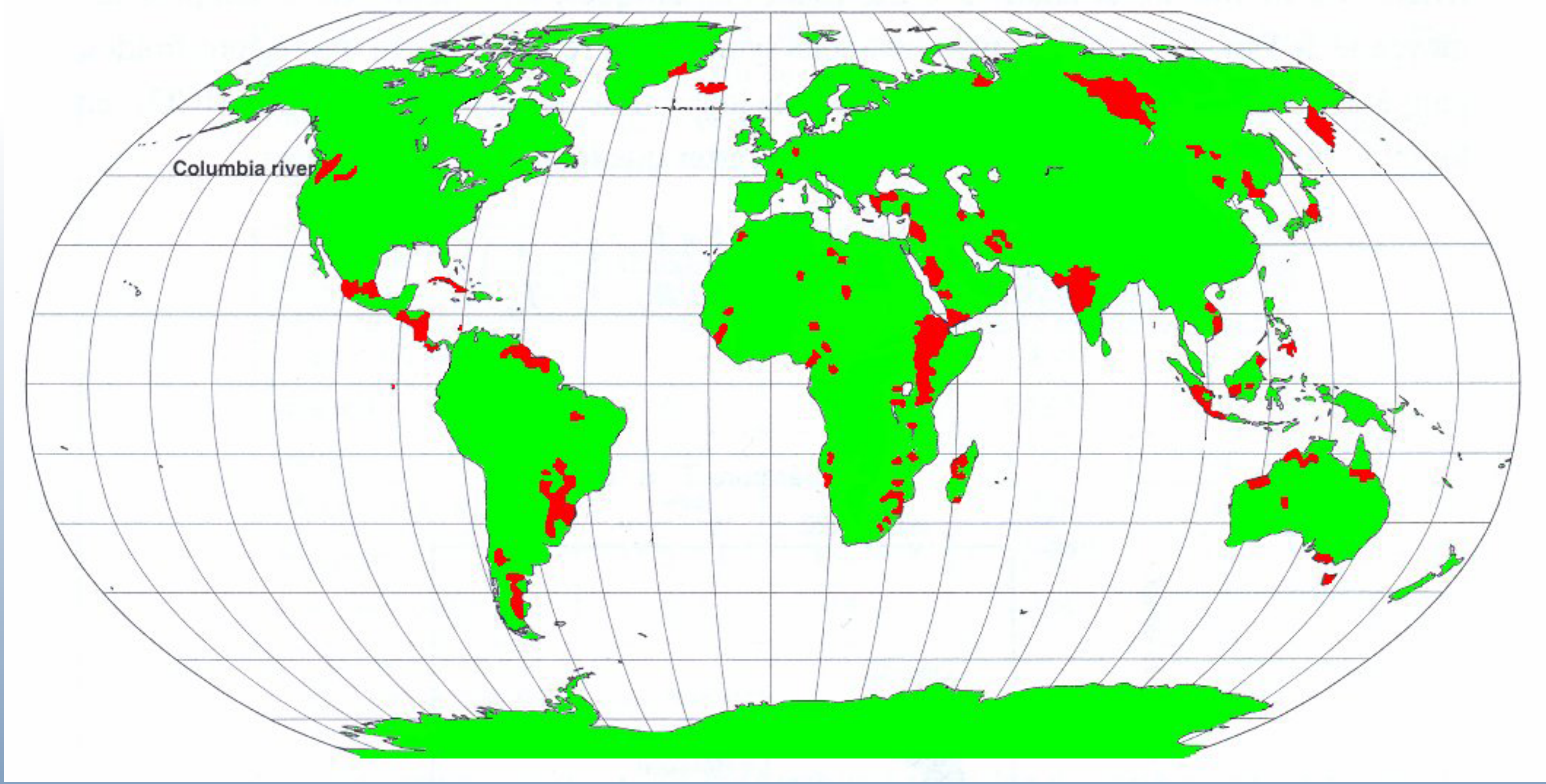
Enhancing chemical weathering:

$CaAl_2Si_3O_8 + 2CO_2 + 3H_2O$ ->

$Al_2Si_2O_5(OH)_4 + Ca^{++} + 2HCO_3^-$ …>

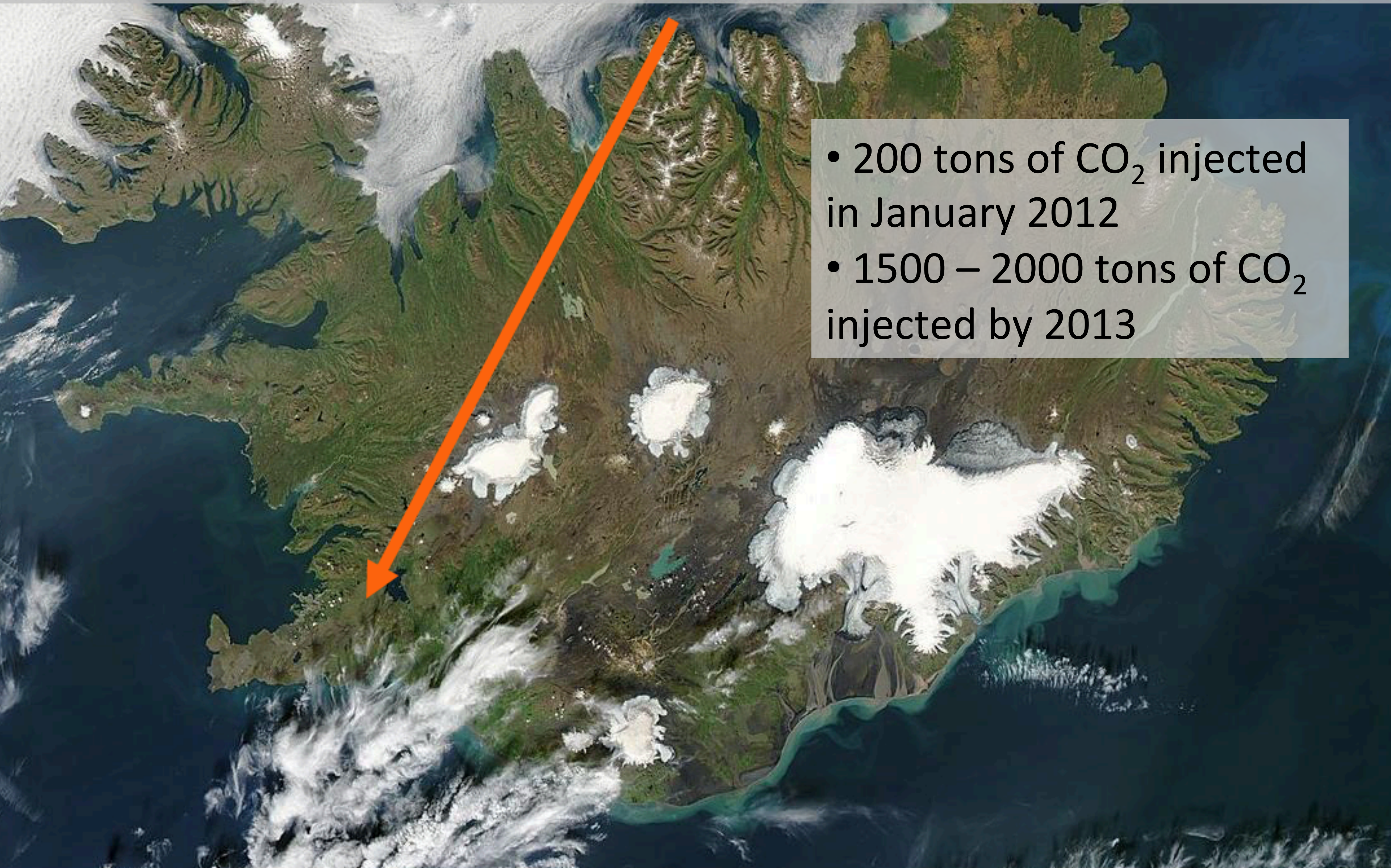
…$CaCO_3 + CO_2 + H_2O$

Global Significance of Basalt



- Columbia River Basalt: 36 to 148 billion tons of CO_2 (McGrail et al. 2006)
- Caribbean Basalt: 1,000 to 5,500 billion tons of CO_2 (Goldberg & Slagle, 2009)

MINERAL CO_2 SEQUESTRATION INTO BASALT: THE CARBFIX PROJECT

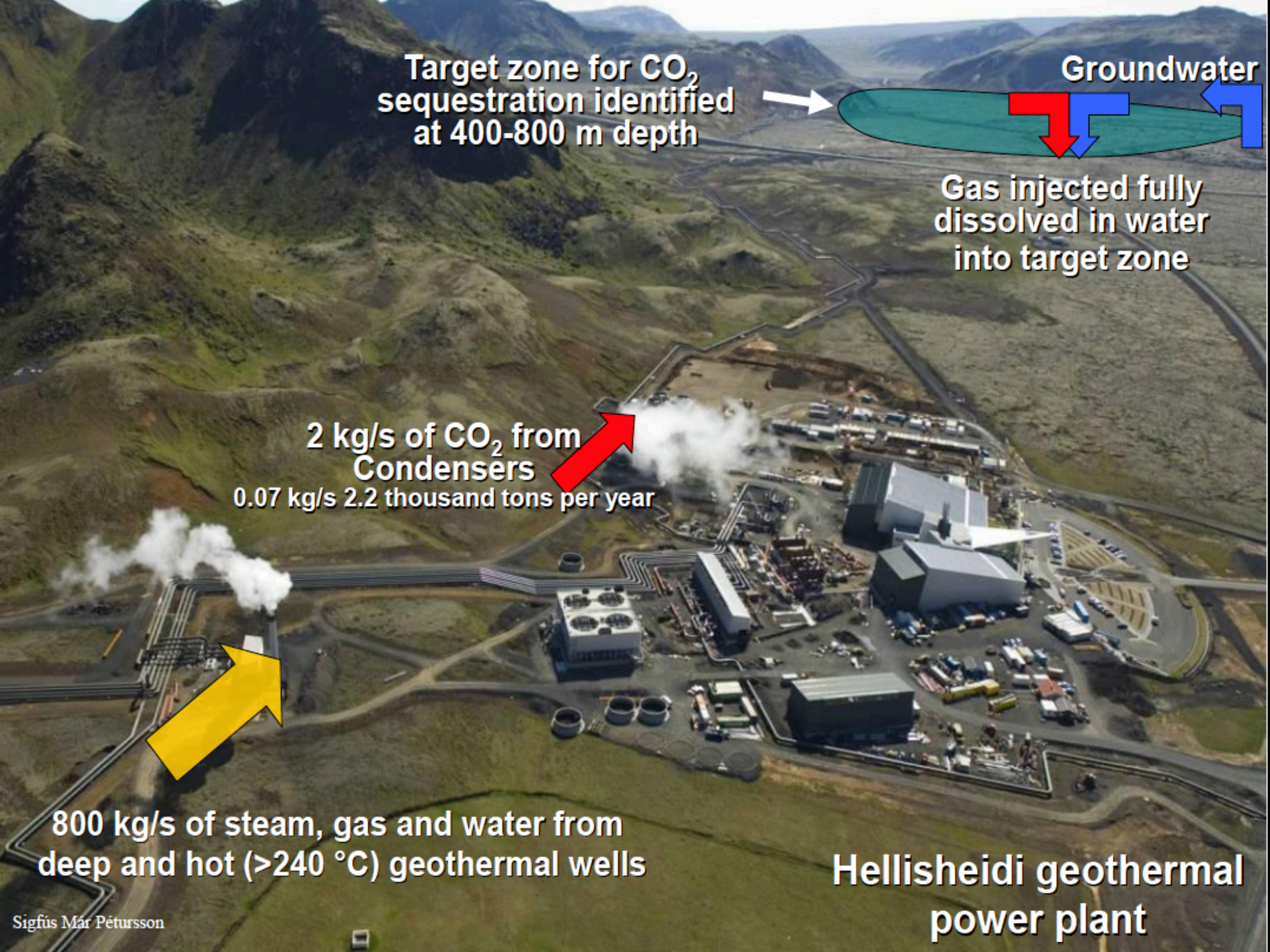


- 200 tons of CO_2 injected in January 2012
- 1500 – 2000 tons of CO_2 injected by 2013

CarbFix Partners

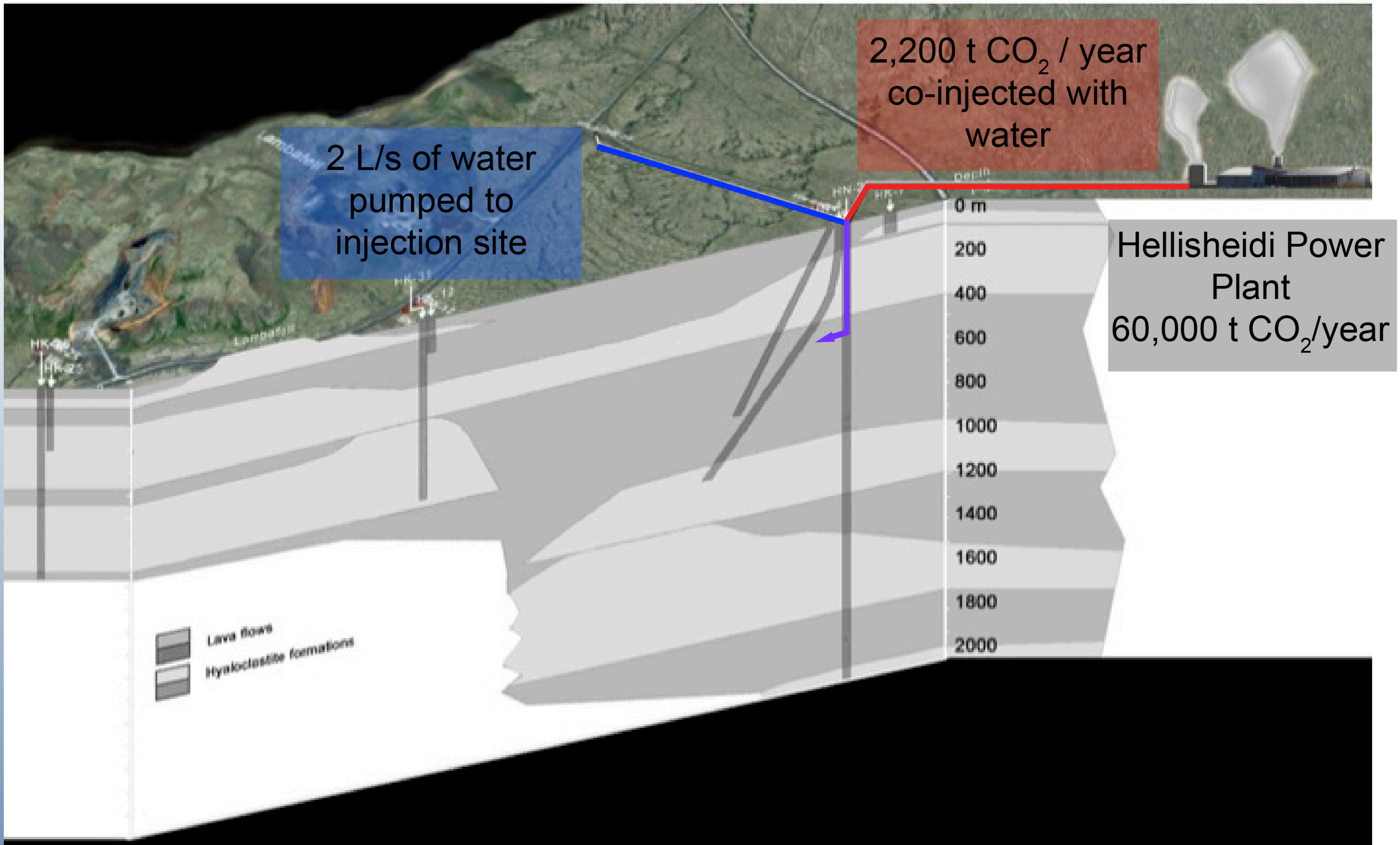
European – U.S. Collaboration

- Orkuveita Reykjavikur (Reykjavik Energy), Iceland
- University of Iceland, Iceland
- CNRS, University of Toulouse, France
- Columbia University, New York, USA



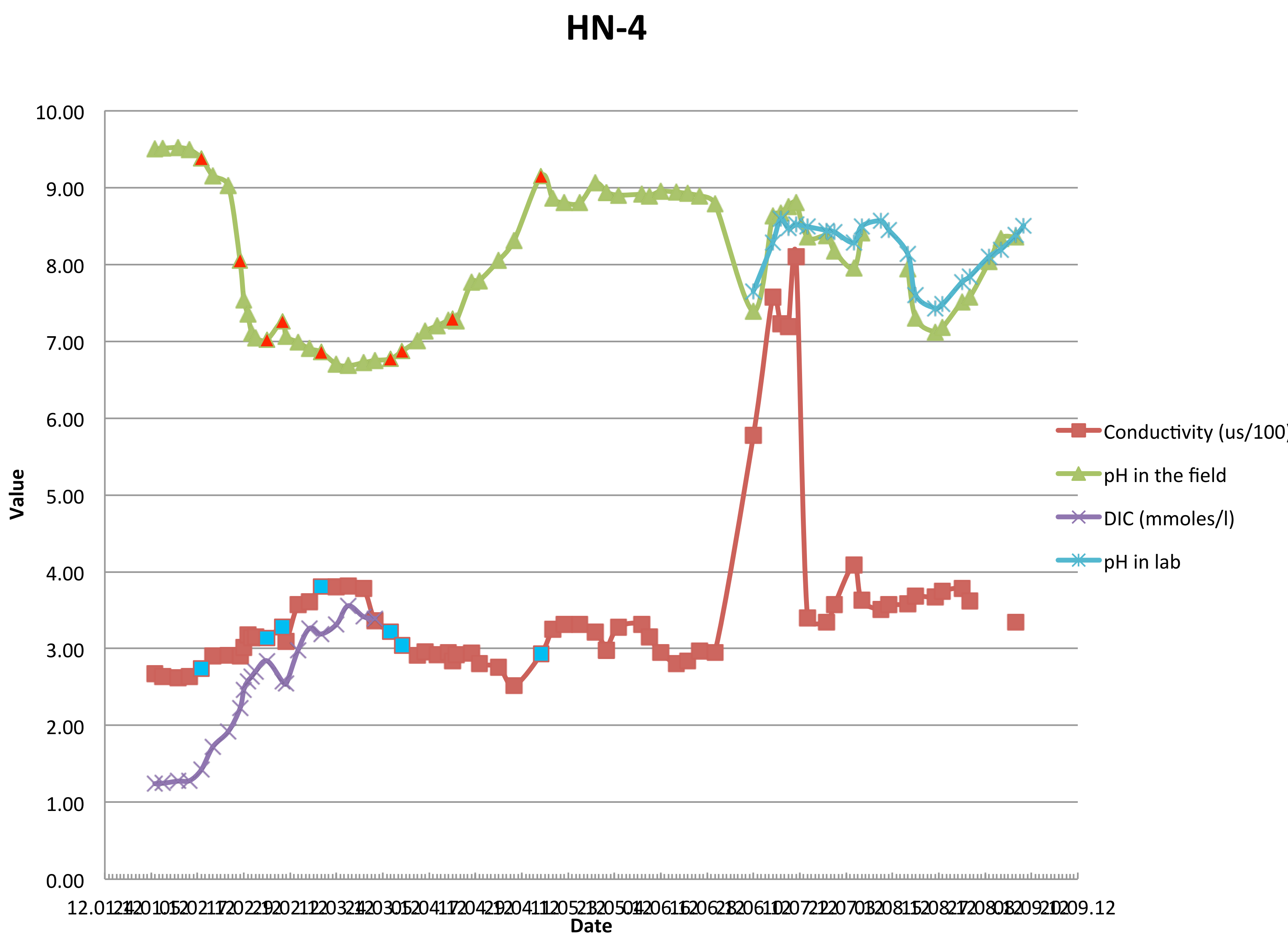
Target zone for CO_2 sequestration identified at 400-800 m depth
Groundwater
Gas injected fully dissolved in water into target zone
2 kg/s of CO_2 from Condensers
0.07 kg/s 2.2 thousand tons per year
800 kg/s of steam, gas and water from deep and hot (>240 °C) geothermal wells
Hellisheidi geothermal power plant
Sigfús Már Pétursson

Injection Process



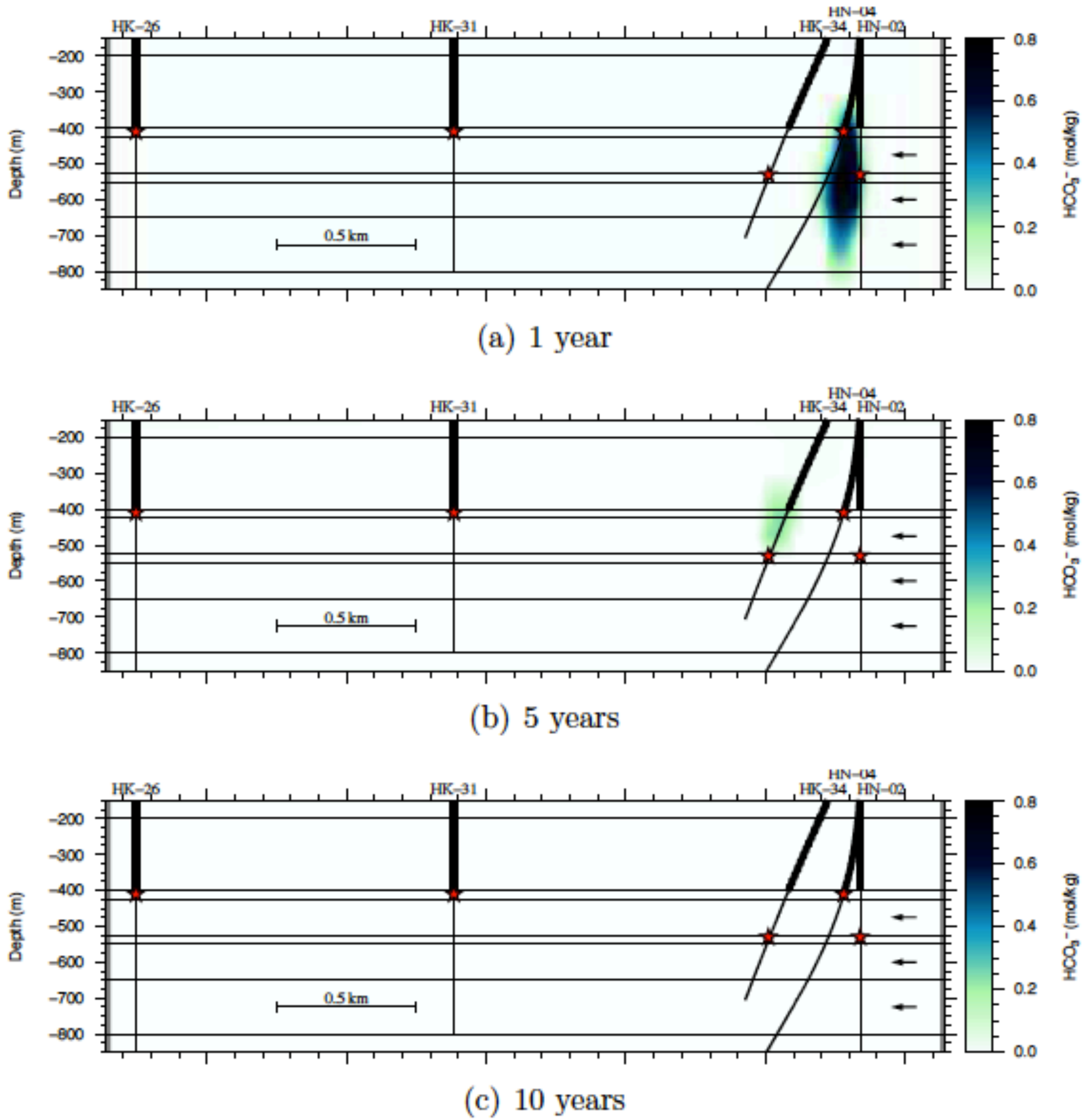
Alfredsson, 2009

In situ CO_2-water-rock reactions



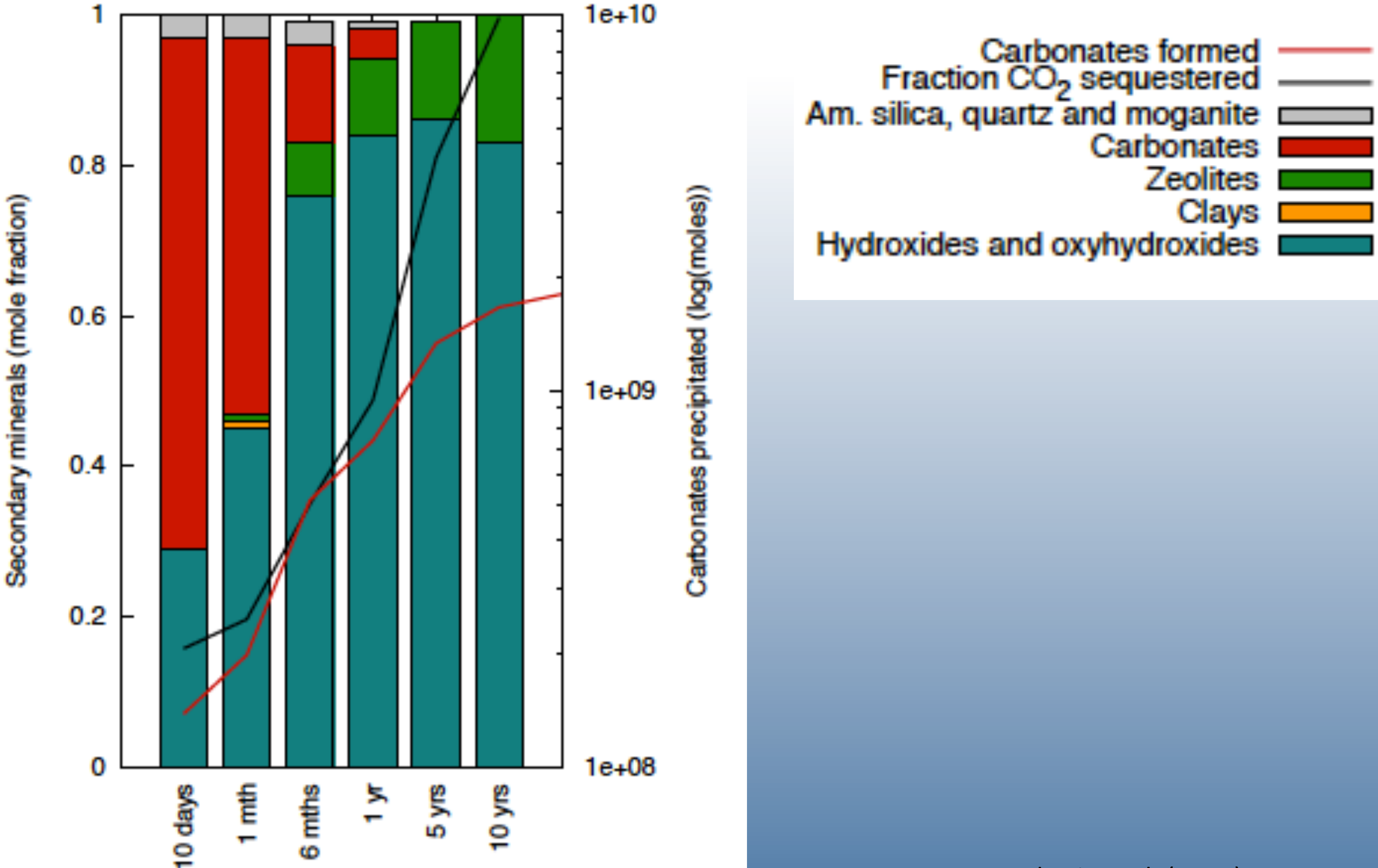
Kiflom et al. (to be published)

3-D reactive transport simulation



Aradottir et al. (2011)

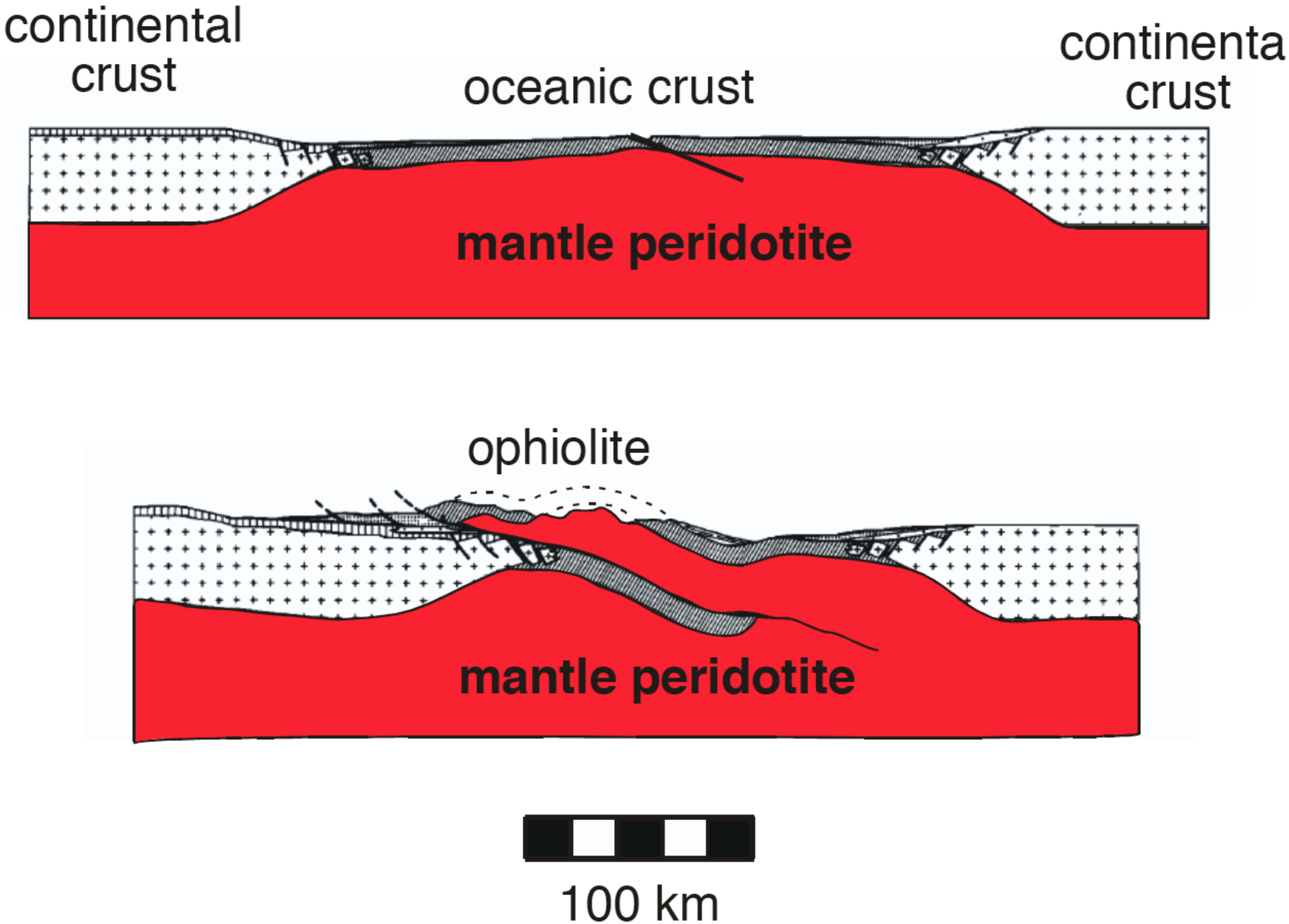
Simulated Secondary Mineral Abundance



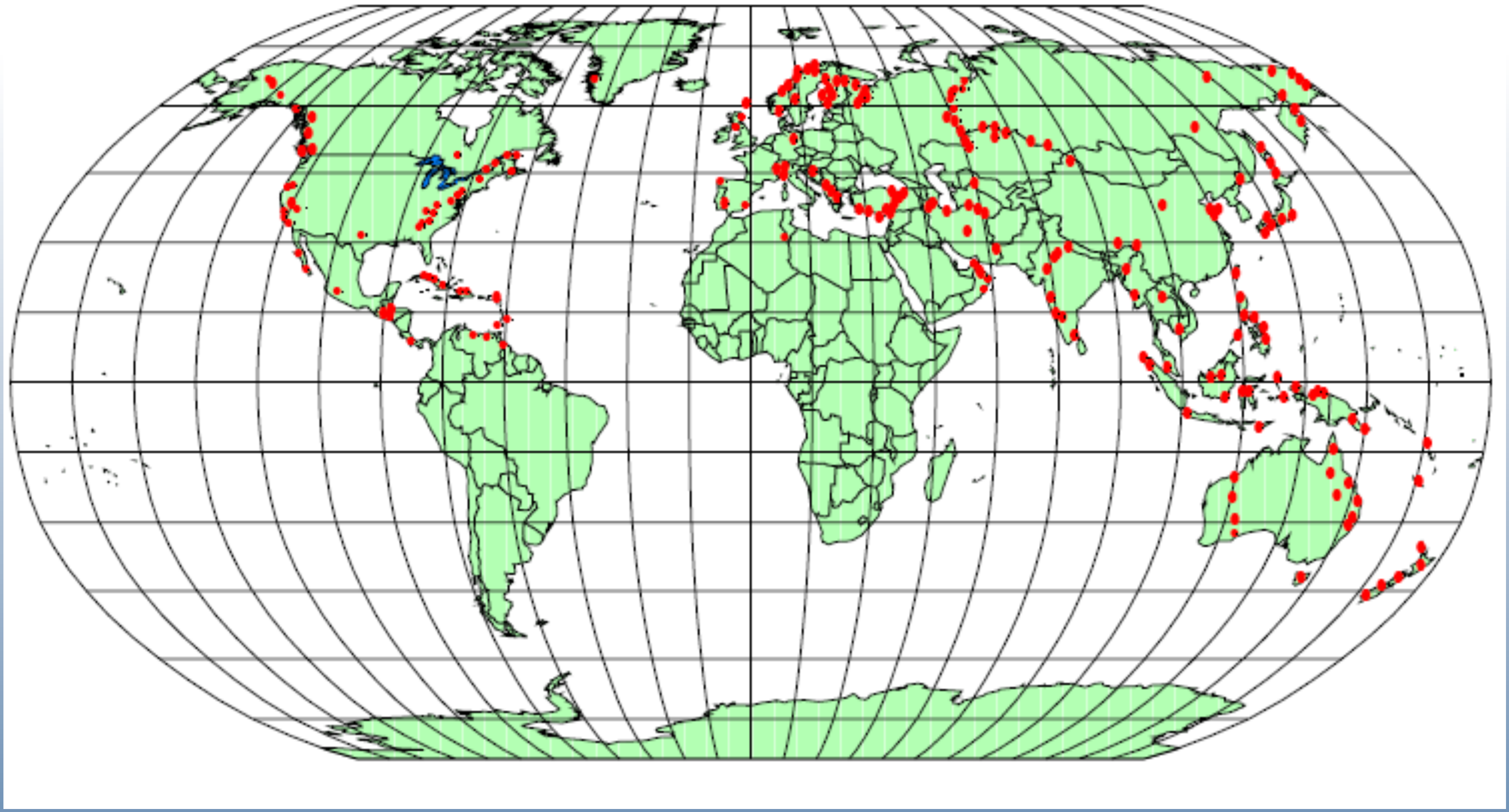
Aradottir et al. (2011)

In Situ Mineral Carbonation in Mantle Peridotite – Sultanate of Oman

Mountains of northern Oman are composed of oceanic crust & upper mantle (peridotite)


continental crust
oceanic crust
continental crust
mantle peridotite
ophiolite
mantle peridotite
100 km

Global Significance of Peridotite



CO_2-fluid-rock reactions

carbonation of olivine

$$4Mg_2SiO_4 + 8CO_2 = 4SiO_2 + 8MgCO_3$$

Mg-olivine quartz magnesite

hydration and carbonation of olivine

$$4Mg_2SiO_4 + 4H_2O + 2CO_2 = 2Mg_3Si_2O_5(OH)_4 + 2MgCO_3$$

Mg-olivine serpentine magnesite

adding calcium

$$4Mg_2SiO_4 + CaMgSi_2O_6 + 6H_2O = Ca(OH)_2 + 3Mg_3Si_2O_5(OH)_4$$

Mg-olivine Ca-pyroxene dissolved Ca-hydroxide serpentine

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

dissolved Ca-hydroxide calcite

Storage Potential

2.9×10^{15} kg of CO_2 in the atmosphere

pre-industrial atmosphere had 2.2×10^{15} kg

change of 0.7×10^{15} kg

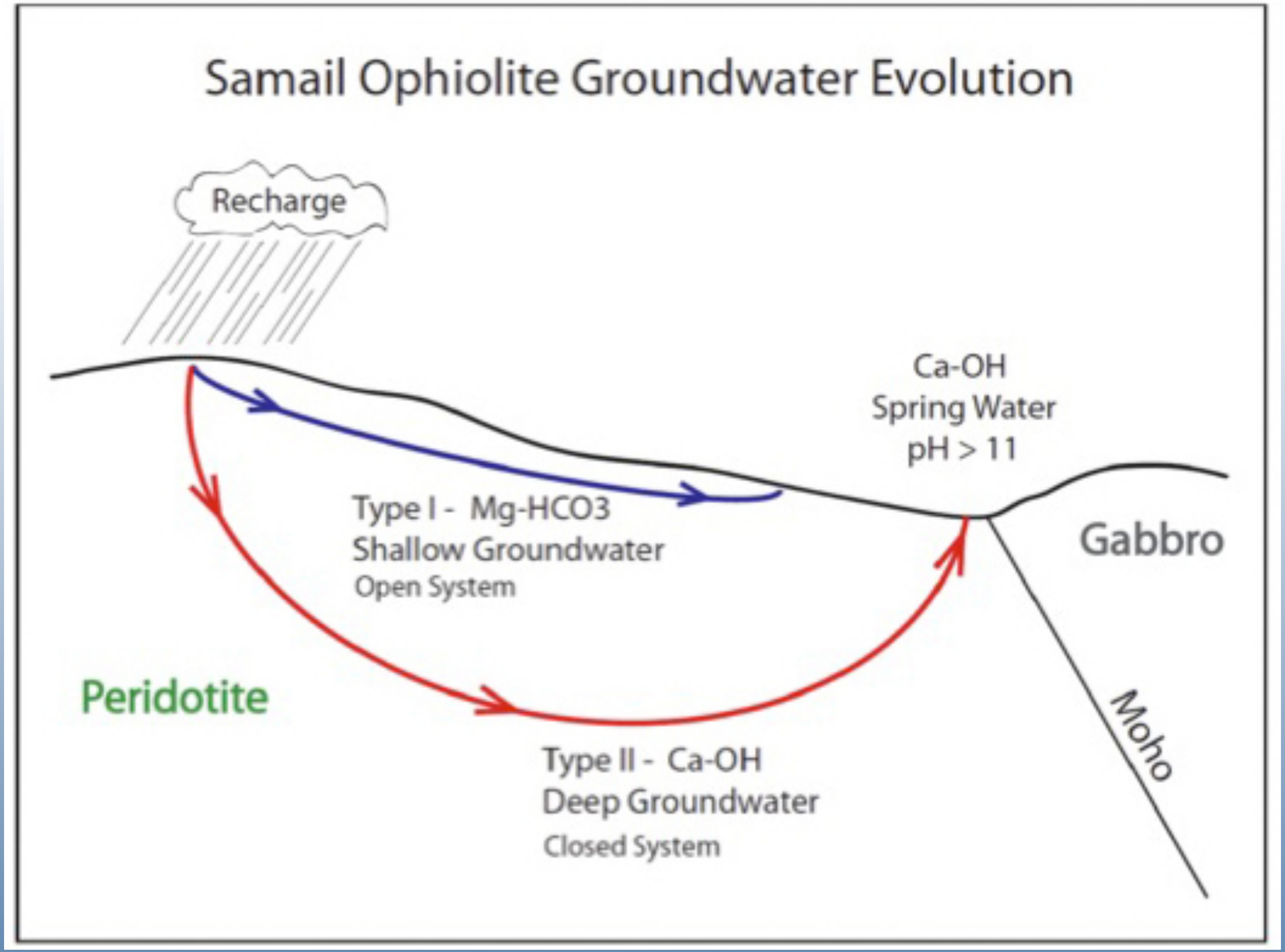
Oman ophiolite >350 km long, ~40 km wide and ~5 km thick

30% residual mantle peridotite, density 3300 kg/m^3

1 wt% CO_2 added to peridotite = **0.7×10^{15} kg**

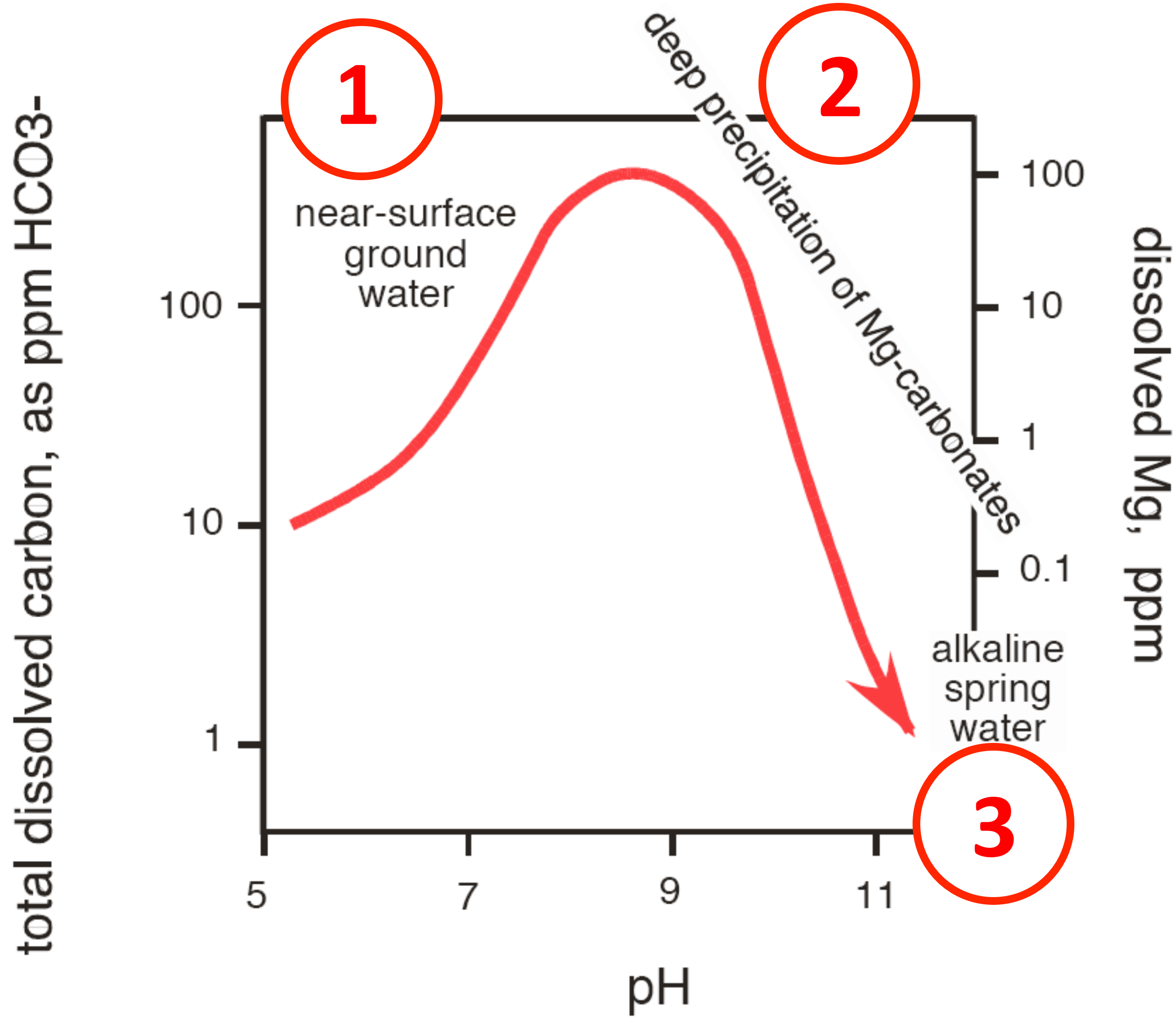
~ ¼ atmospheric CO_2

Groundwater system in mantle peridotite



Paukert et al., Chemical Geology, 2012

Natural *In situ* Carbonation



- Rate of solid carbonate formation in upper 10-15 m is now

~ 10^4 to 10^5 tons/yr

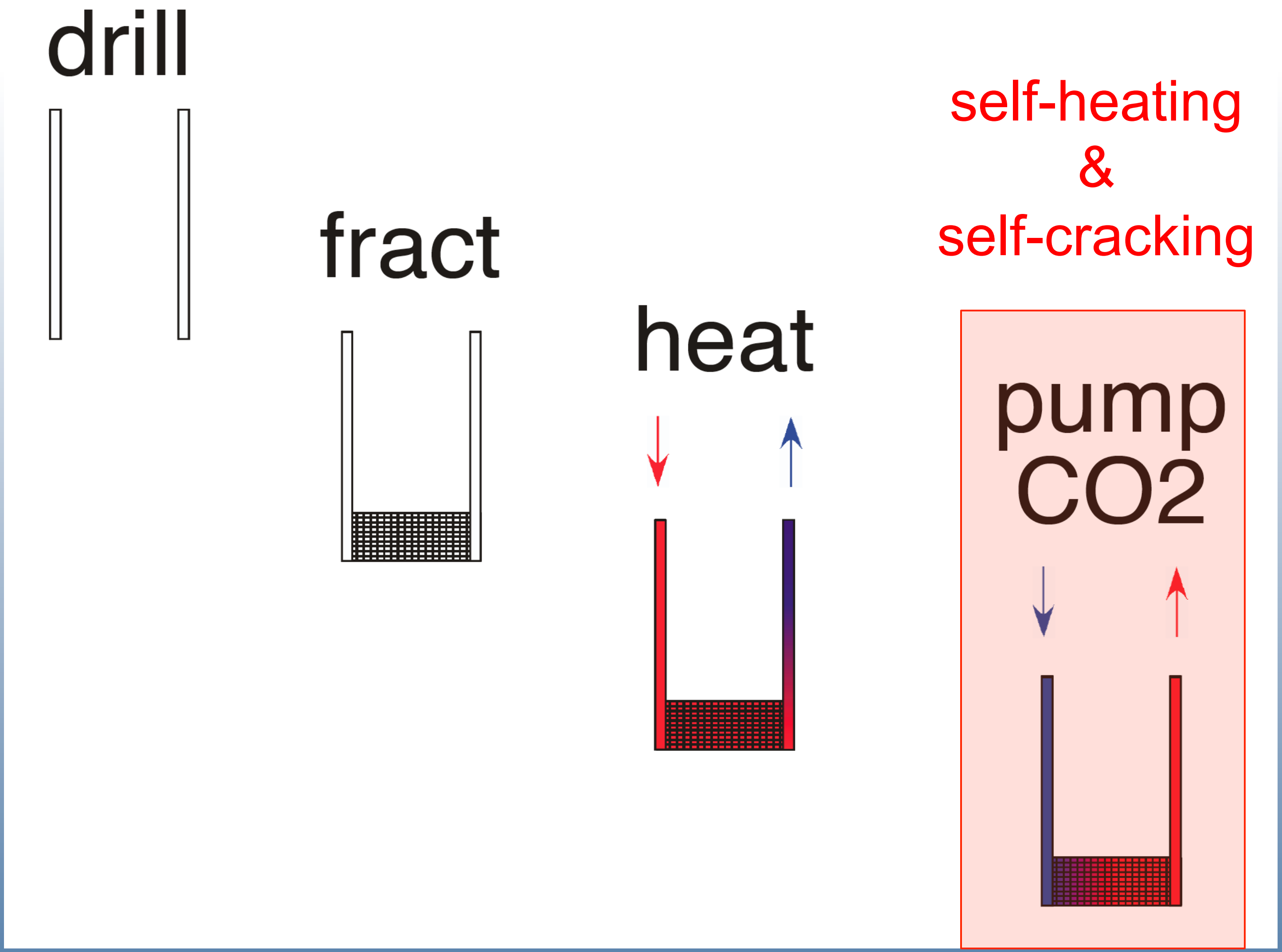
(~$3x10^3$ tons/km^3/yr)

- For comparison, anthropogenic CO_2 input to atmosphere

~$3x10^{10}$ tons/yr

Can we enhance the natural rate?

Geoengineering *In Situ* Mineral Carbonation



Kelemen & Matter, Proceedings of the National Academy of Sciences, 2008

carbonate reaction gives off energy
~760 kJ/kg of olivine consumed

this can be converted to heat

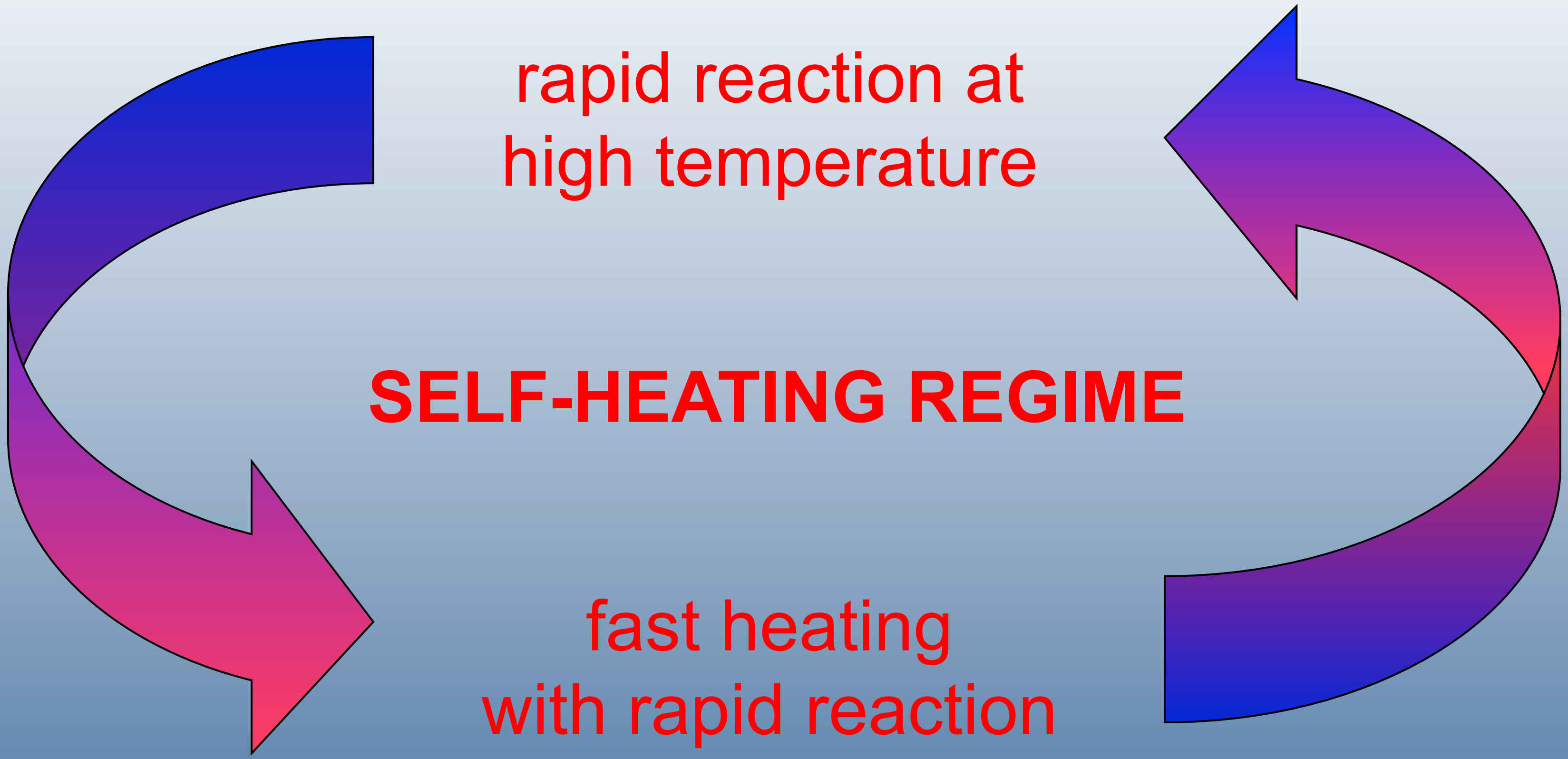
heat capacity of peridotite
~900 J/(kg°C)

12% carbonation of 1 kg olivine would

raise the temperature ~100°C
in a perfectly insulated container

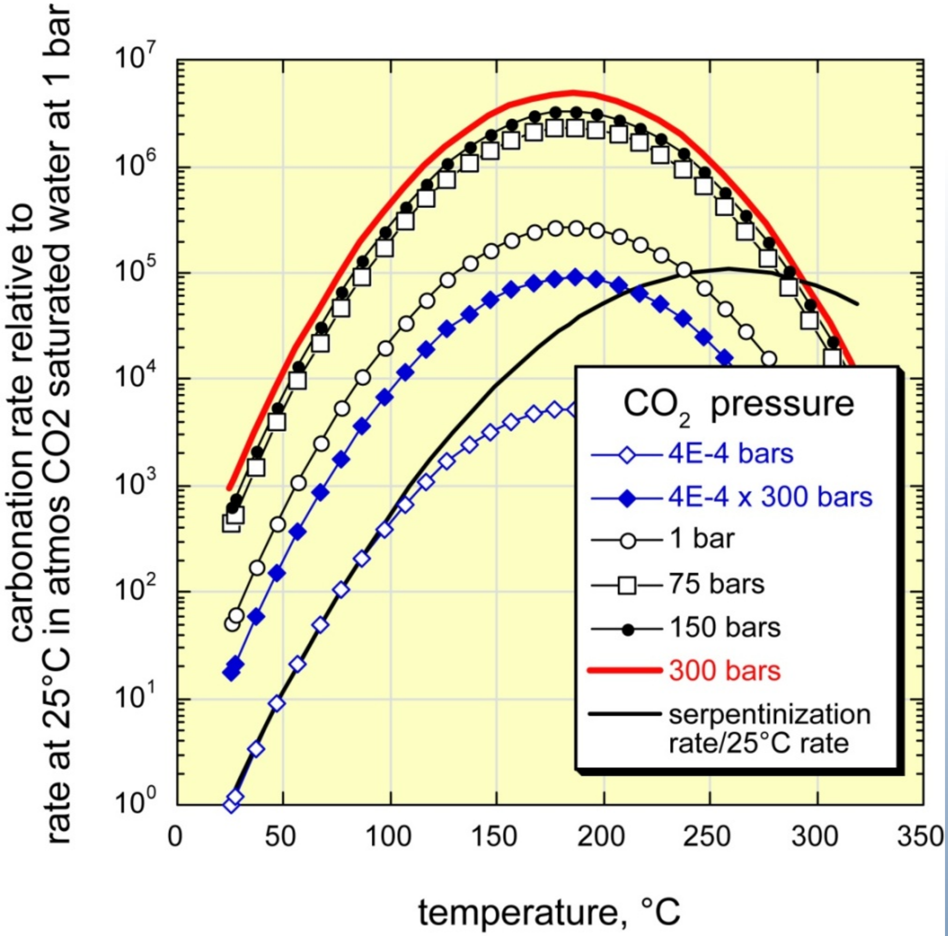
olivine + gas => hydrous silicate + solid carbonate + HEAT + STRESS

- Reaction Rate increases with increasing temperature



Kelemen & Matter , 2008

Enhanced Carbonation Rate



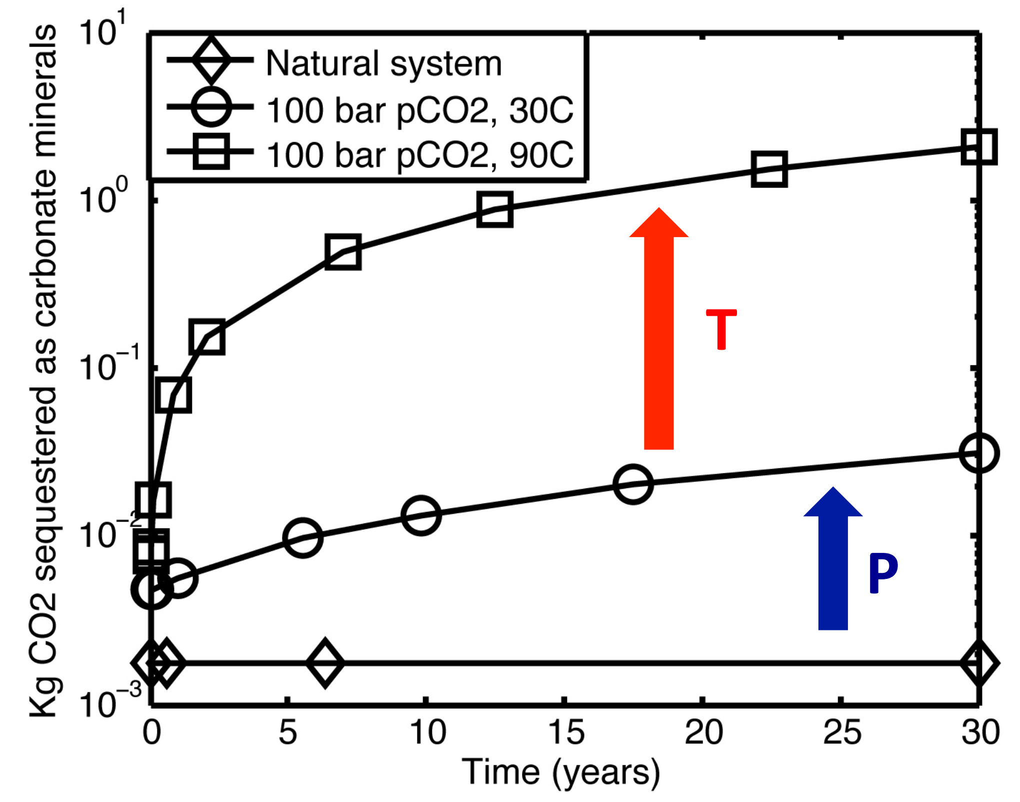
•carbonation rate (Gerdemann et al. 2003 data)

$\Gamma \sim 1.15 \cdot 10^{-5} (P_{CO2}, \text{bars})^{1/2} \exp[-0.000334 (T - 185°C)^2]$

heating & raising P_{CO2} increase carbonation rate by $>10^6$

Kelemen & Matter, PNAS, 2008

Enhanced CO_2 mineralization



- Total amount of CO_2 mineralized in the 90°C scenario is ~1200 x the amount sequestered in the natural system over the same time frame.
- The kg CO_2/kg peridotite ratio in the 90°C scenario is 0.61, which indicates almost complete mineralization (complete forsterite mineralization -> 0.63 ratio)

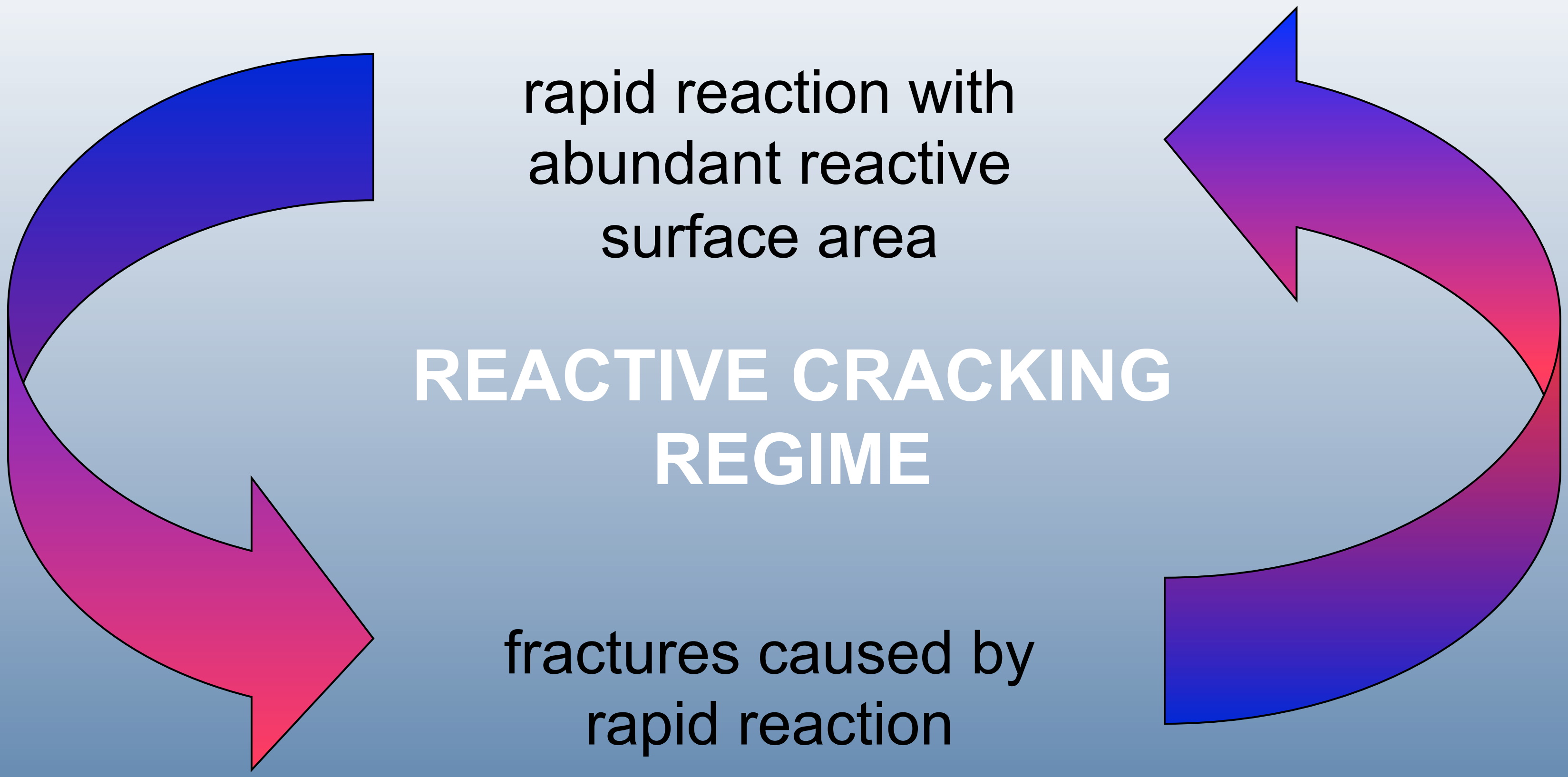
Paukert et al. Chemical Geology 2012

- Reducing permeability and porosity by secondary minerals

- Armoring reactive surface area with secondary minerals

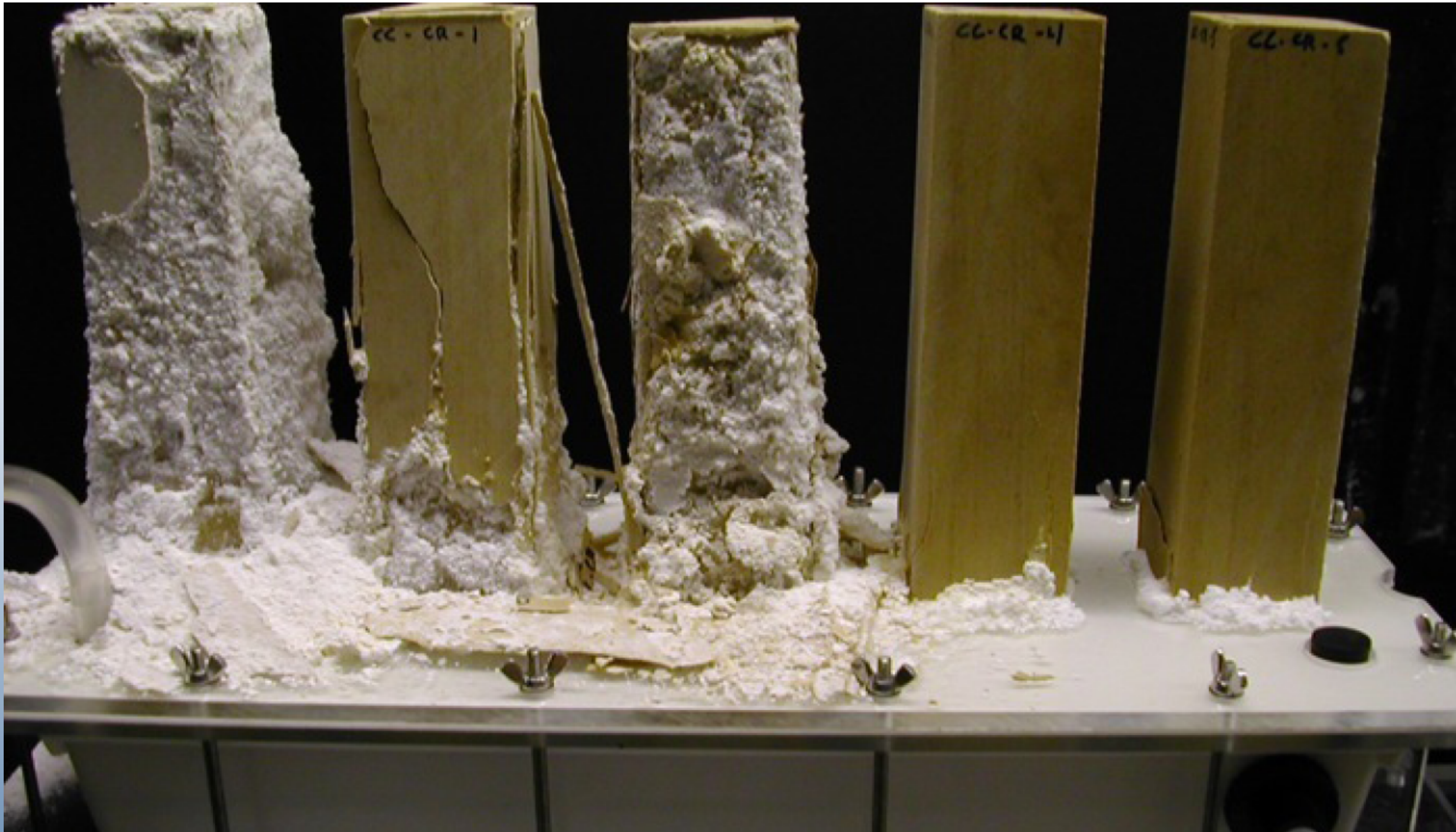
olivine + gas => hydrous silicate + solid carbonate + HEAT + STRESS

- surface area increases with fracture

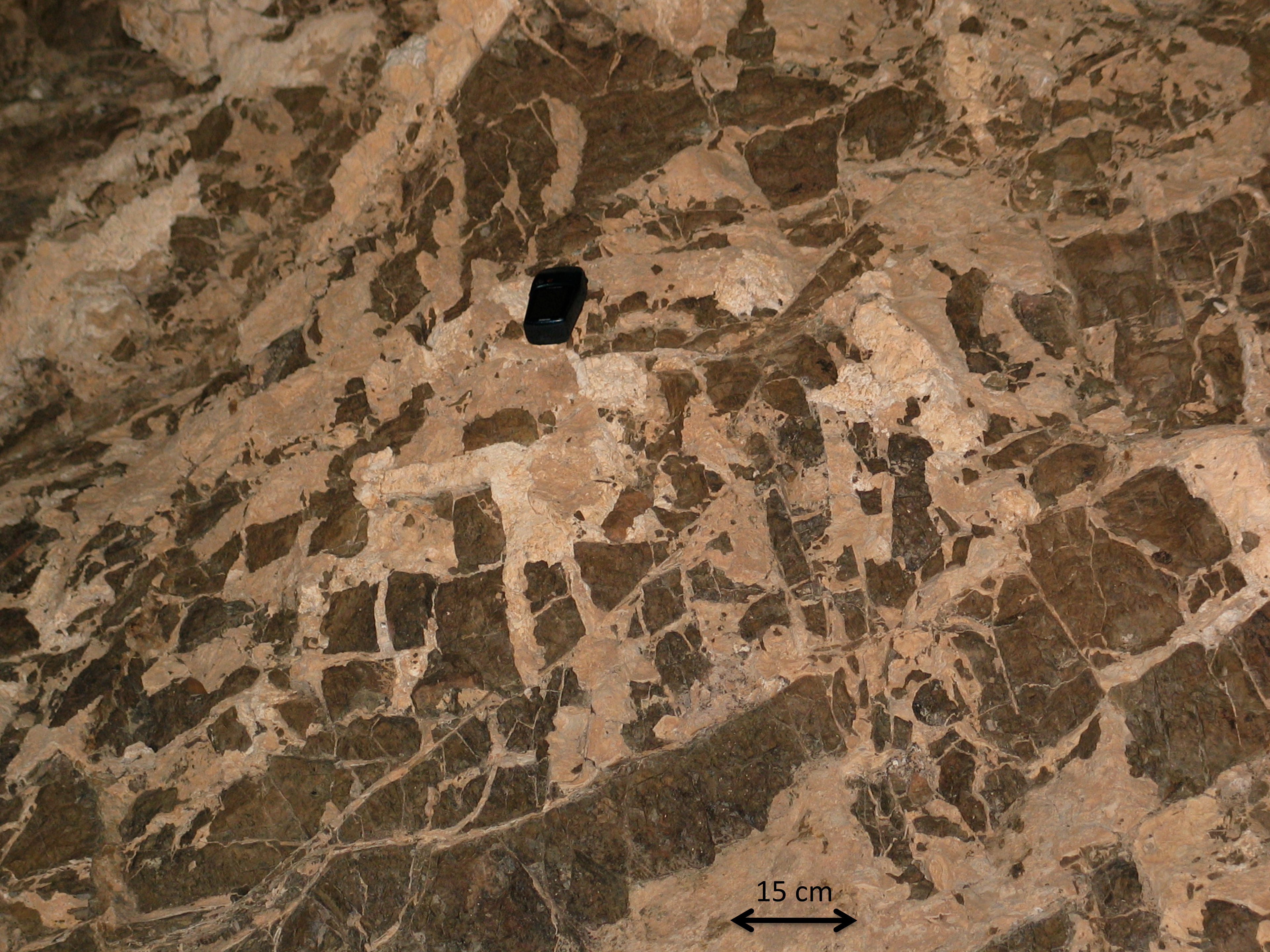


Kelemen et al. 2009

Reactive Cracking



http://web.mac.com/gwscherer1/SchererGroup/Salt_Crystallization.html


15 cm


Thank you