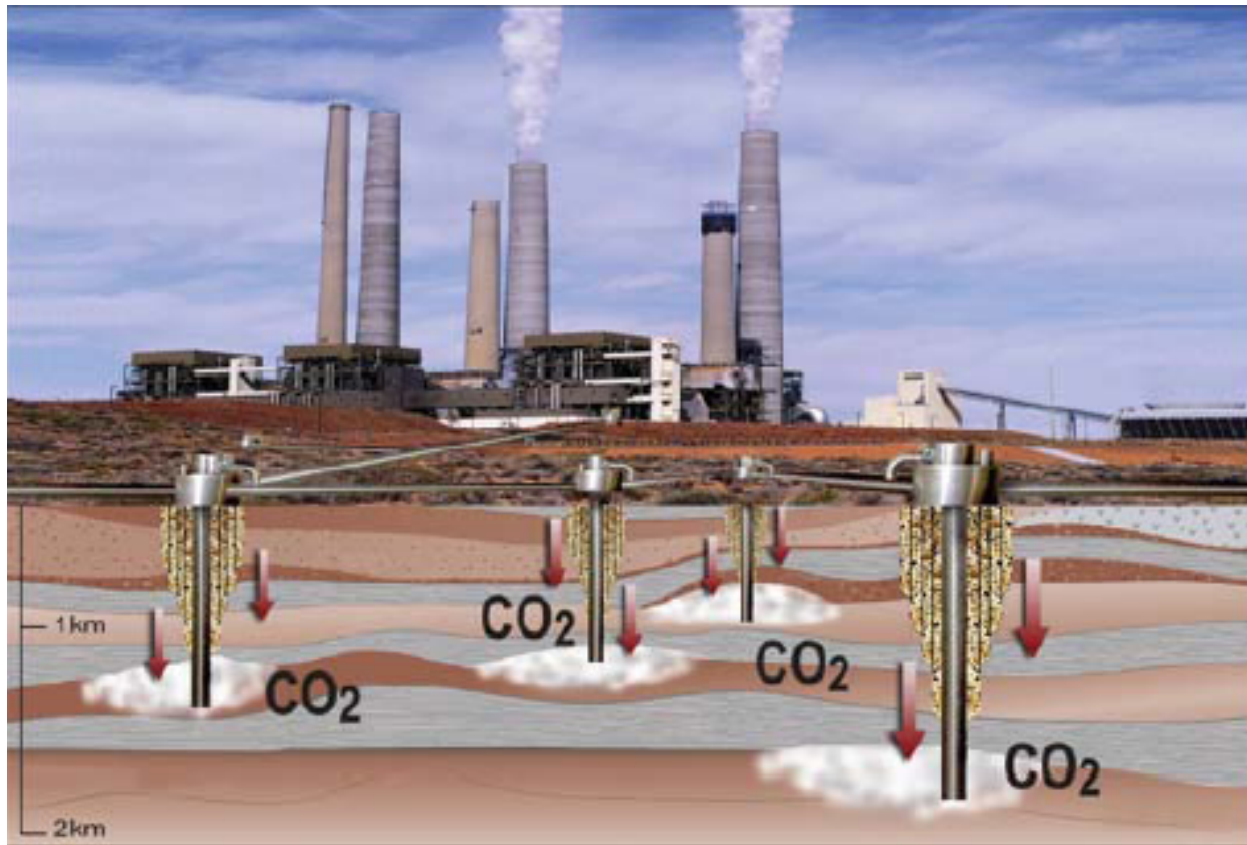


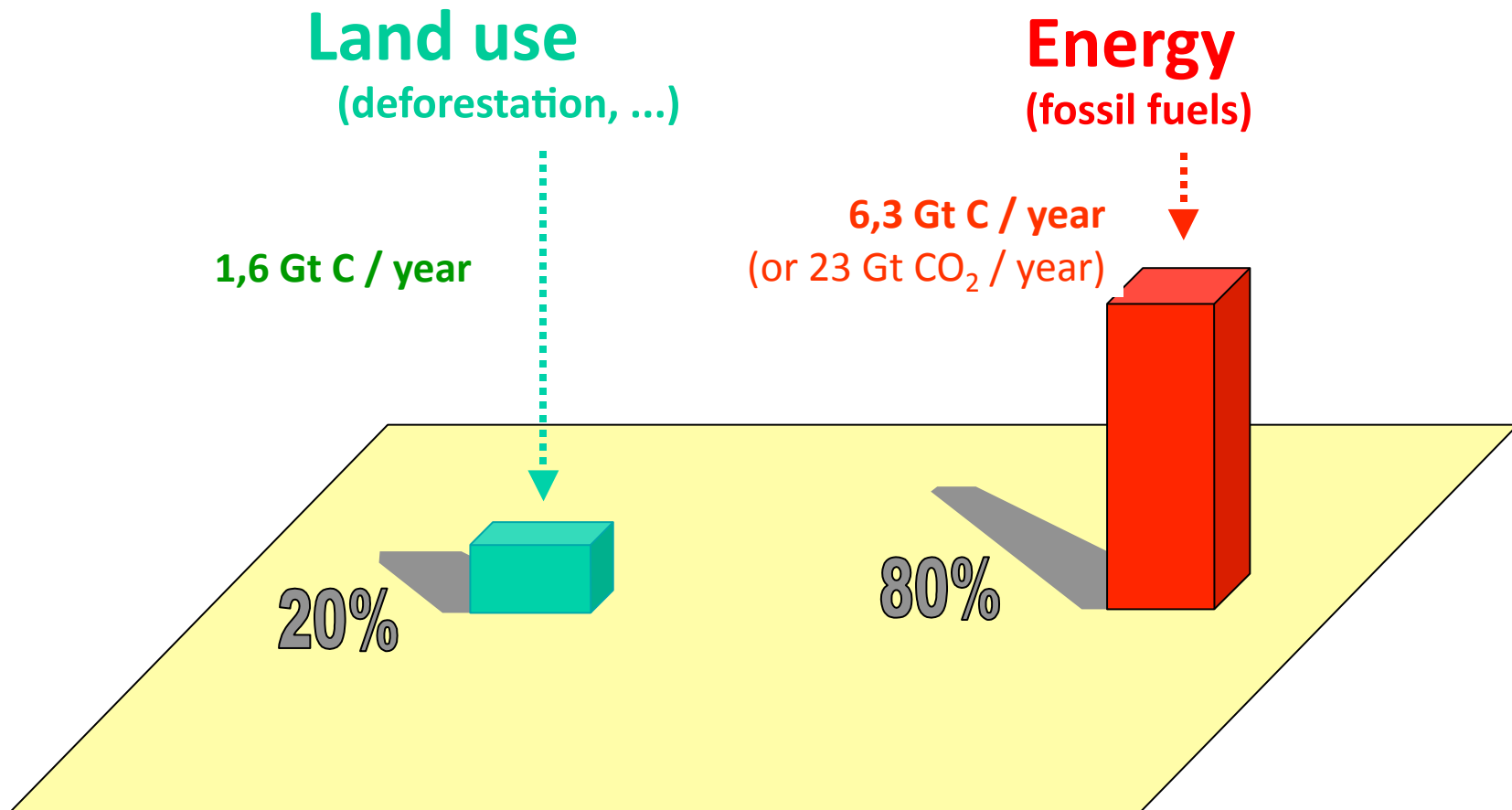
# Enhanced Sinks I:

## Carbon Capture and Storage



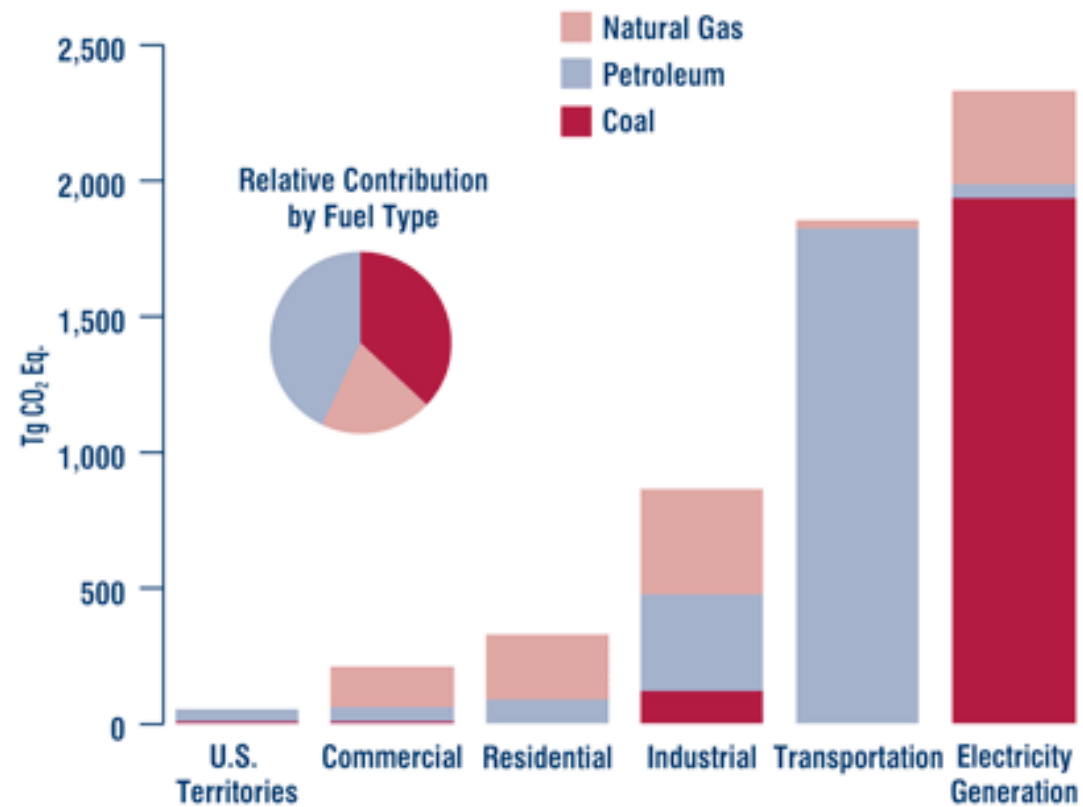
Courtesy of S. Benson

# Origin of Anthropogenic CO<sub>2</sub> Emissions



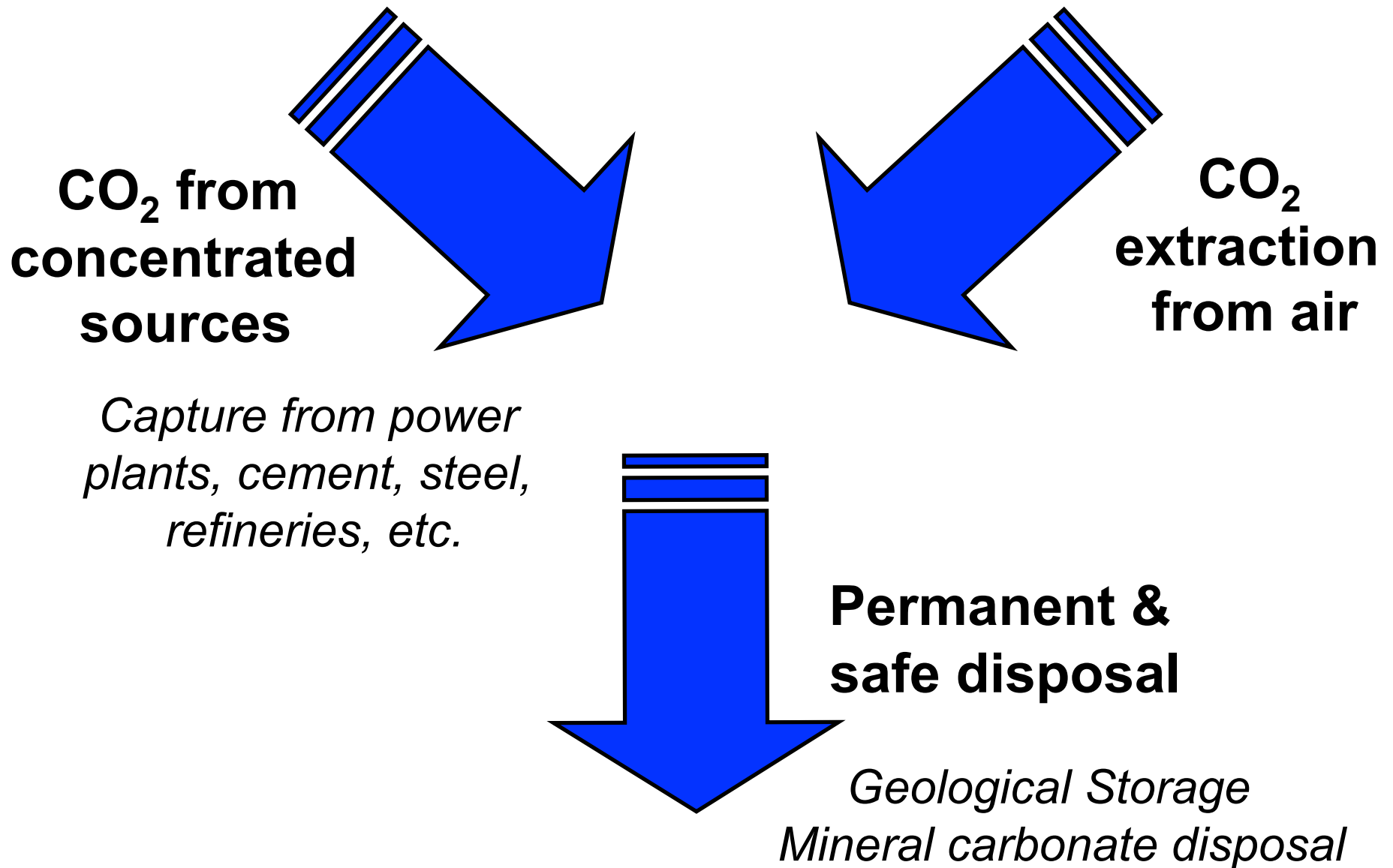
World annual emissions: 8 Gt C / year, or 30 Gt CO<sub>2</sub> / year

## 2006 CO<sub>2</sub> Emissions from Fossil Fuel Combustion by Sector and Fuel Type



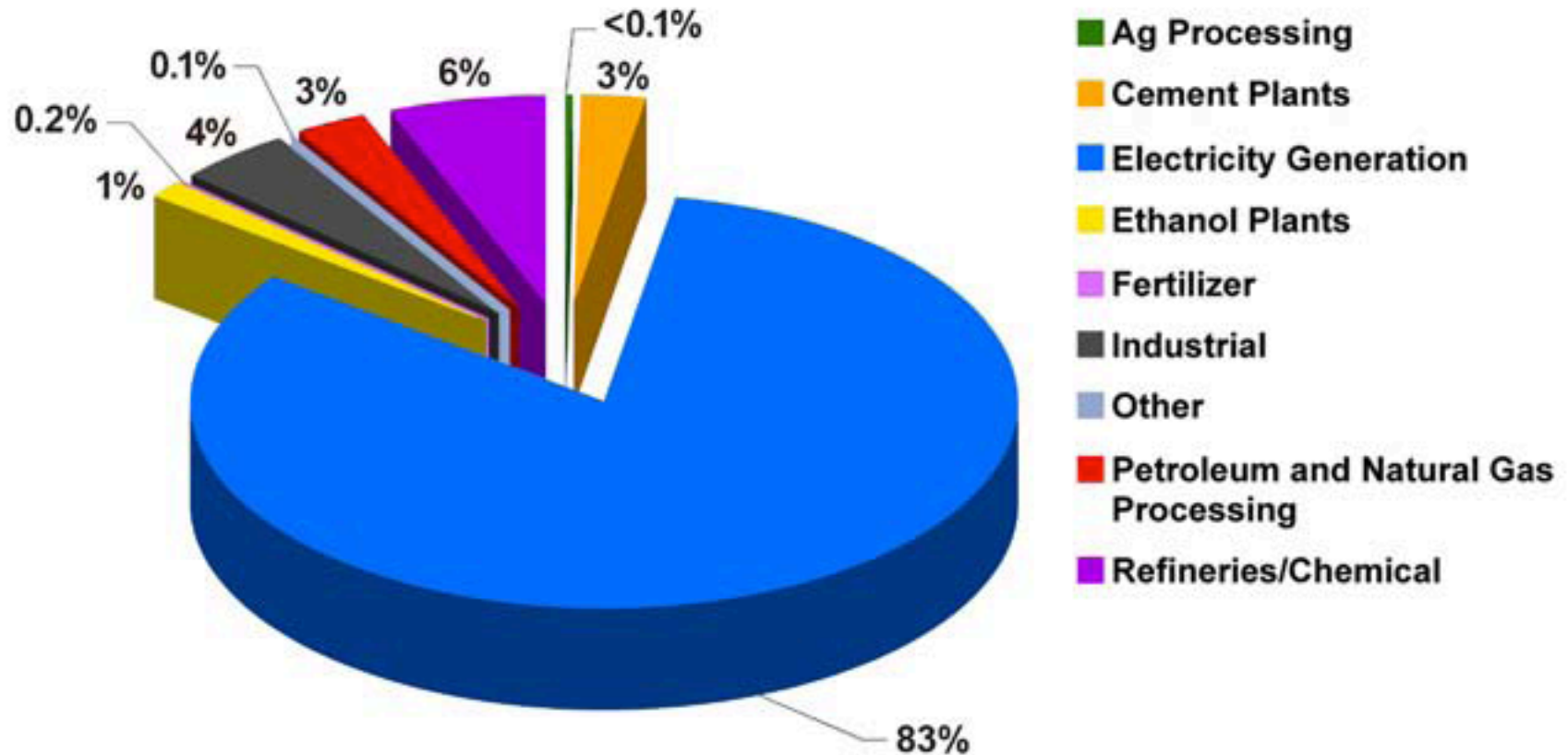
Source: US EPA

# Net Zero Carbon Economy



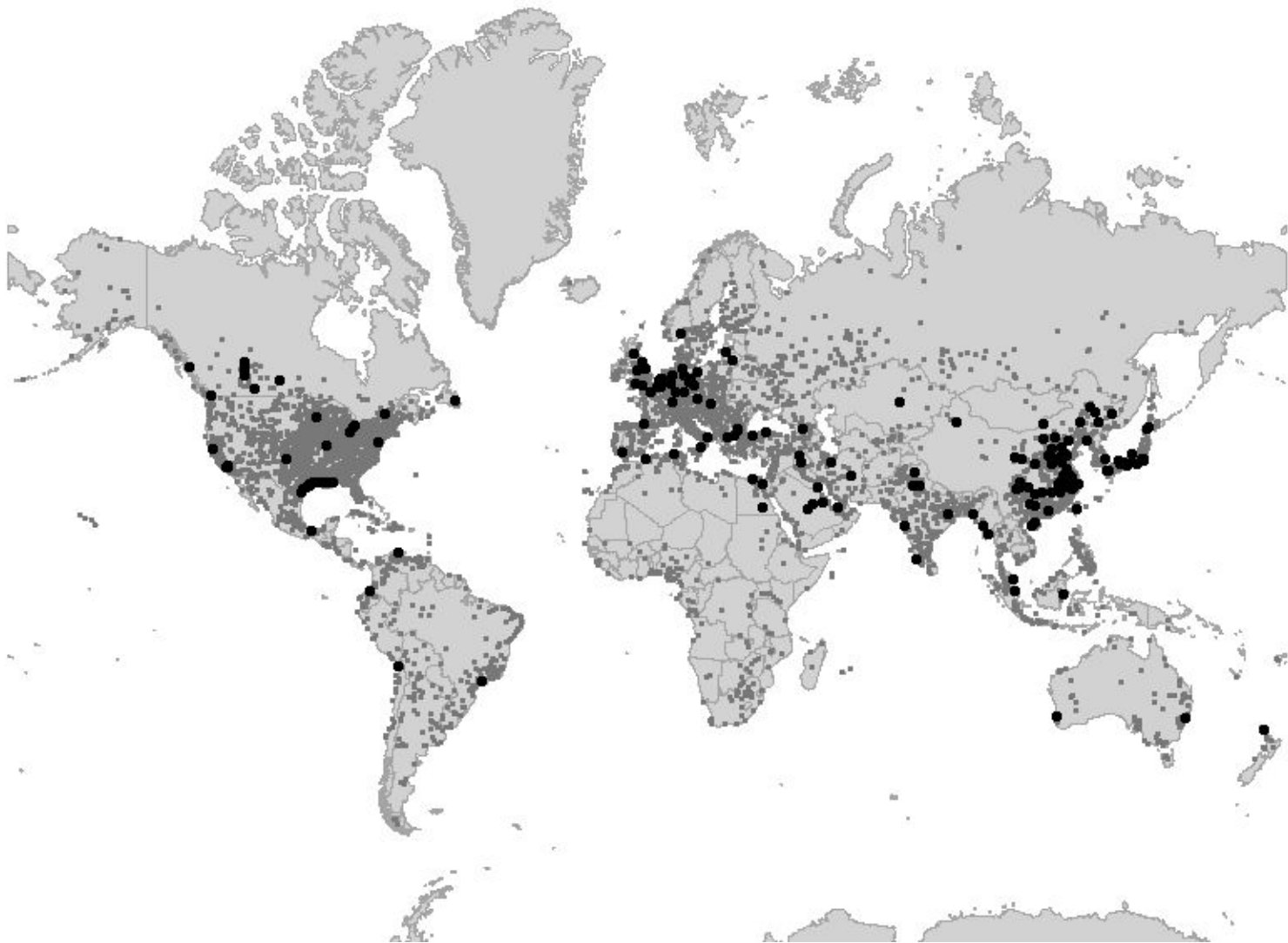


## CO<sub>2</sub> Stationary Source Emissions by Category

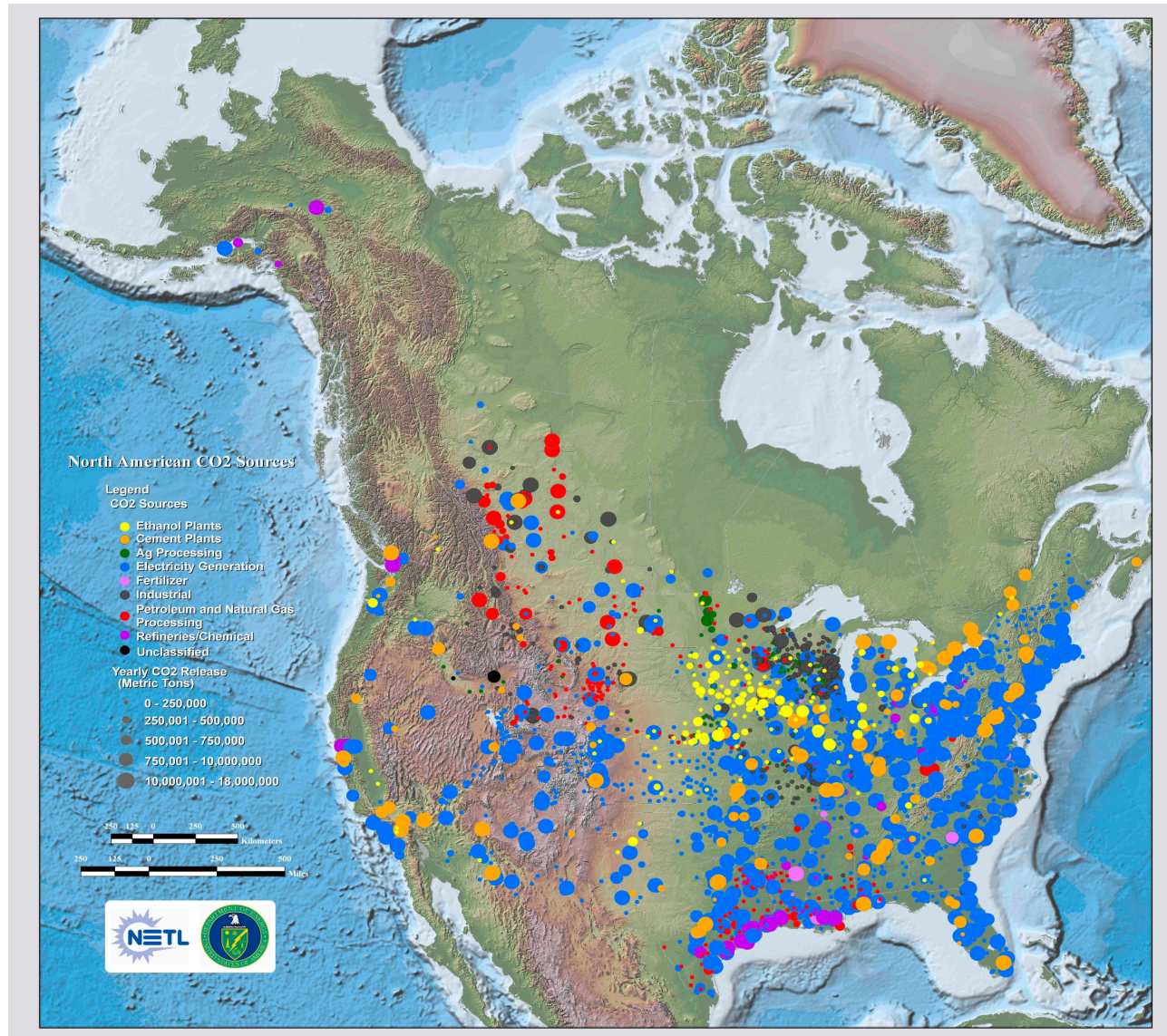


Source: 2008 Carbon Sequestration Atlas of the United States and Canada (NETL)

# Global Distribution of Stationary Sources

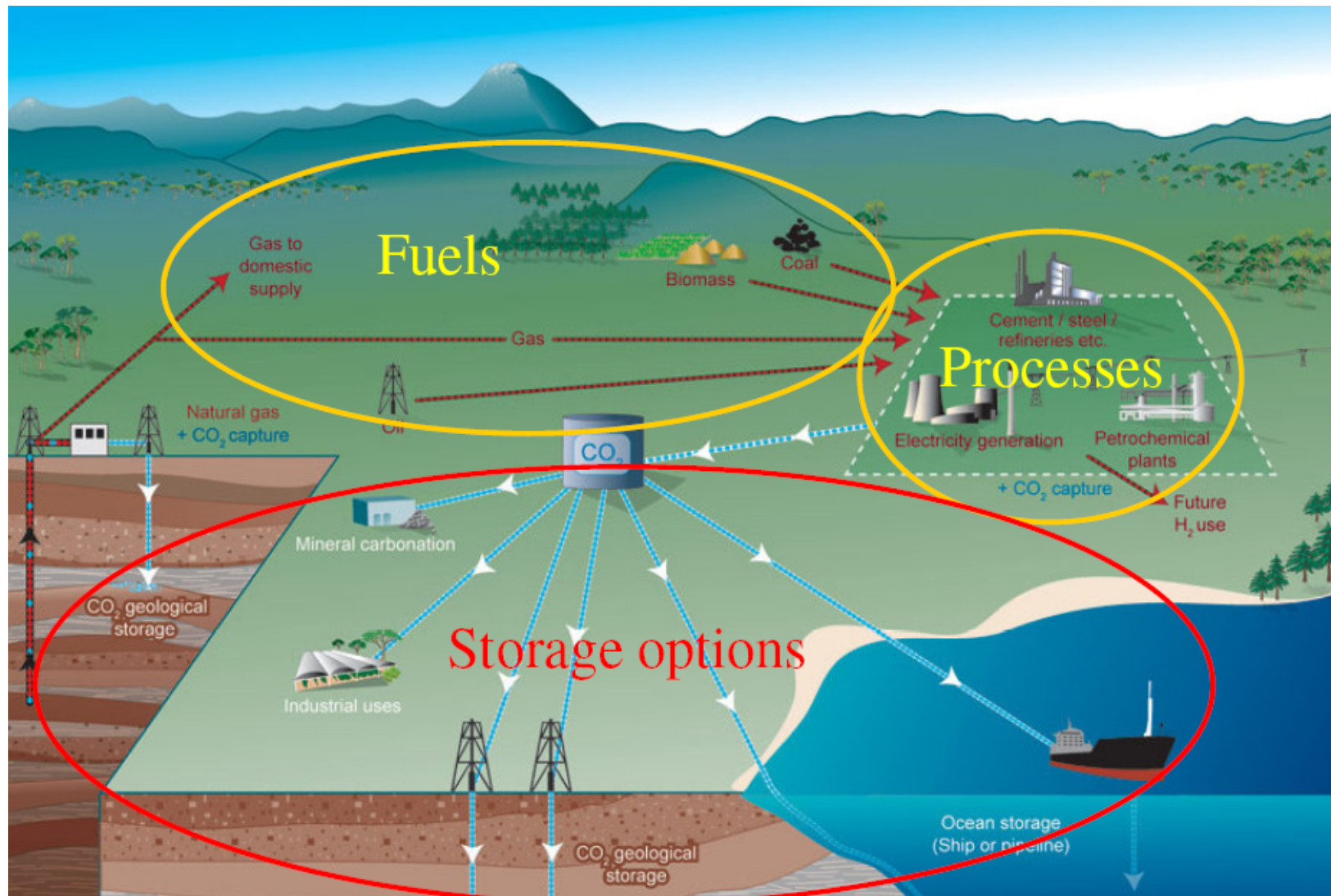


# Stationary Sources in US



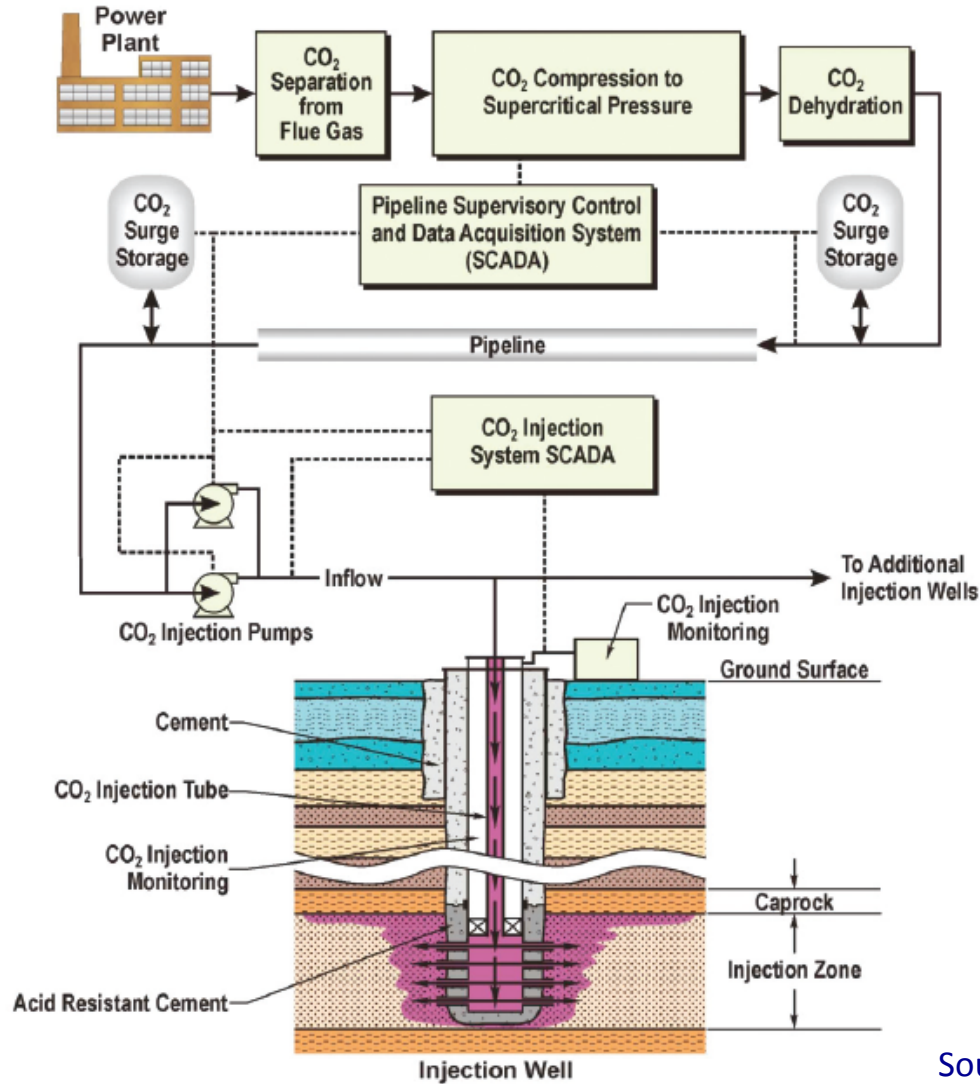


# Carbon Dioxide Capture and Storage (CCS)



Source: IPCC Carbon Capture and Storage Special Report 2005

# CCS - System



**CO<sub>2</sub> Capture**

**Ancillary Systems**

**CO<sub>2</sub> Transport**

**CO<sub>2</sub> Injection /  
Storage**

**Measurement, Monitoring,  
Verification (MMV)**

Source: Global Energy Technology Strategy Program

# Carbon Dioxide Capture (stationary sources)

- **Post-combustion**

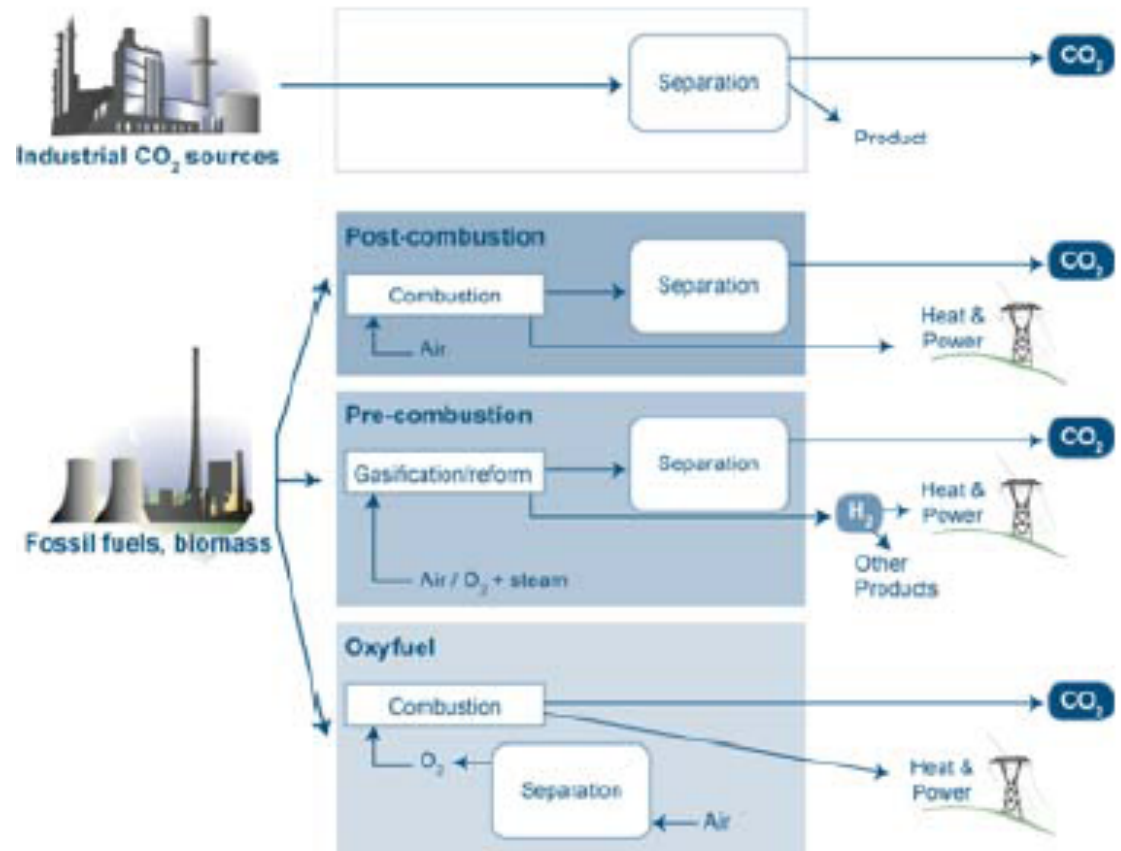
- Established technology

- **Pre-combustion**

- Established technology for other applications
- not demonstrated for power production

- **Oxygen combustion**

- Not demonstrated for power production





- Air extraction can compensate for CO<sub>2</sub> emissions anywhere

# Air Capture Separate Sources from Sinks

Prof. Klaus Lackner, Earth & Environmental Engineering,  
Columbia University

# Anionic Exchange Resins

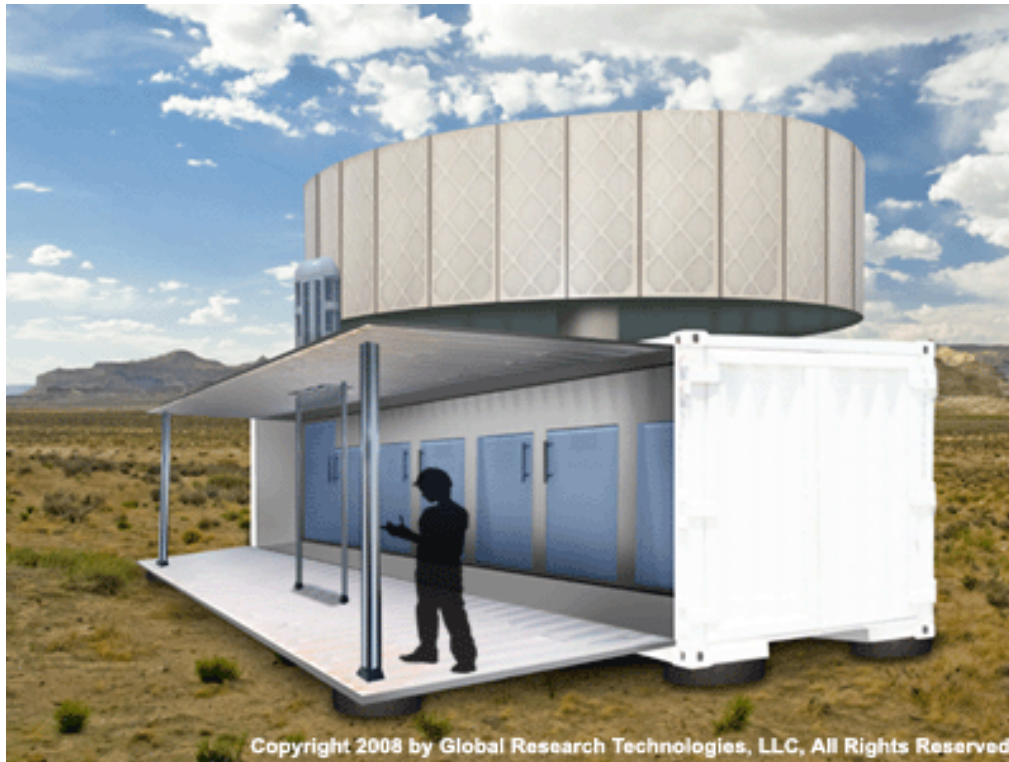


## -> Moisture driven CO<sub>2</sub> swing

- Positive ions fixed to polymer matrix
  - Negative ions are free to move
  - Negative ions are hydroxides, OH<sup>-</sup>
- Dry resin loads up to bicarbonate
  - $\text{OH}^- + \text{CO}_2 \rightarrow \text{HCO}_3^-$  (hydroxide → bicarbonate)
- Wet resin releases CO<sub>2</sub> to carbonate
  - $2\text{HCO}_3^- \rightarrow \text{CO}_3^{2-} + \text{CO}_2 + \text{H}_2\text{O}$



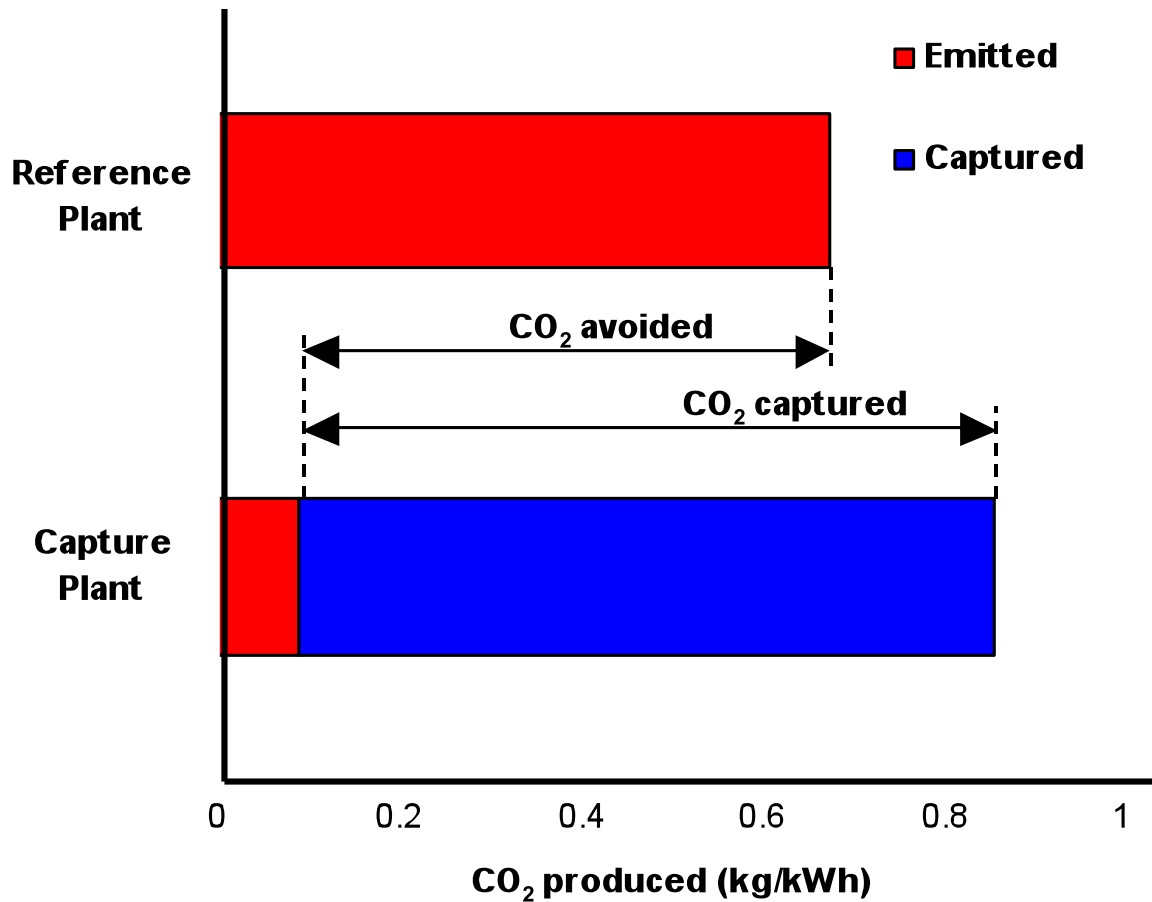
# Setting the Scale for 1 ton/day



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

# CO<sub>2</sub> capture versus avoided

$$\text{CO}_2 \text{ avoidance costs} = (\text{COE}_{\text{cap}} - \text{COE}_{\text{ref}}) / (E_{\text{ref}} - E_{\text{cap}})$$



# The 3 Big Storage Options

## Geologic

- Injection of CO<sub>2</sub> as a liquid or supercritical gas in permeable geological formations
- Demonstration Phase / Mature market (EOR)

## Ocean

- Injection of CO<sub>2</sub> as a liquid into the deep ocean (depths > 1,000 m)
- Research / Demonstration Phase

## Mineral Carbonation

- Chemical reaction of CO<sub>2</sub> with metal oxide bearing materials to form chemically stable carbonates
- Research

### **Geological Sequestration:**

- low cost solution per ton of CO<sub>2</sub>
- experience from EOR, gas storage, liquid waste injection
- extensive monitoring needed
- leakage risk (contamination of groundwater resources and soils)
- public awareness and perception

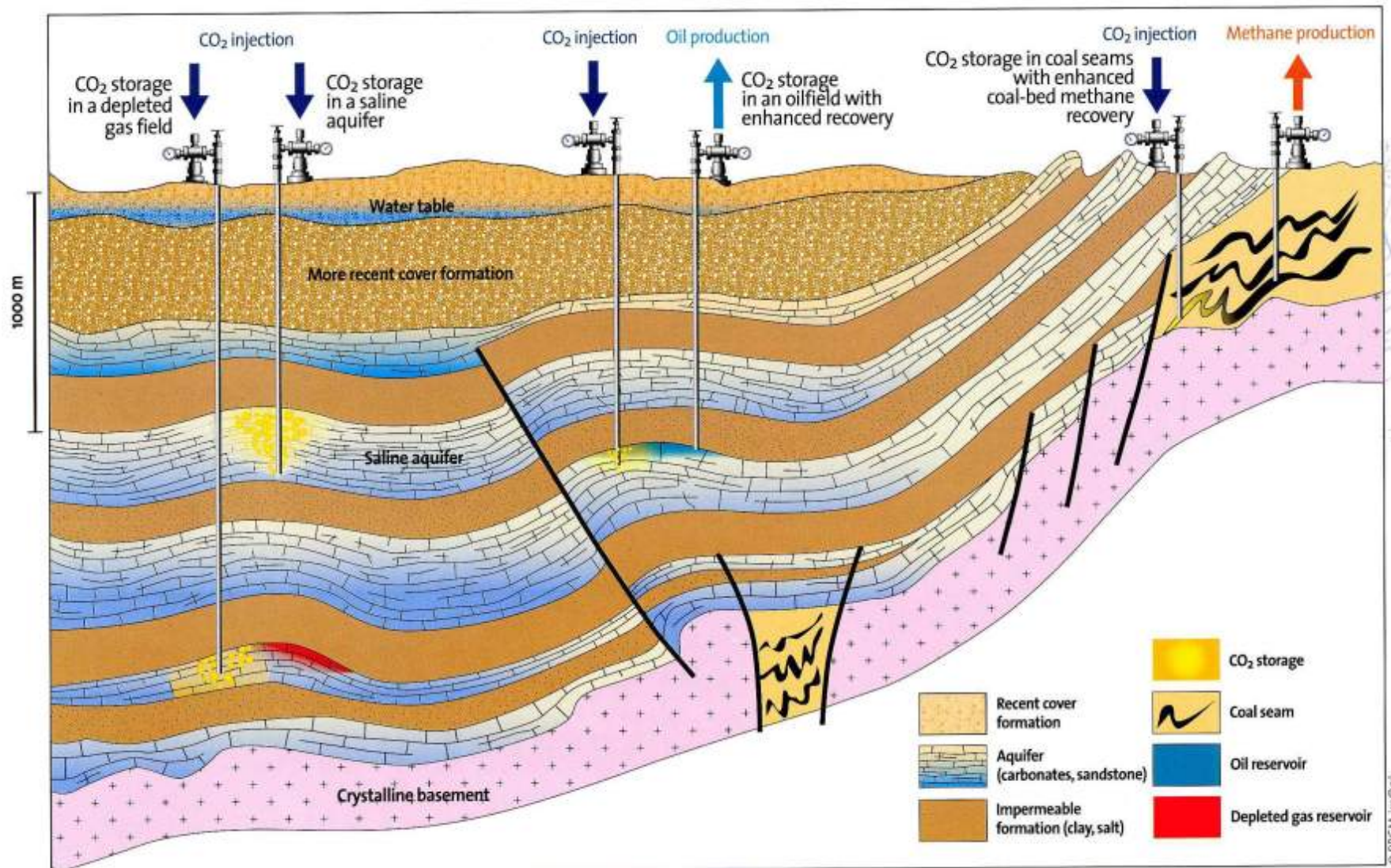
### **Ocean Storage:**

- unlimited storage capacity
- long residence time (hundreds of years)
- acidification, change in ocean chemistry
- impact on marine life
- public perception
- no experience

### **Mineral Carbonation:**

- permanent storage
- long residence time
- no long-term monitoring monitoring needed
- expensive
- large environmental footprint

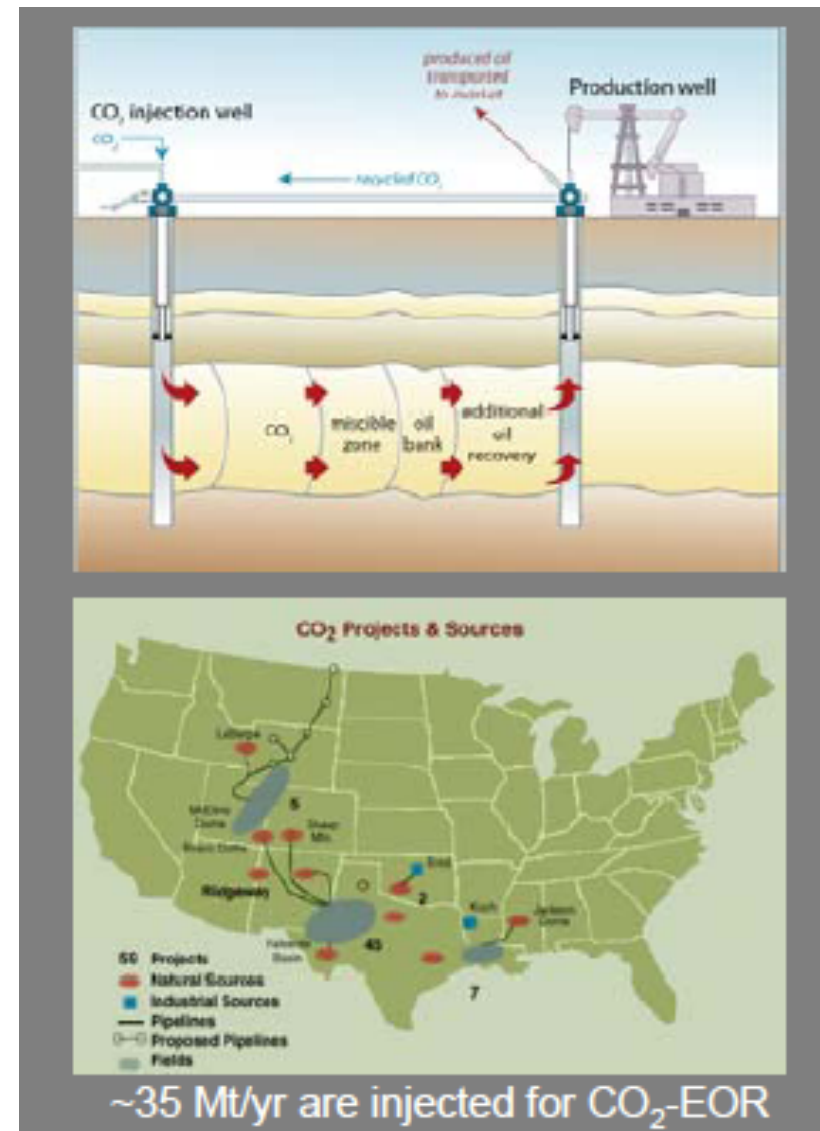
# Geologic Storage Sites



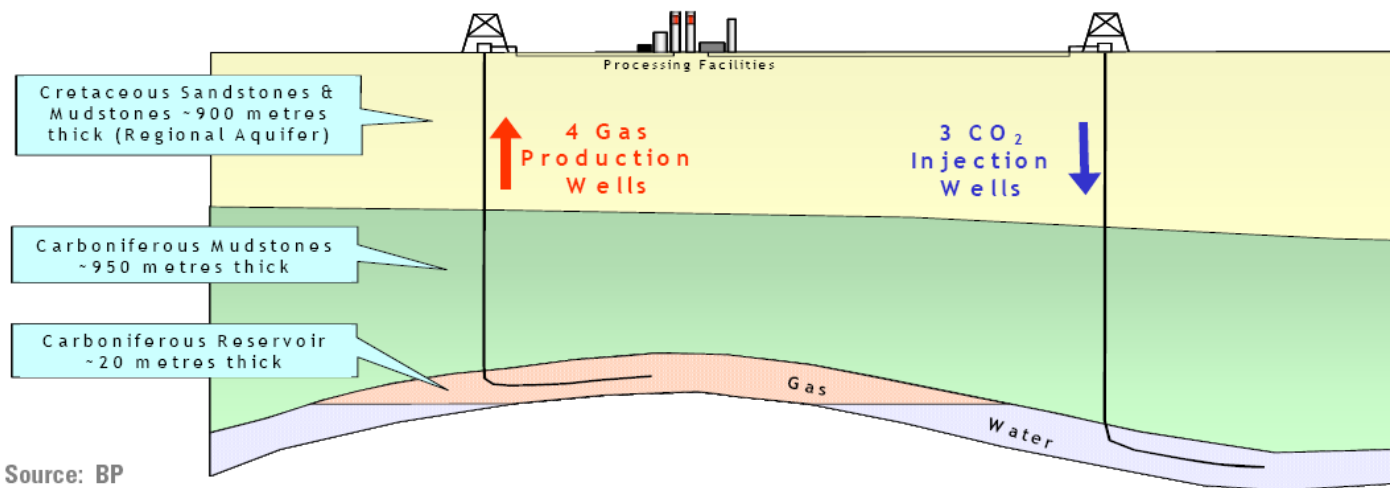


# Experience in CO<sub>2</sub> Storage

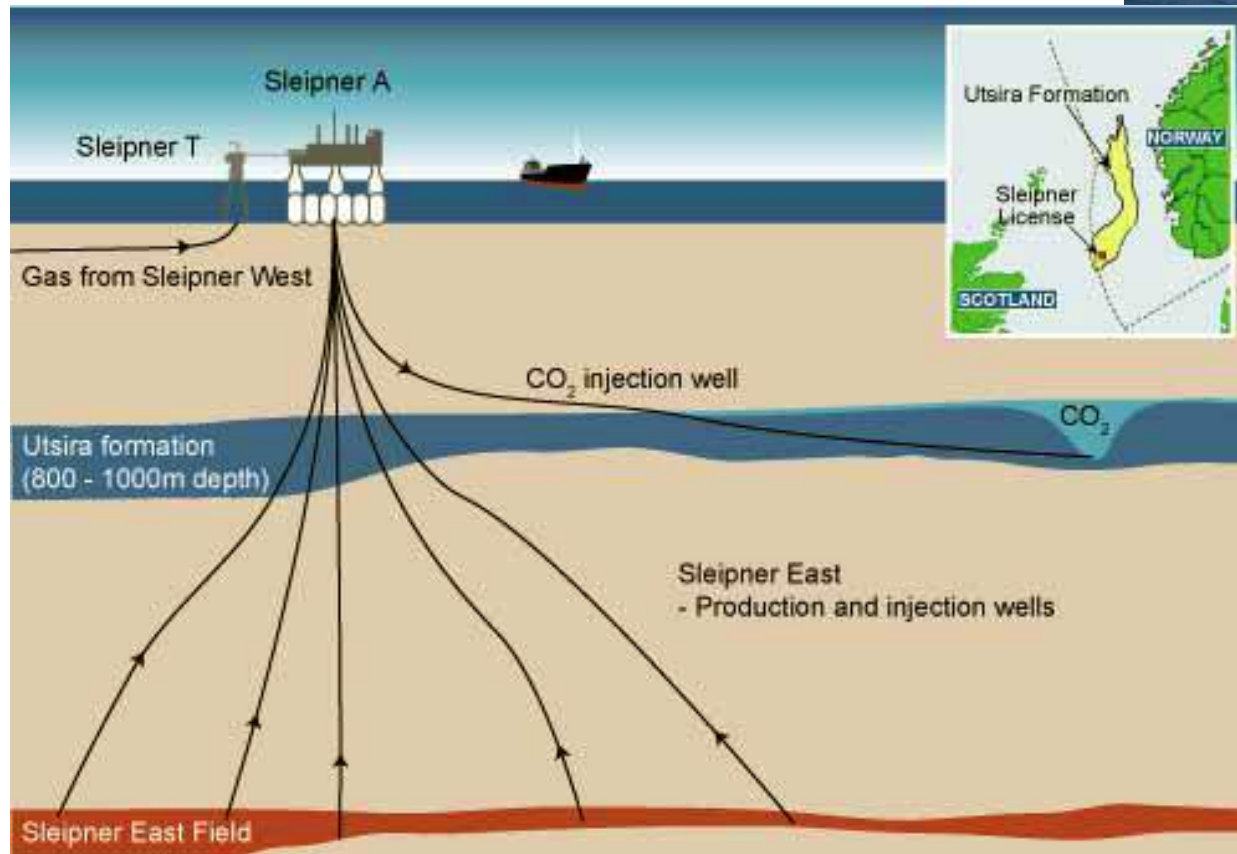
- Natural analogs (oil/gas reservoirs, CO<sub>2</sub> reservoirs)
- Performance of industrial analogs
  - 30+ years experience with CO<sub>2</sub> EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- ~10 years of performance of actual CO<sub>2</sub> storage projects
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004



# In Salah Gas Project



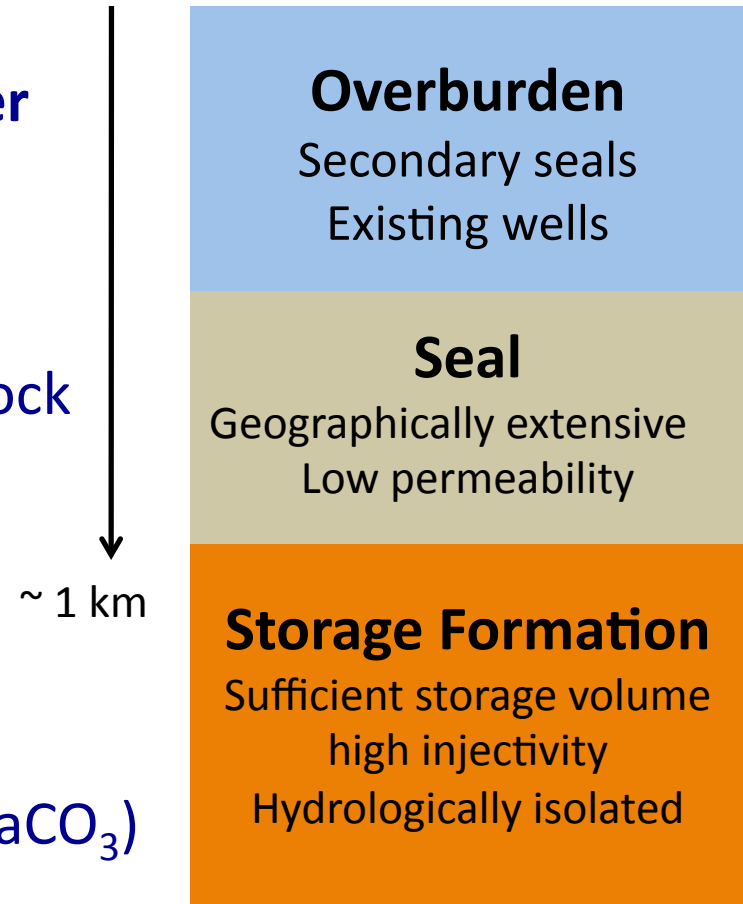
# Sleipner Project – North Sea



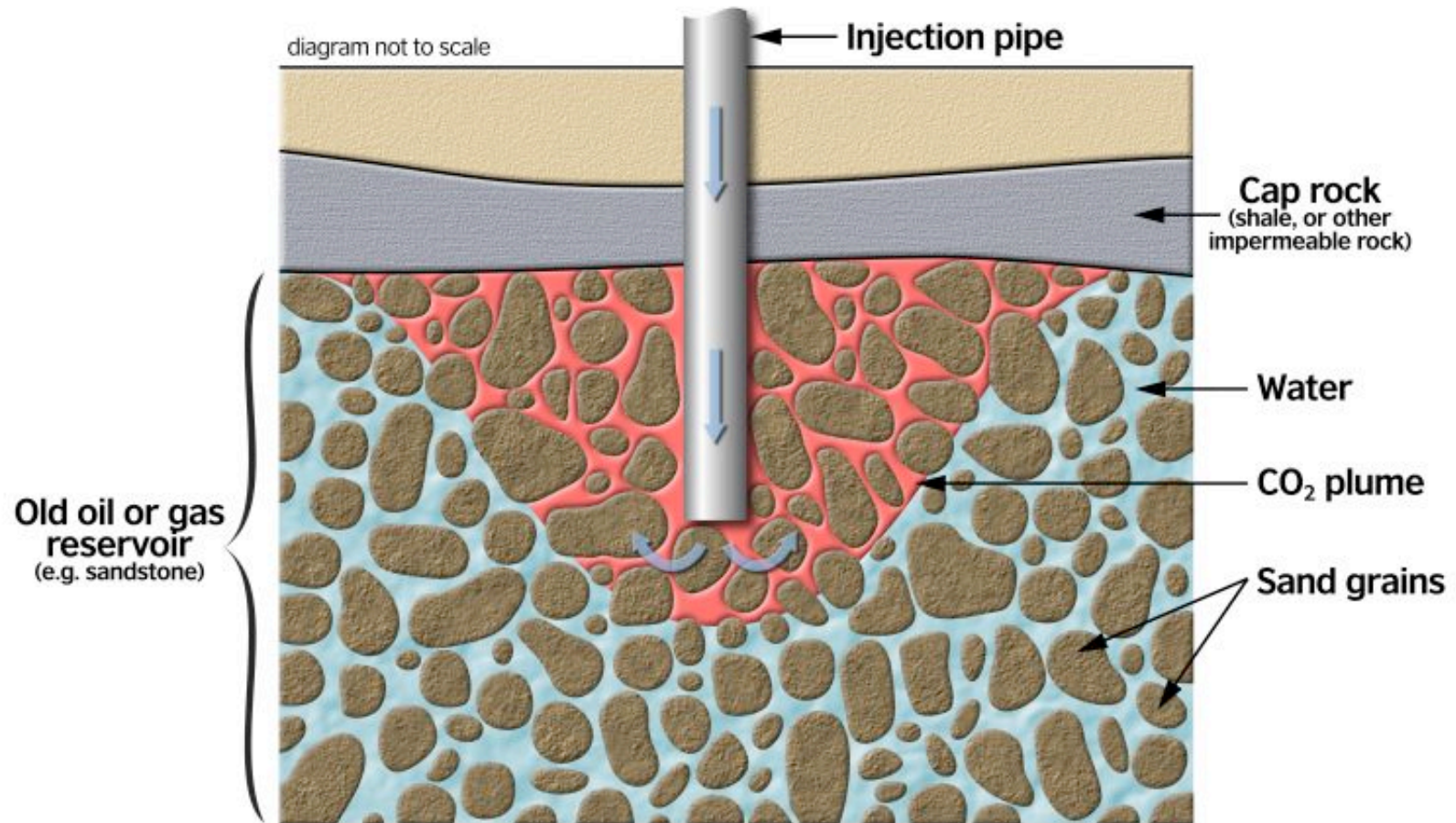


# What Keeps CO<sub>2</sub> Underground?

- **Injected at depths of ~1 km or deeper into porous rock**
- **Primary trapping**
  - Beneath seals of lower permeability rock
- **Secondary trapping**
  - CO<sub>2</sub> dissolved in water
  - CO<sub>2</sub> is trapped by capillary forces
  - CO<sub>2</sub> is mineralized to solid minerals (CaCO<sub>3</sub>)



# Storage Mechanism

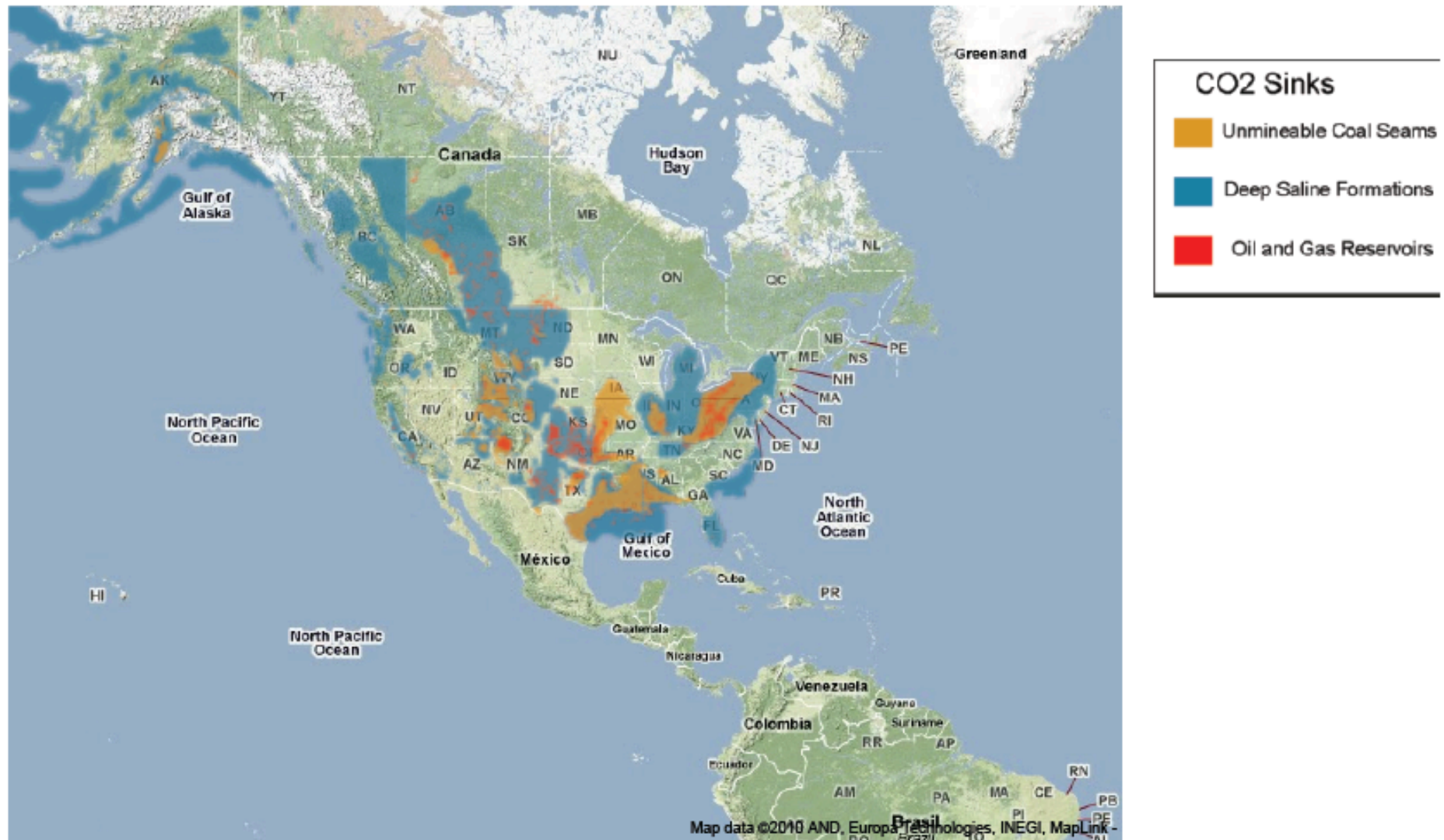


# Scale of the Problem

- 1,000 Mwe coal-fired power plant: 10 Mt CO<sub>2</sub>/year -> 700 Mt CO<sub>2</sub>
- Total CO<sub>2</sub> volume ~1 km<sup>3</sup> (density of 780 kg/m<sup>3</sup> at 40°C, 150 bar)
- CO<sub>2</sub> foot print in the subsurface could reach 100 km<sup>2</sup> (Pruess et al. 2001)
- US: 1,500 coal-fired generators, capacity of 335,830 MWe

➤ **CCS Scale Million – Billion Tons per year**

# Potential Storage Reservoirs



Source: [www.natcarb.org](http://www.natcarb.org)

# Geologic Storage Capacity in the United States

- Assumption: only 1 – 4% of geologic capacity can be used for CO<sub>2</sub> storage.
- total estimated geological CO<sub>2</sub> storage: 3,600 – 12,900 billion tons of CO<sub>2</sub>.
- To put that in perspective, the United States' current annual CO<sub>2</sub> emissions are about ~ 7 billion tons per year.

# Physical Properties of CO<sub>2</sub>

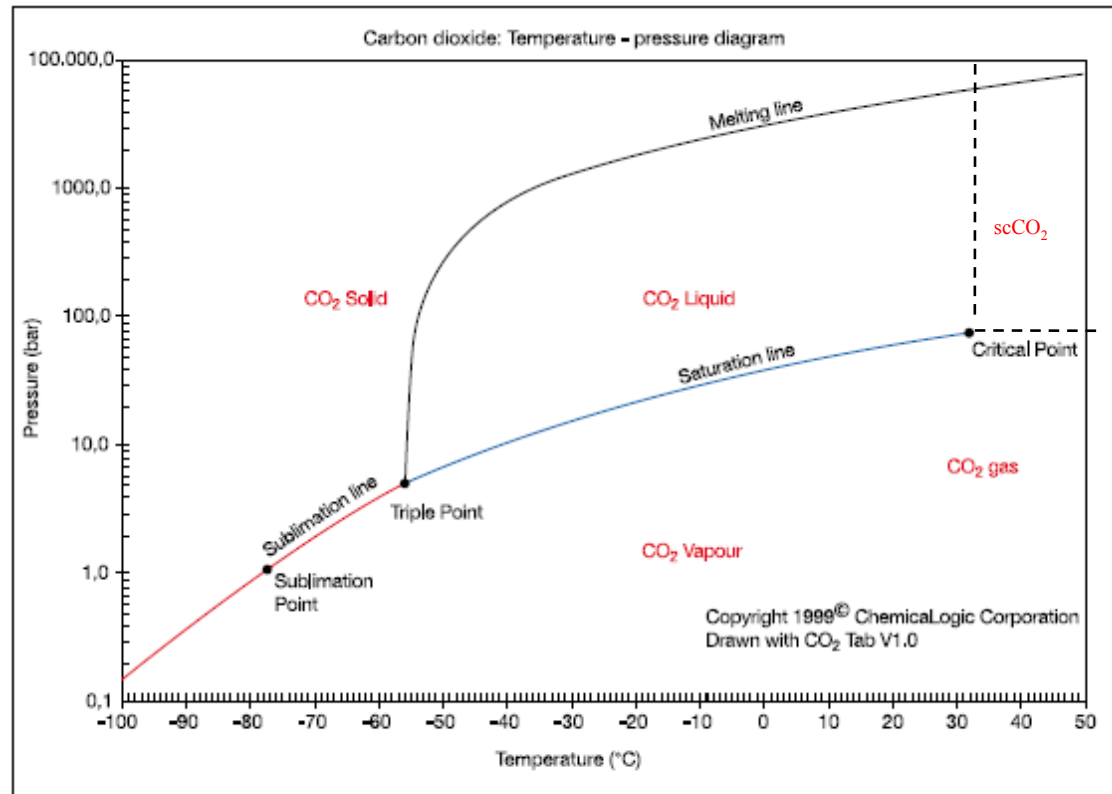


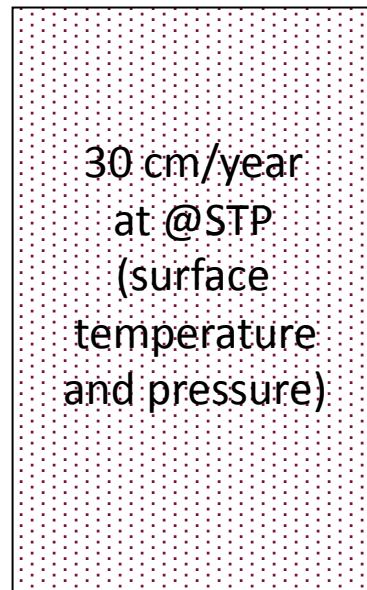
Figure AI.1 Phase diagram for CO<sub>2</sub>. Copyright © 1999 ChemicalLogic Corporation, 99 South Bedford Street, Suite 207, Burlington, MA 01803 USA. All rights reserved.

- CO<sub>2</sub> is in a supercritical state at temperatures > 31.1°C and pressures > 7.38 MPa (73.8 bar).
- A supercritical fluid has some of the properties of a liquid (e.g. density) and a gas (e.g. low viscosity)
- CO<sub>2</sub> in a supercritical state is not miscible with water

# Assessing Adequacy of Subsurface Volumes: the Value of Compression

- At depths  $>800$  m  $\text{CO}_2$  is stored as a dense phase (1 metric ton = about 1.6 cubic m)

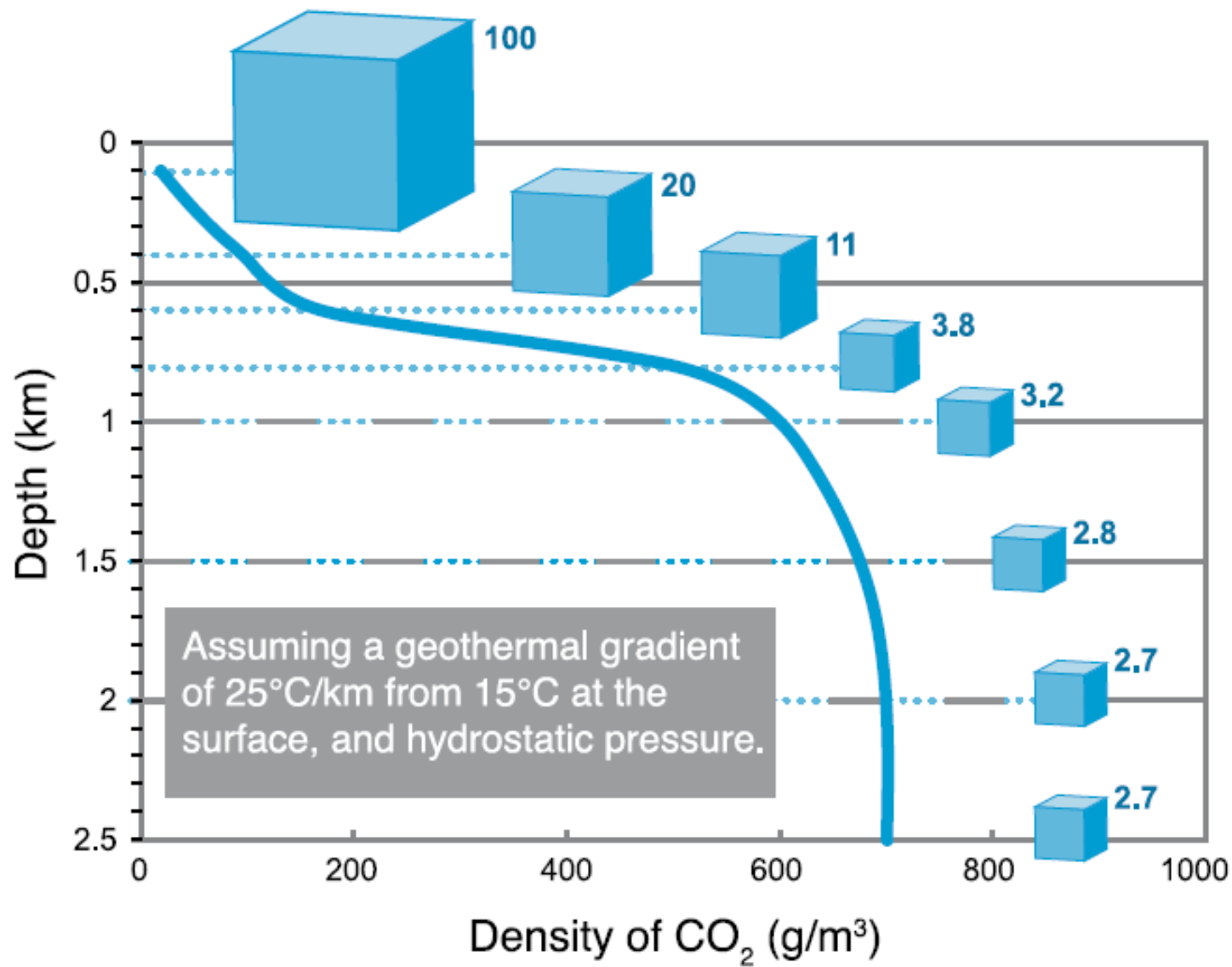
7 Gigatons ( $7 \times 10^9$ T)  $\text{CO}_2$ /year US emissions from stationary sources:  
if spread evenly over US:



0.4 mm/year at  
reservoir conditions

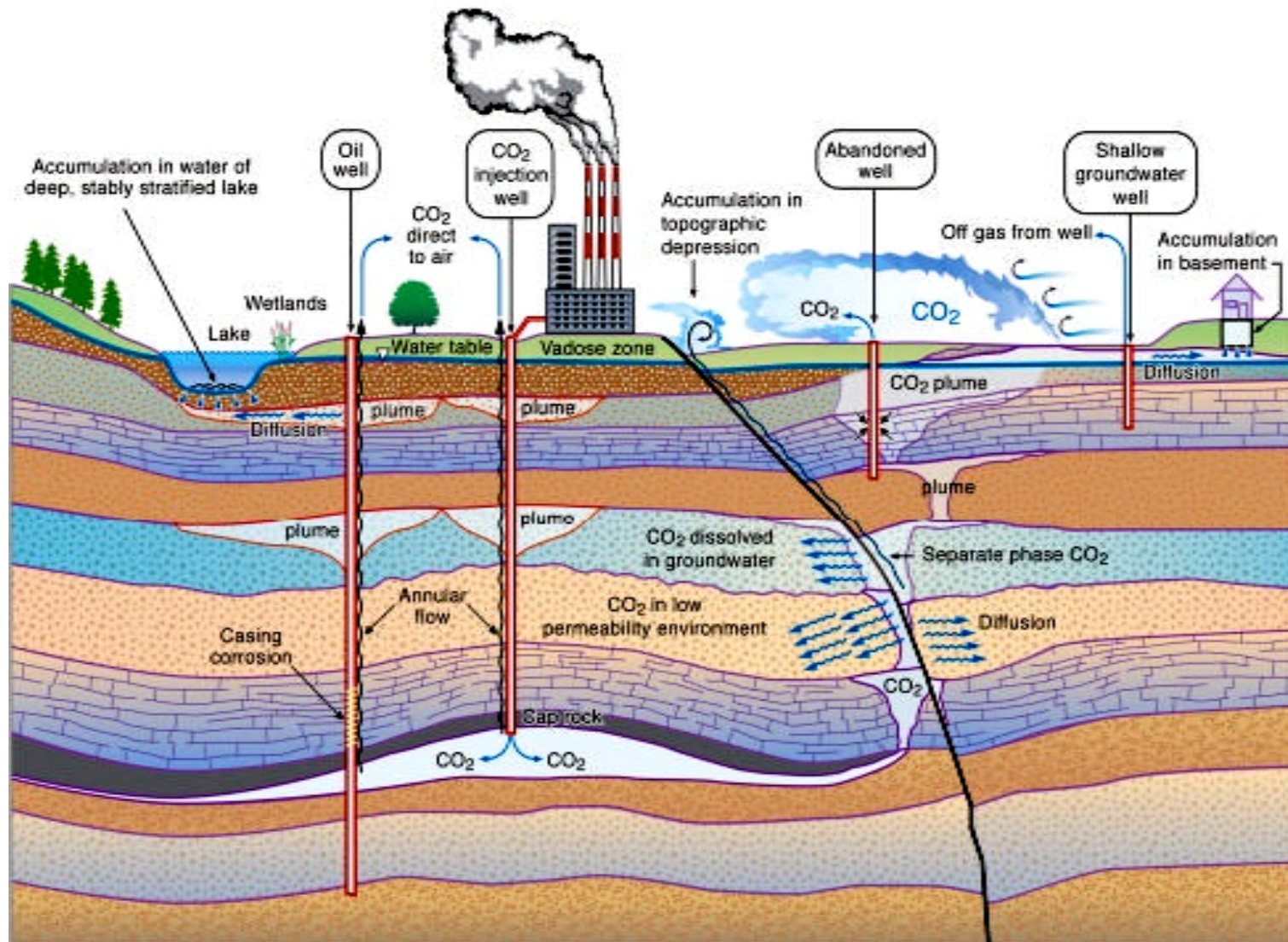


# Density of CO<sub>2</sub>

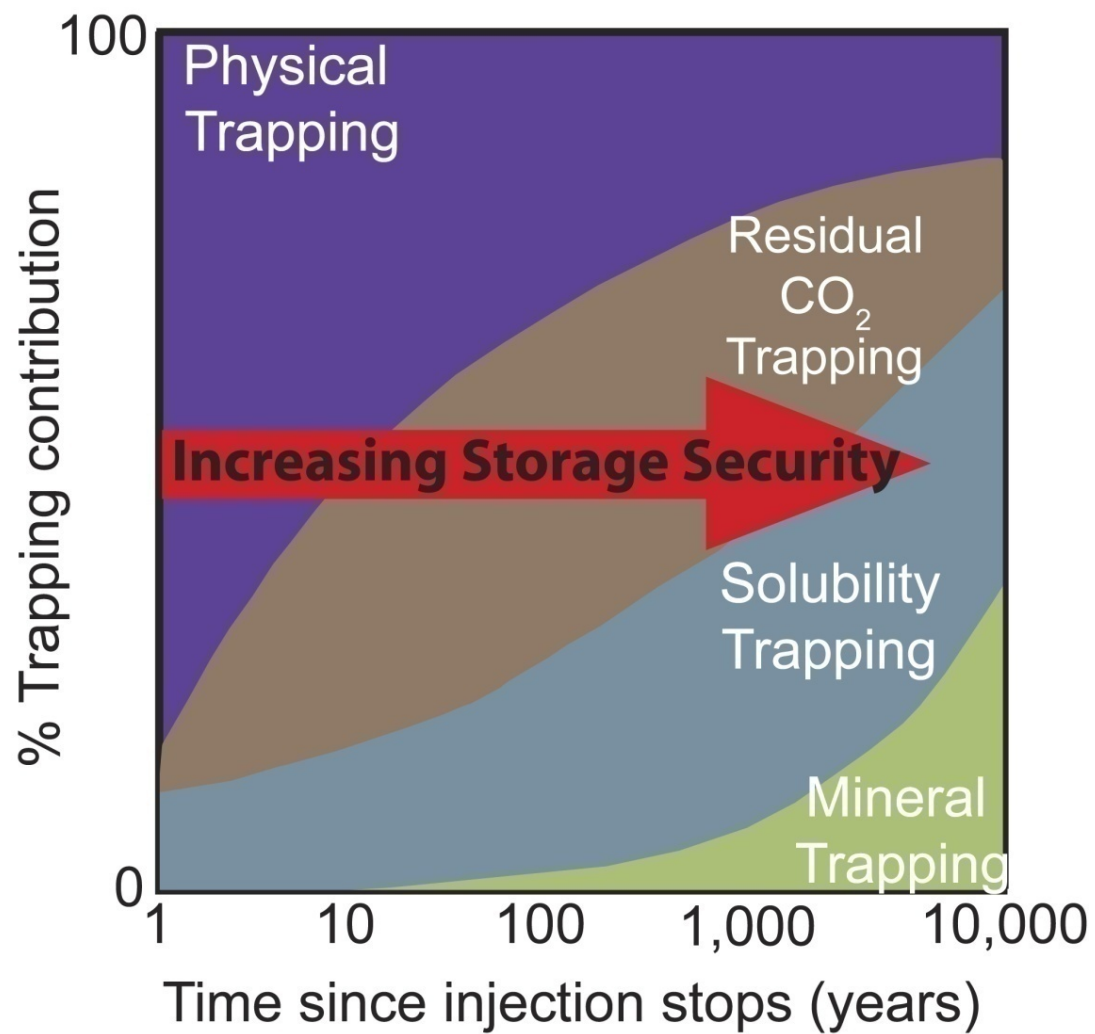


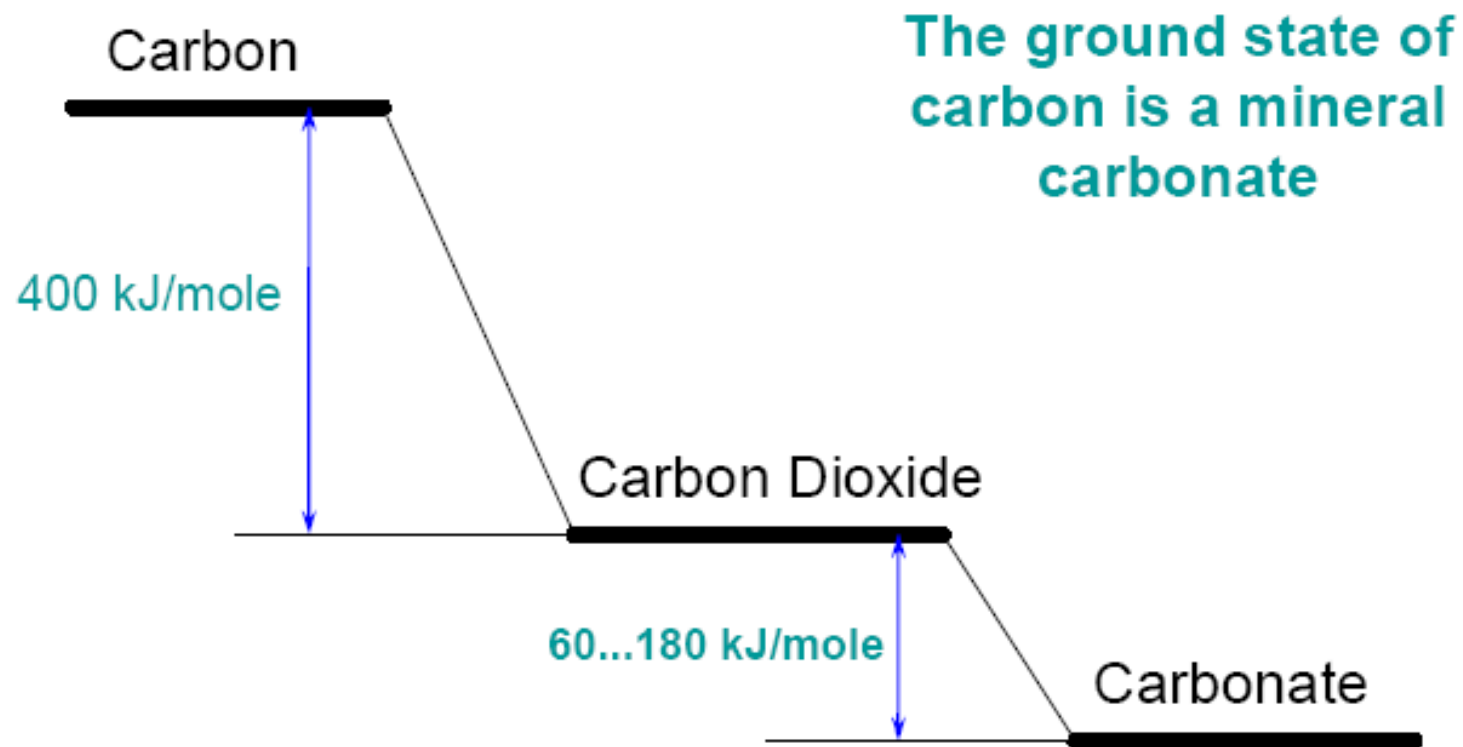


# Earth is not a leak proof container



Source: [www.westcarb.org](http://www.westcarb.org)





## Nature shows us.....

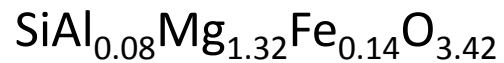
- rocks convert atmospheric CO<sub>2</sub> (dissolved in surface waters) to stable, inert carbonate minerals
- they do this surprisingly fast, and the process gives off energy
- we could speed up this process, taking advantage of natural energy sources

# Mineral Carbonation

basalt

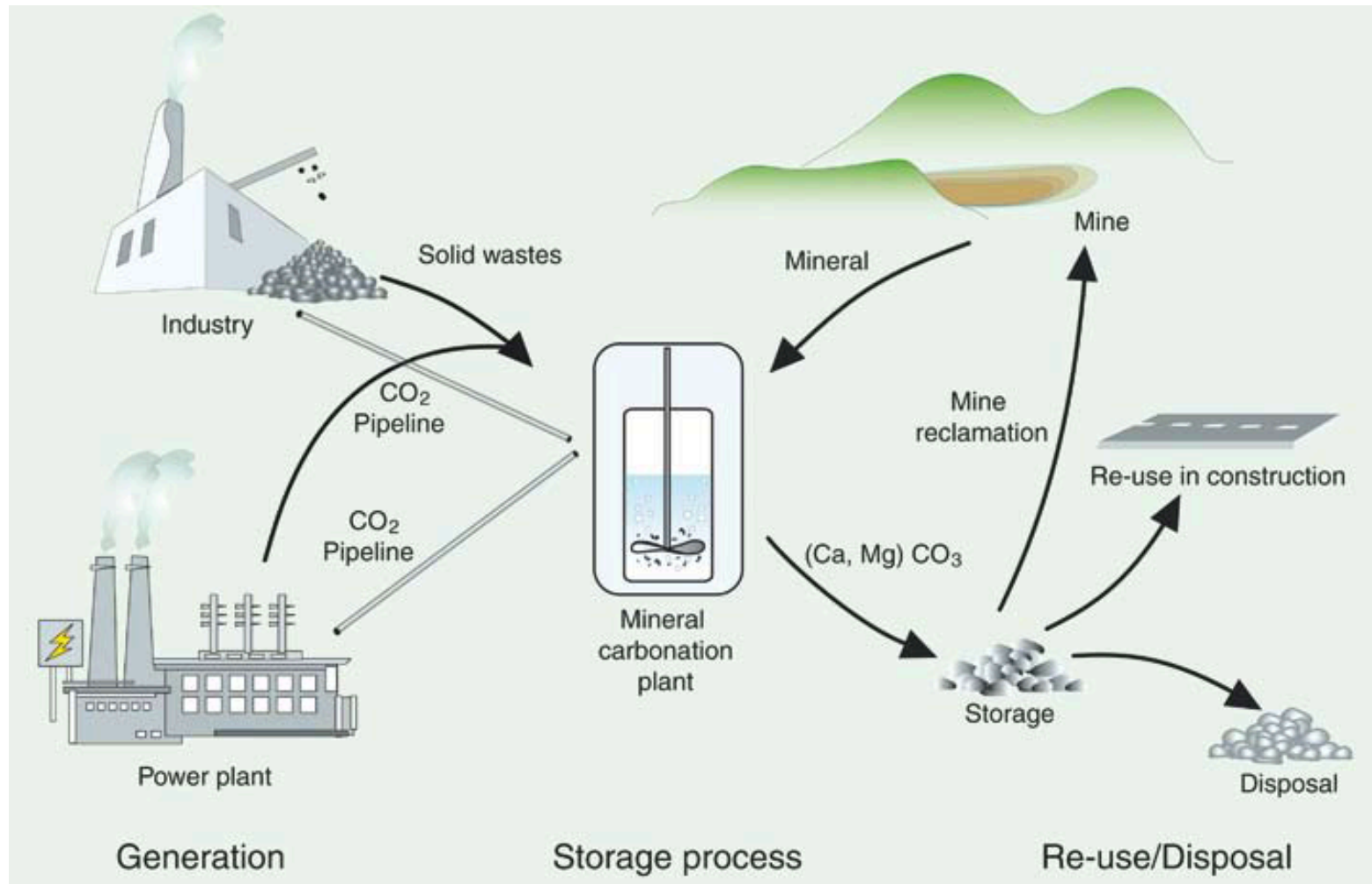


peridotite



Calcite  
Magnesite  
siderite

# Ex-situ Mineral Carbonation





# Mineral Carbonation of Mine Tailings

Clinton Creek mine, Yukon -> 160,000 tons of CO<sub>2</sub> sequestered



Courtesy of G. Dipple, UBC



# Basalt

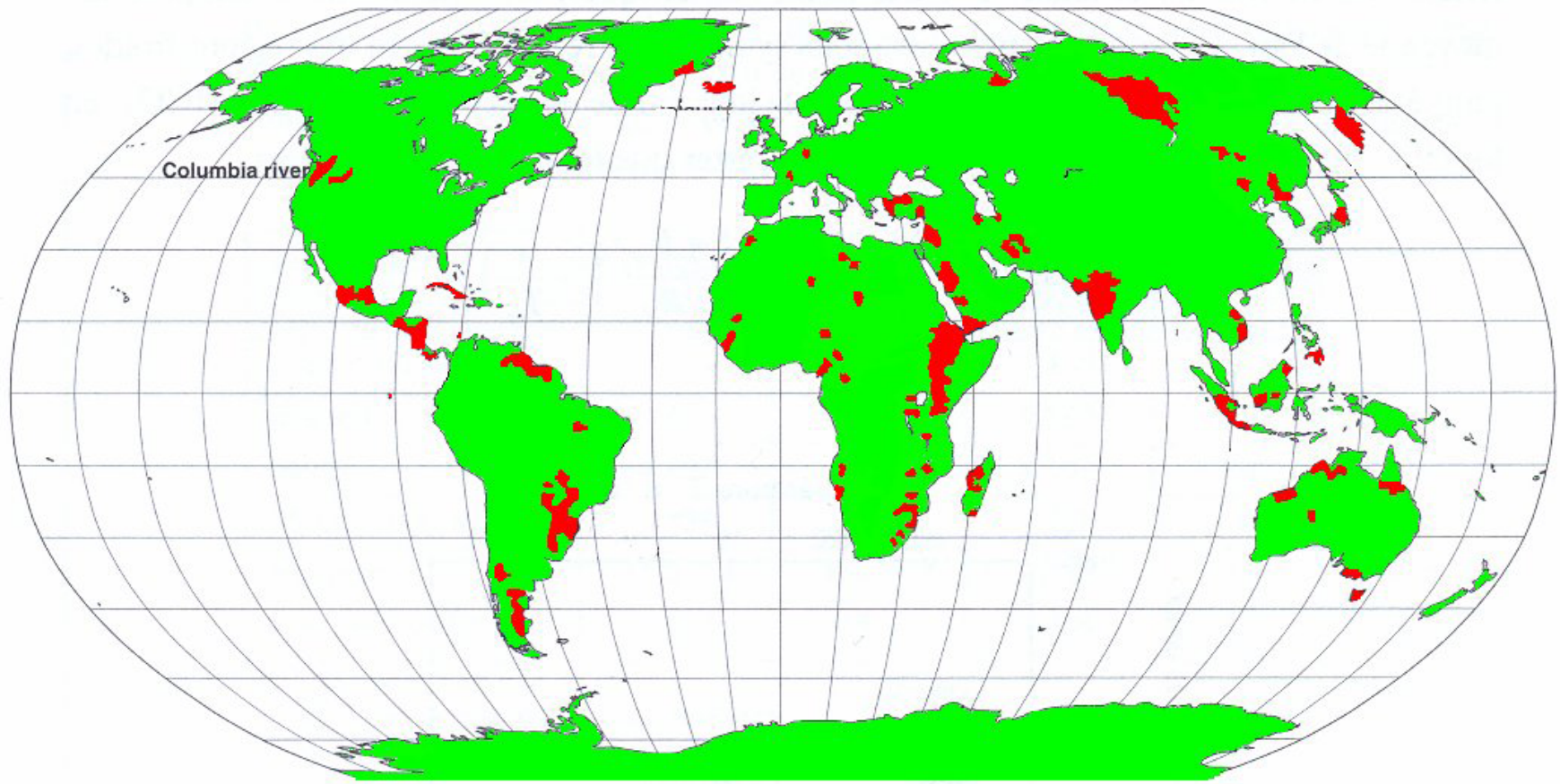
Mineral name	Potential CO <sub>2</sub> fixed, kg/m <sup>3</sup> mineral
Plagioclase	436
Olivine	2015-1896
Pyroxene	1404
Serpentine	1233
Mica group	62
Clay Minerals	161

Source: Pruess et al. 2001

- Basalt contains about 10 wt% CaO and 6 wt% MgO which can be used for mineral carbonation



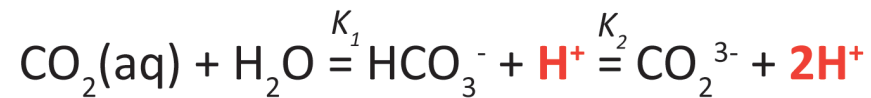
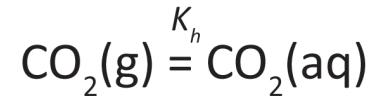
# CO<sub>2</sub> Storage in Basalts



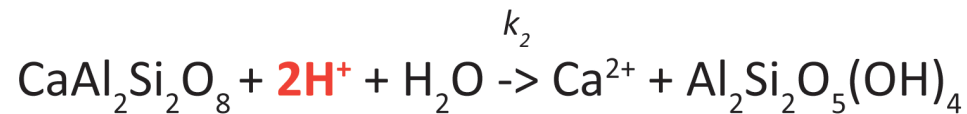
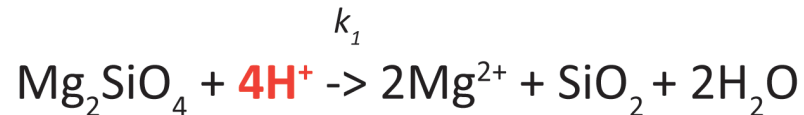
- Columbia River Basalt: 36 to 148 billion tons of CO<sub>2</sub> (McGrail et al. 2006)

# In Situ Mineral Carbonation

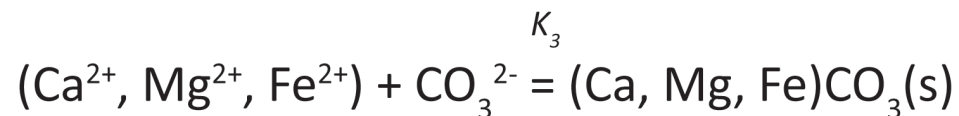
## Dissolution of CO<sub>2</sub> and Dissociation



## Mineral Dissolution

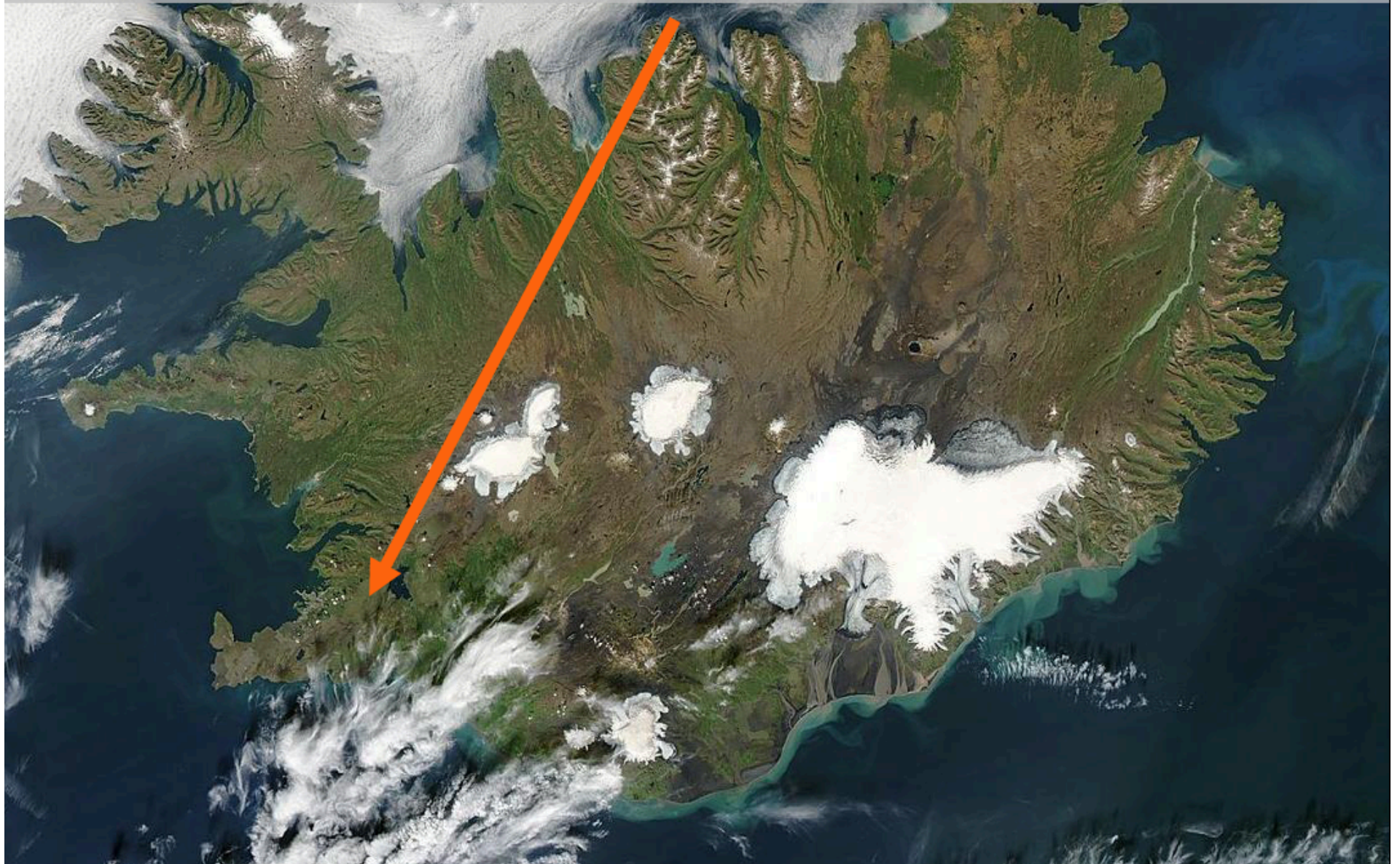


## Mineral Precipitation

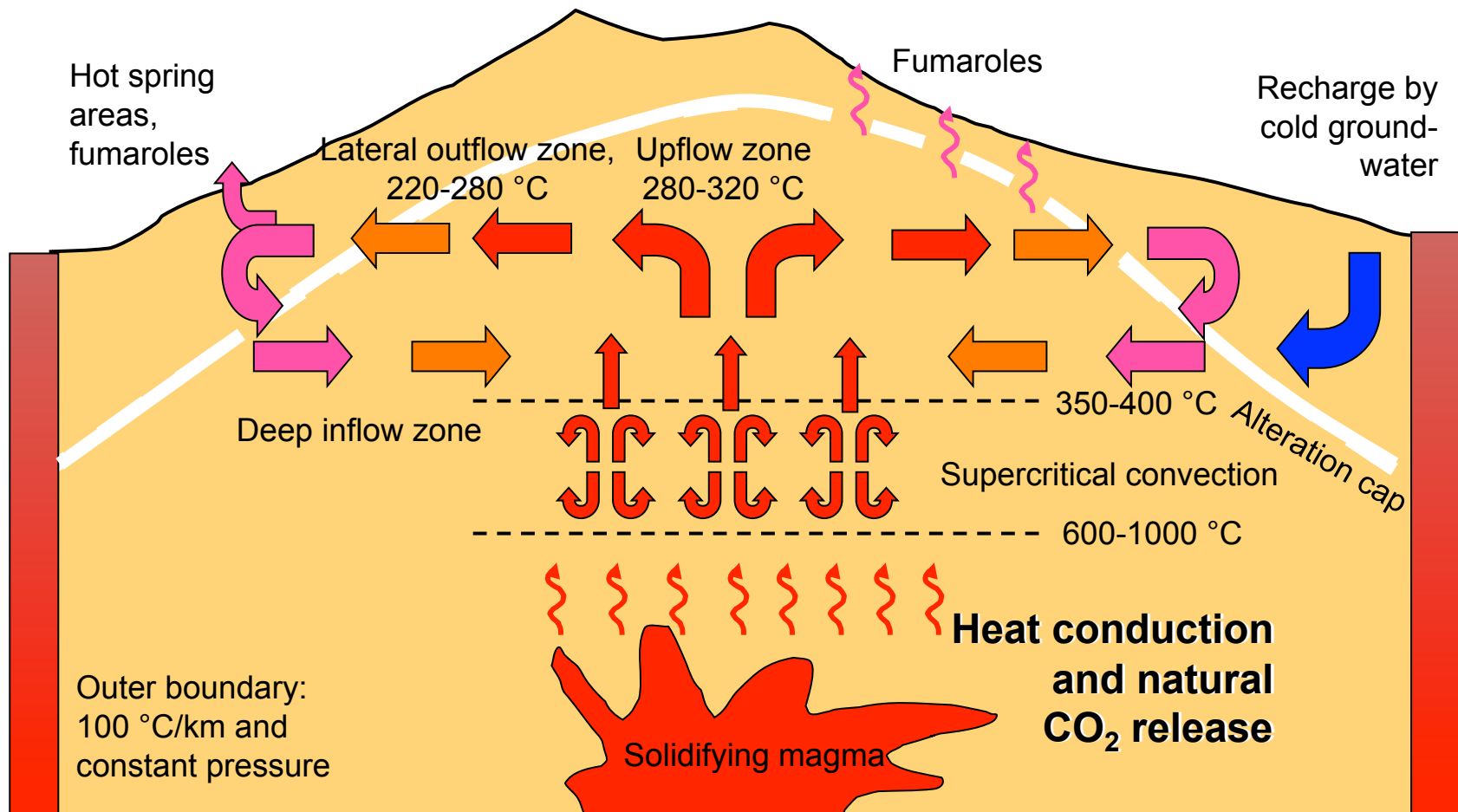




# MINERAL CO<sub>2</sub> SEQUESTRATION INTO BASALT: THE CARBFIX PROJECT



# Magmatic CO<sub>2</sub> Source





Target zone for CO<sub>2</sub> sequestration identified at 400-800 m depth

Groundwater

Gas injected fully dissolved in water into target zone

2 kg/s of CO<sub>2</sub> 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



**Gas mmol/kg**

**CO<sub>2</sub> 103**

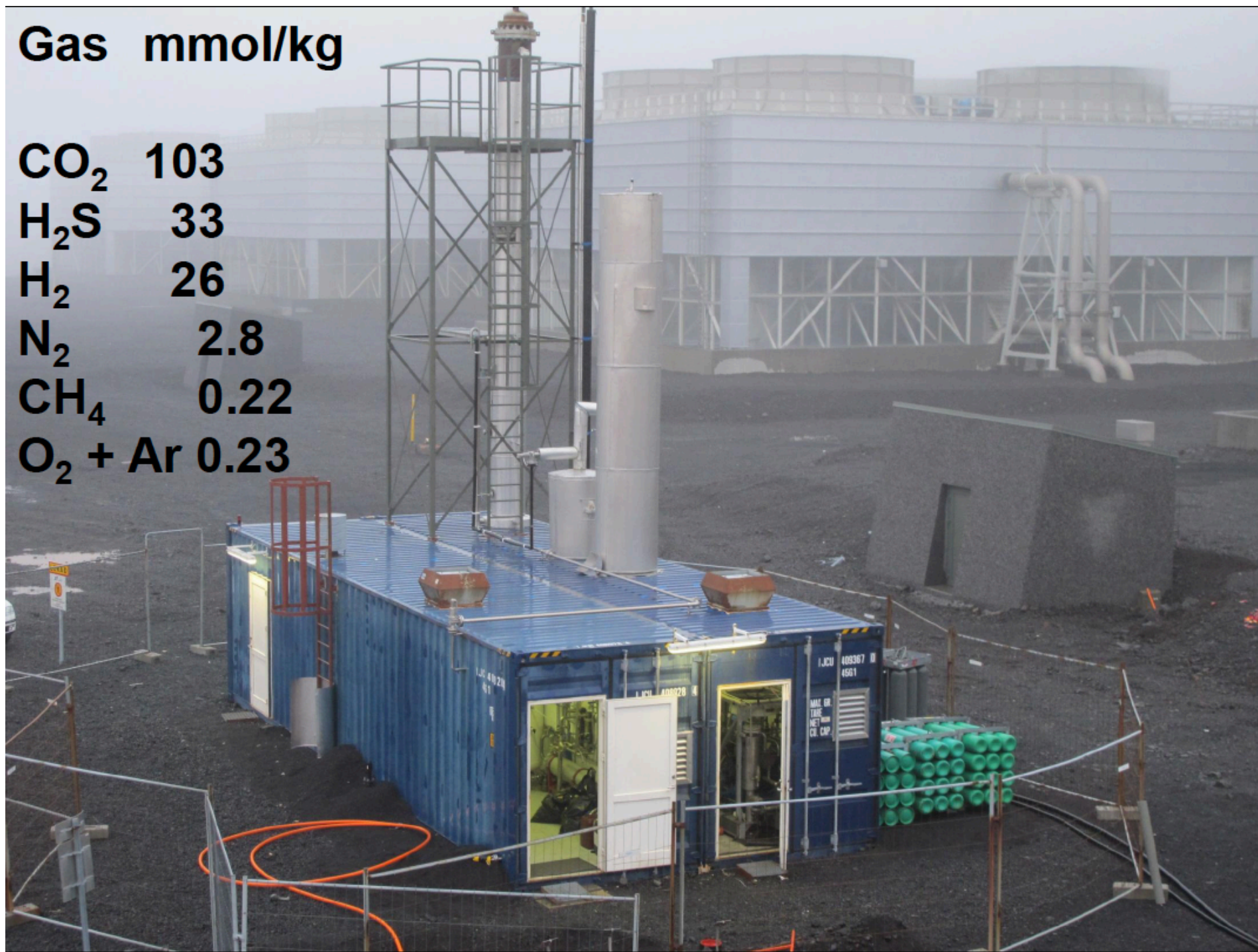
**H<sub>2</sub>S 33**

**H<sub>2</sub> 26**

**N<sub>2</sub> 2.8**

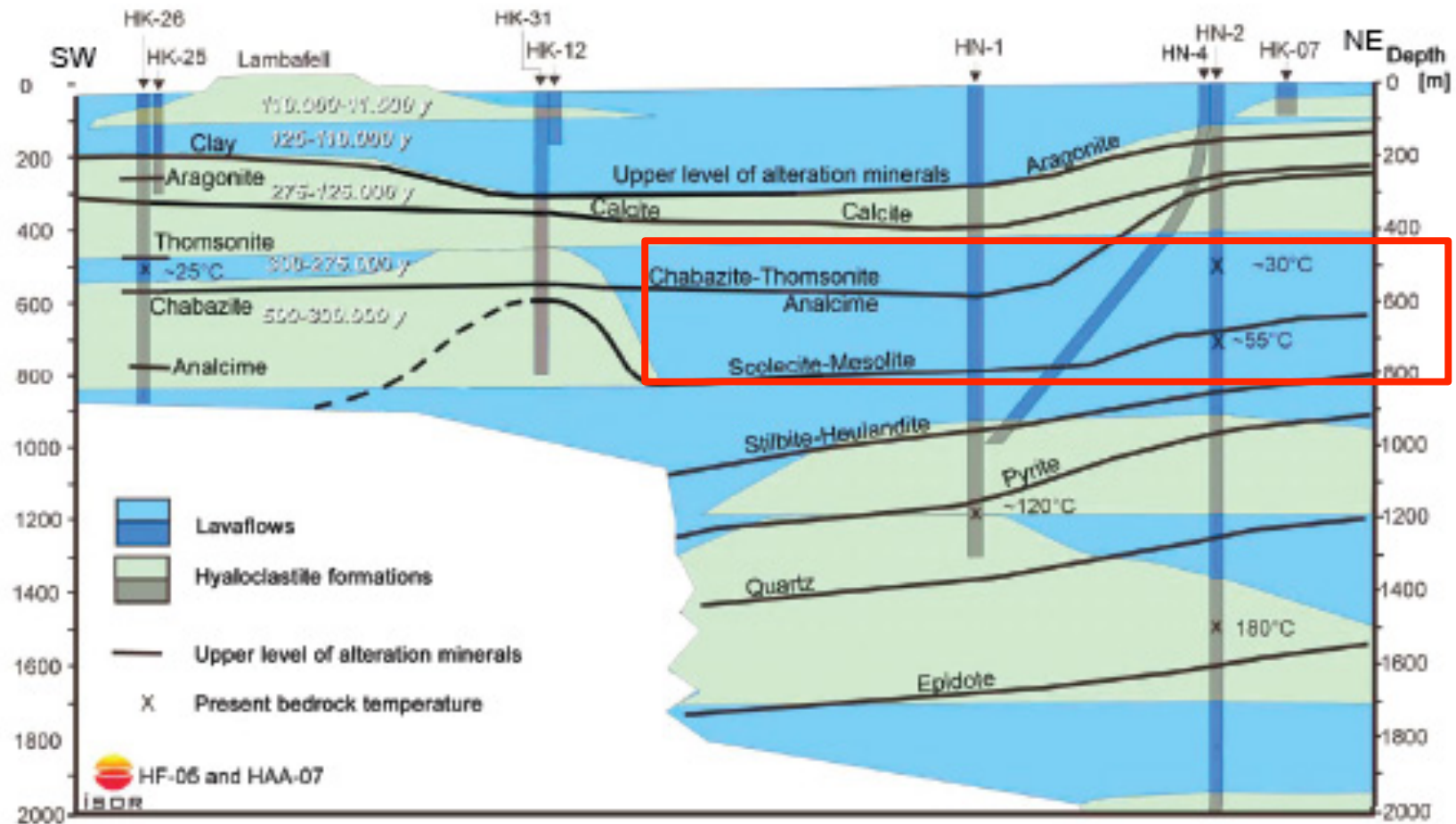
**CH<sub>4</sub> 0.22**

**O<sub>2</sub> + Ar 0.23**

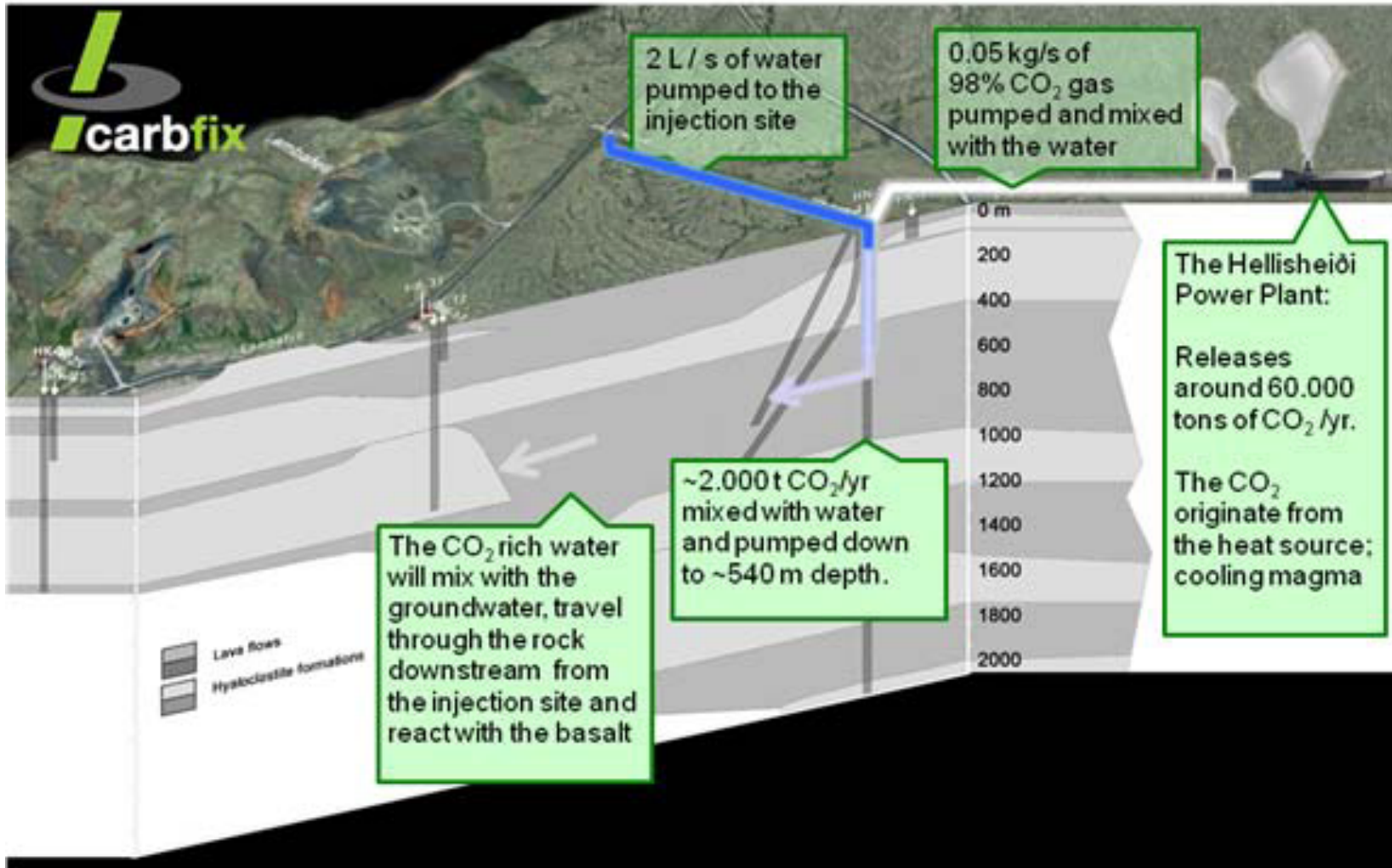




# Storage Formation



Gislason et al., Int. J. Greenhouse Gas Control (2010)



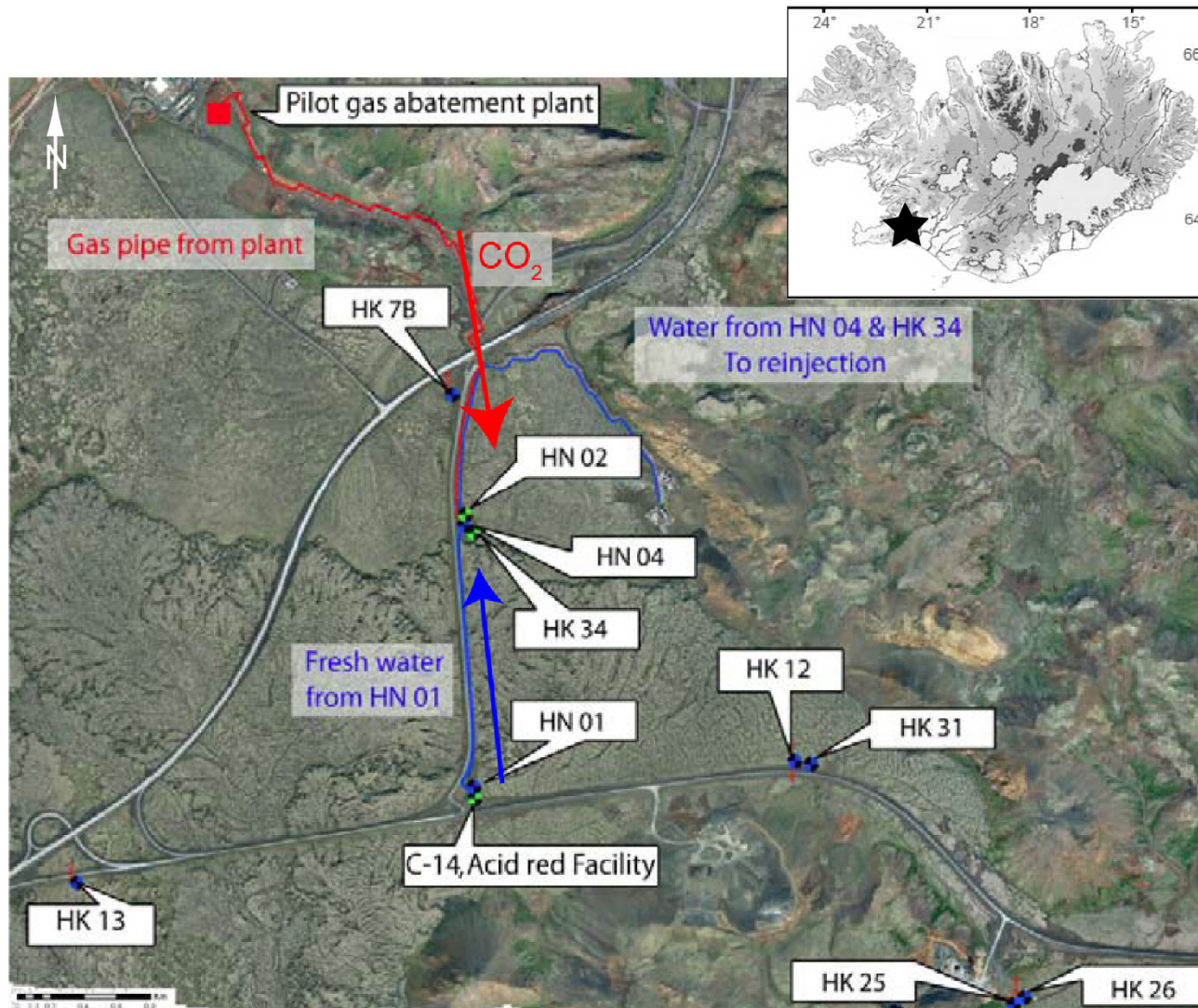


# CO<sub>2</sub> Injection Well





# CarbFix Test Site - Monitoring





Monitoring hut



Monitoring well, HK-34

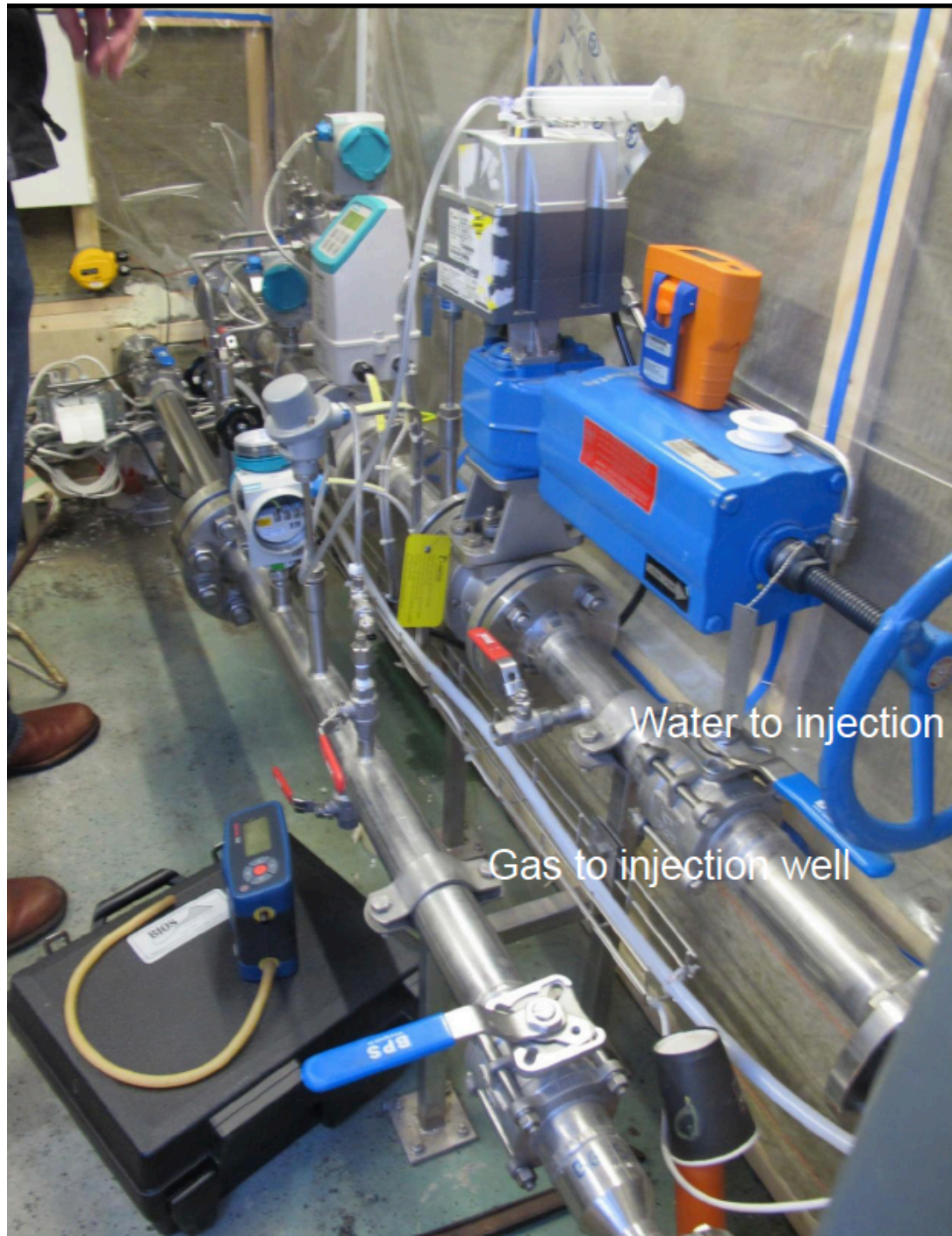




Monitoring  
well, HK-34

Monitoring  
well, HN-4





Water to injection v

Gas to injection well

## MVA Needs Quantification

- Distinguish stored CO<sub>2</sub> from natural CO<sub>2</sub> sources

### **Radiocarbon Tagging Method**

- Labeling the injected CO<sub>2</sub> with an isotopic tracer



# Carbon-14 ( $^{14}\text{C}$ ) as a MVA tool

## Carbon Isotopes

Stable:  $^{12}\text{C}$  - 98.93%

$^{13}\text{C}$  - 1.07%

$^{13}\text{C}/^{12}\text{C} = 0.01$

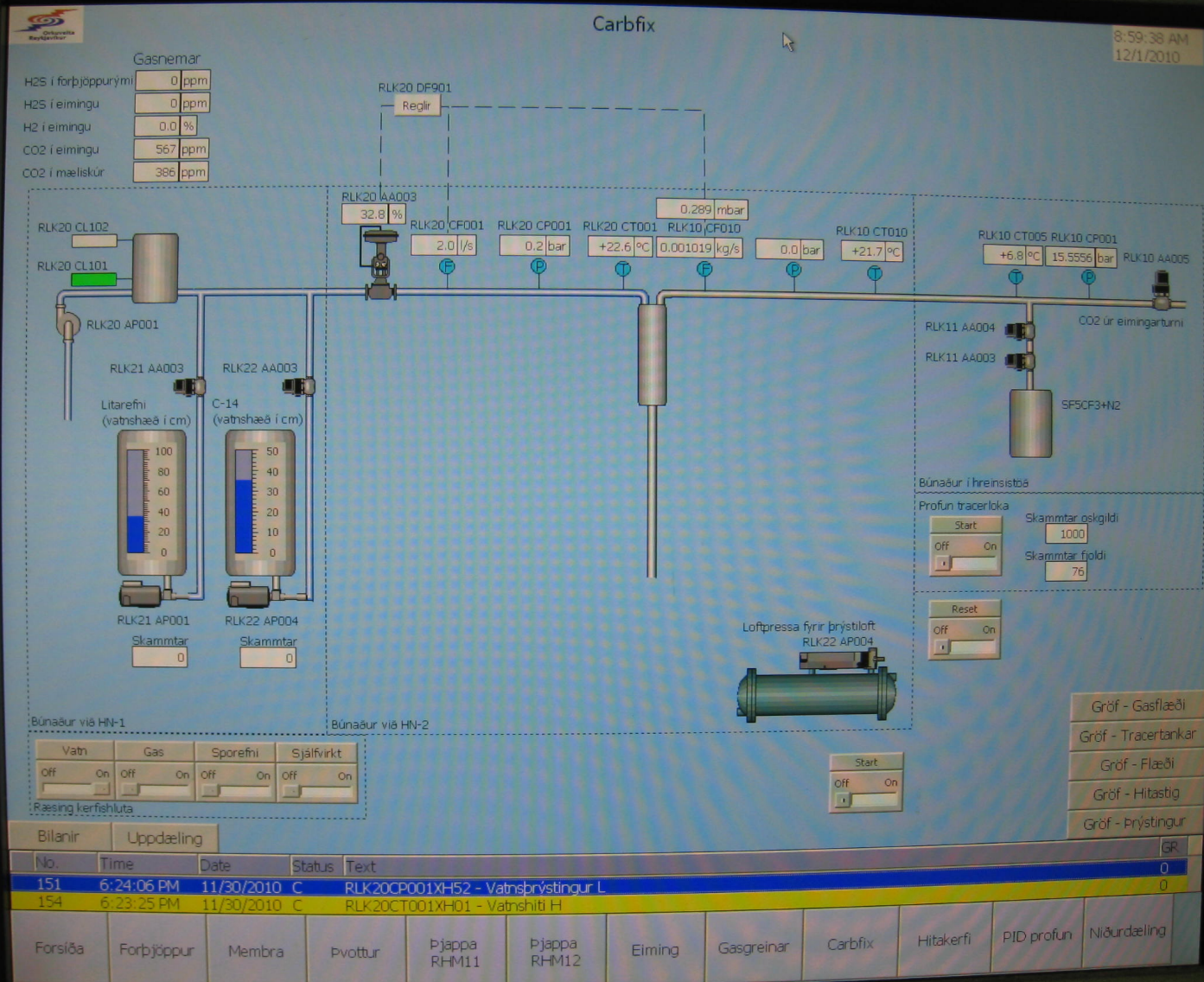
Radioactive:  $^{14}\text{C}$  1ppt

$^{14}\text{C}/^{12}\text{C} = 1.3 \times 10^{-12}$

half-life of about 5730 years

- deep reservoirs have no or very small amounts of  $^{14}\text{C}$
- $^{14}\text{C}$  is a smart tracer for:
  - reaction processes (dissolution – precipitation)
  - biogeochemical processes
  - mixing processes in combination with conservative tracers
  - inventory of stored  $\text{CO}_2$
- Tagging of 1Gt  $\text{CO}_2$  requires 320 grams of pure  $^{14}\text{C}$







# Challenges for CCS

- Regulatory framework
- Liability issues (e.g. power space ownership)
- Monitoring & accounting
- Financing
- Public opposition (e.g. “stop coal”)

