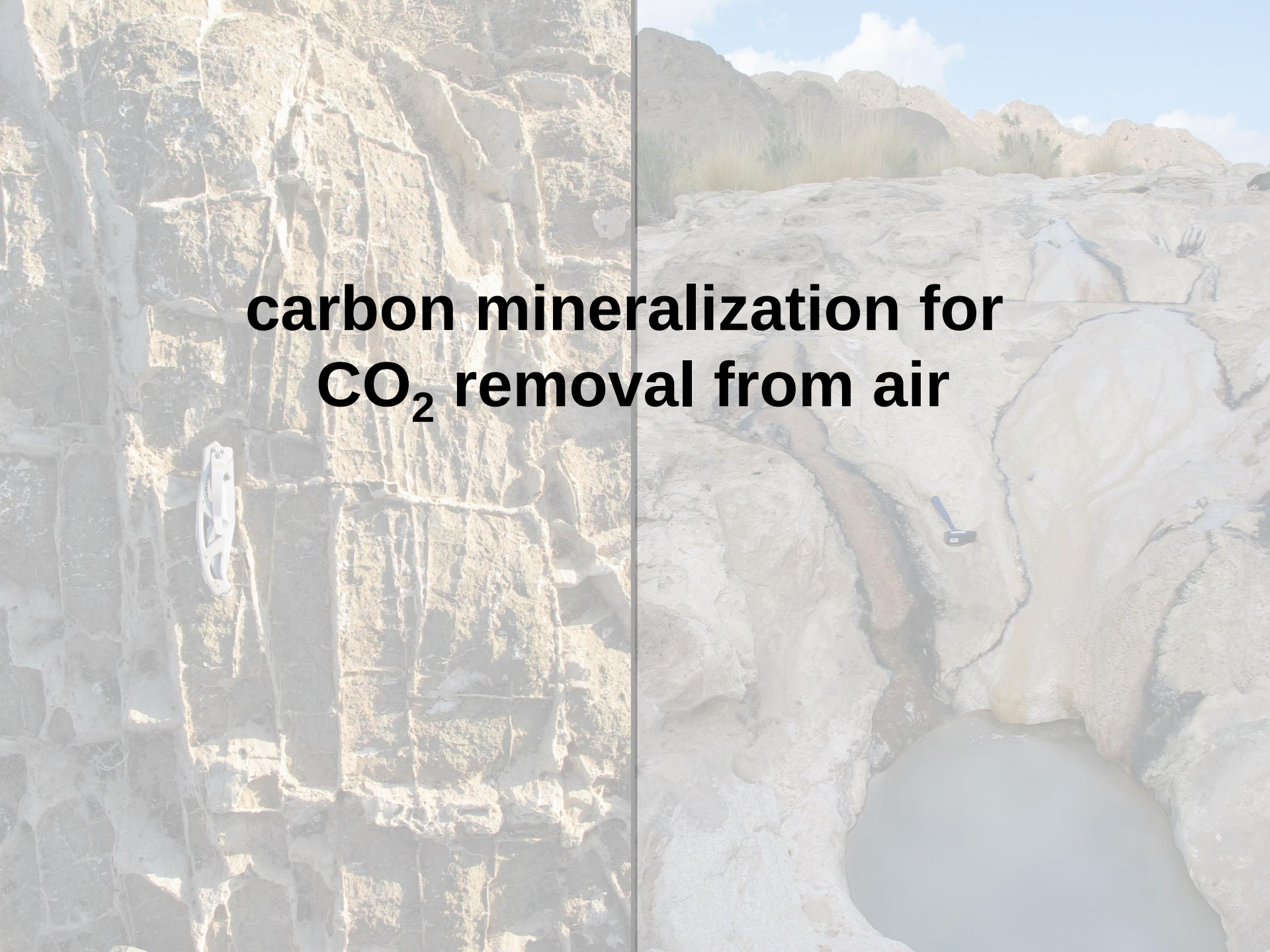
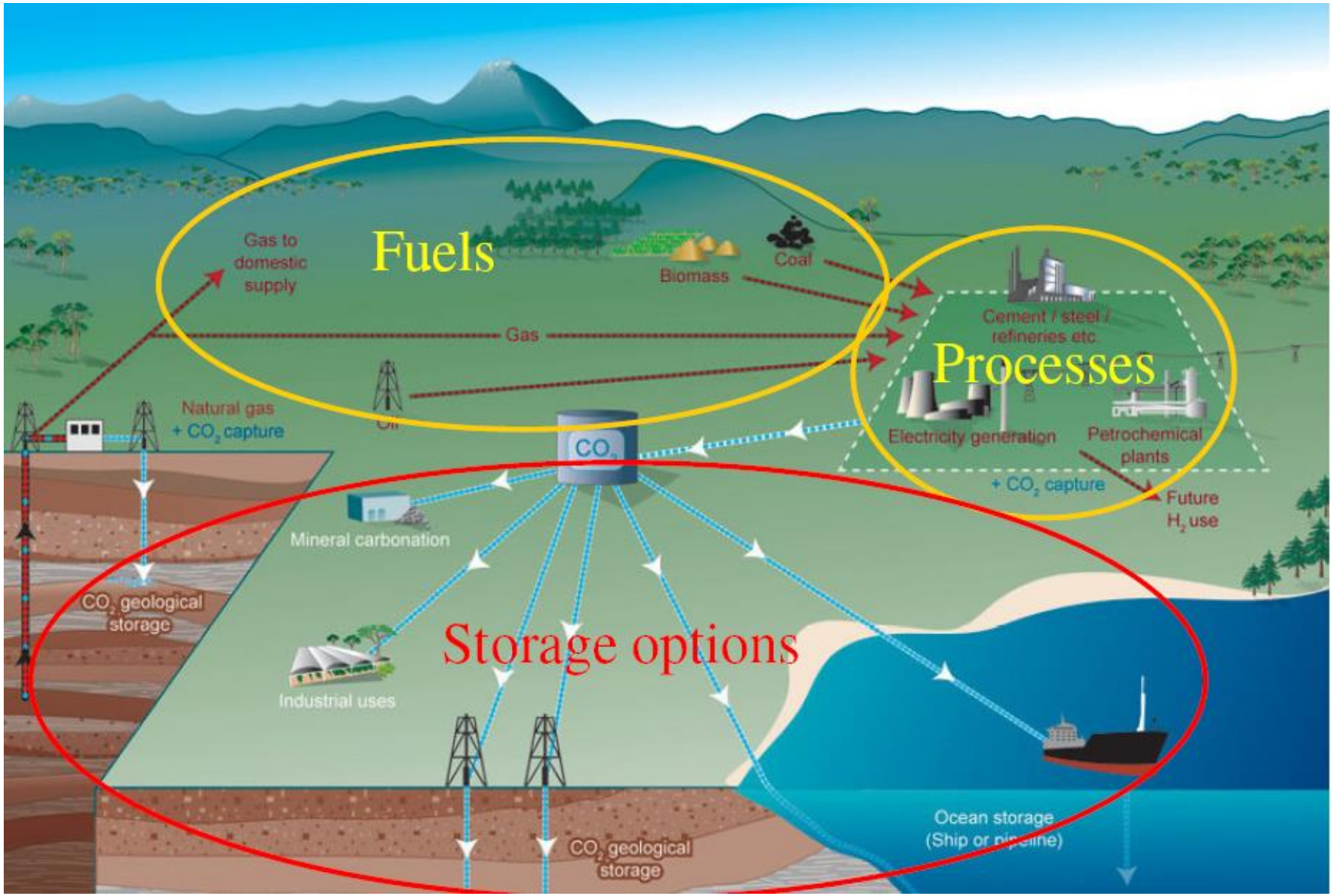
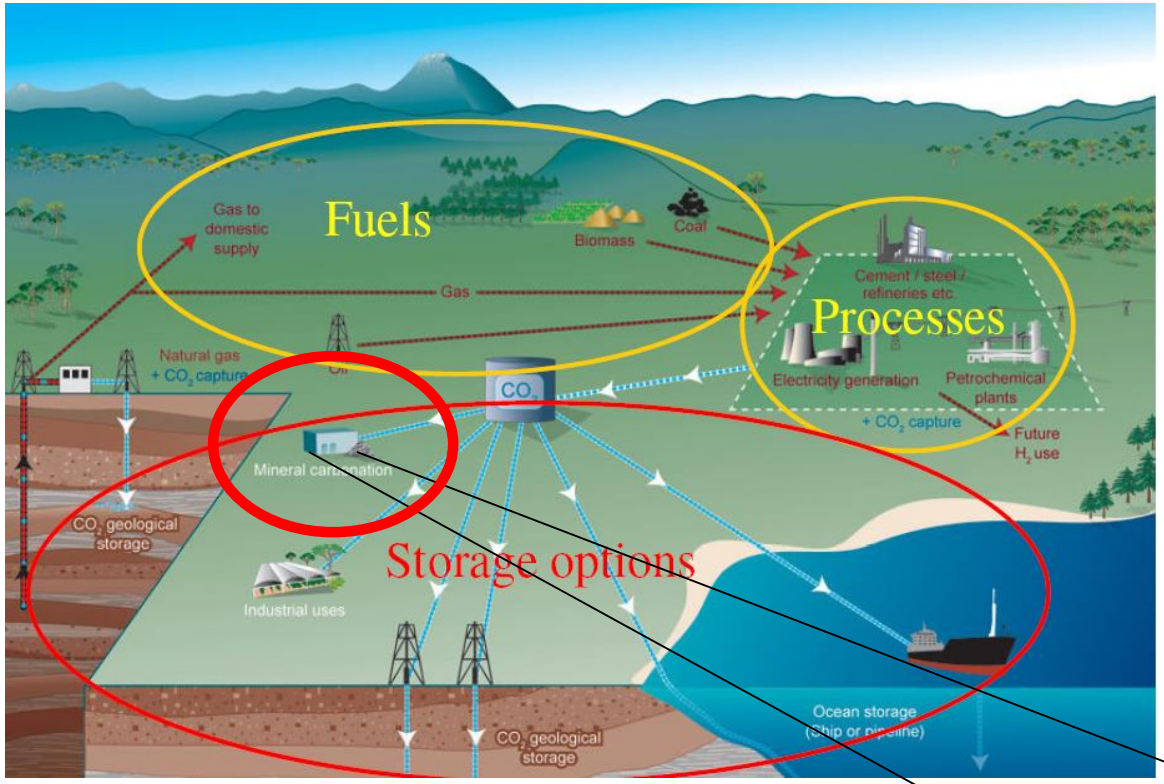


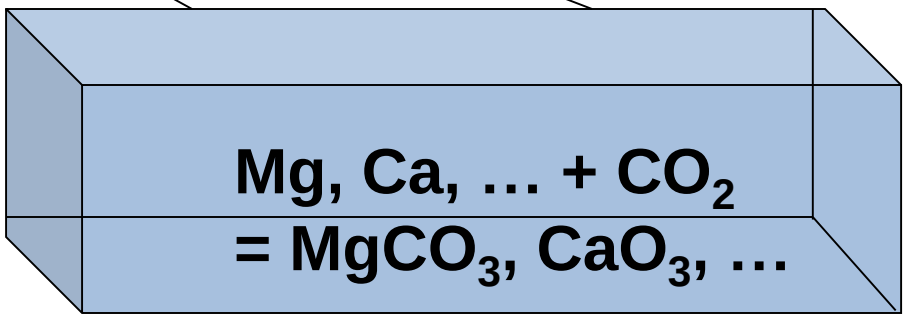
carbon mineralization for CO_2 removal from air

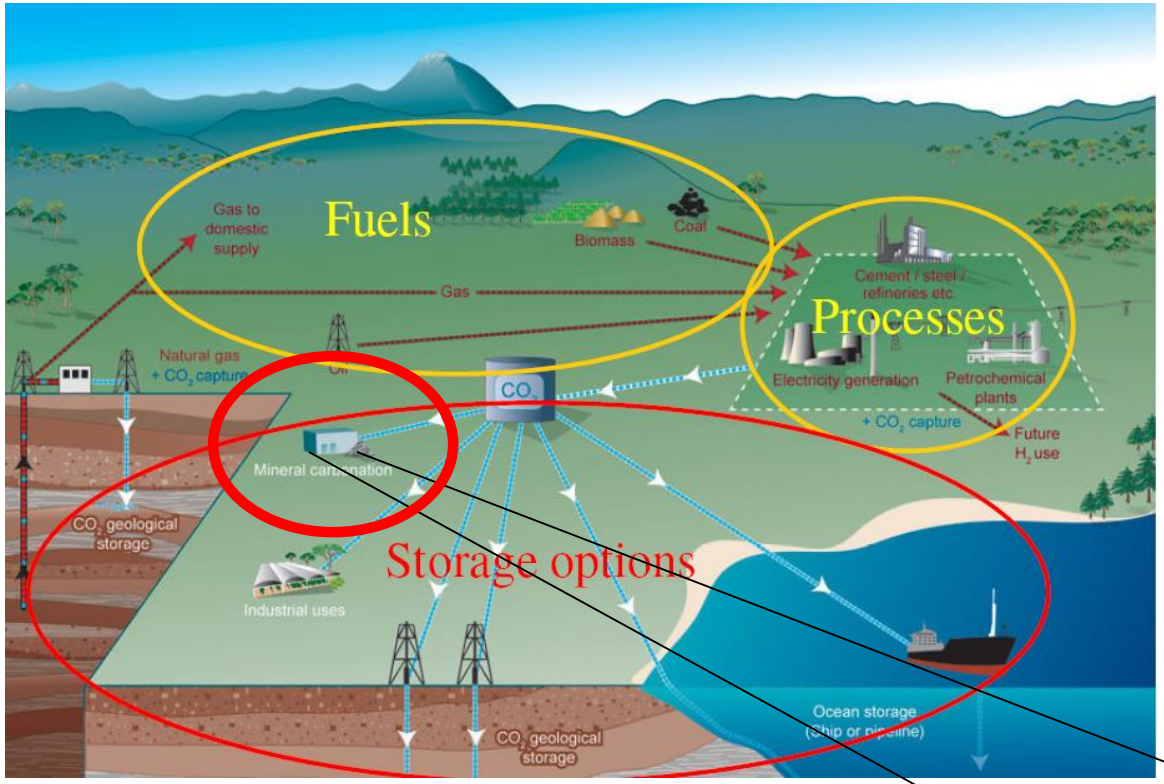


IPCC Report on Carbon Capture & Storage, 2005



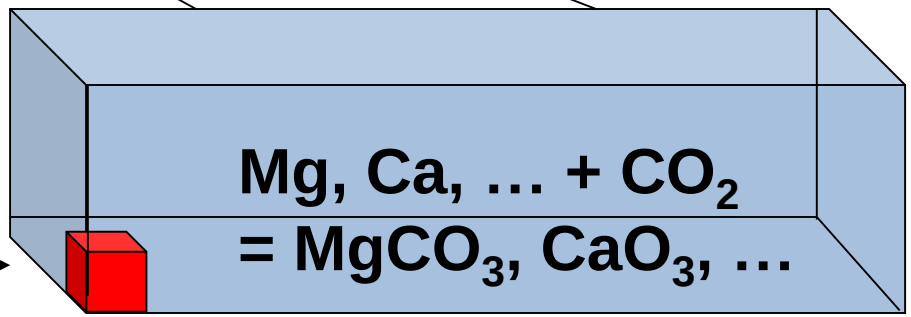
small blue building:
proportion of scientists
working on
carbon mineralization,
mainly for storage





small blue building:
proportion of scientists
working on
carbon mineralization,
mainly for storage

little red room
in small blue building:
proportion of scientists studying
carbon mineralization
for CO_2 removal from air



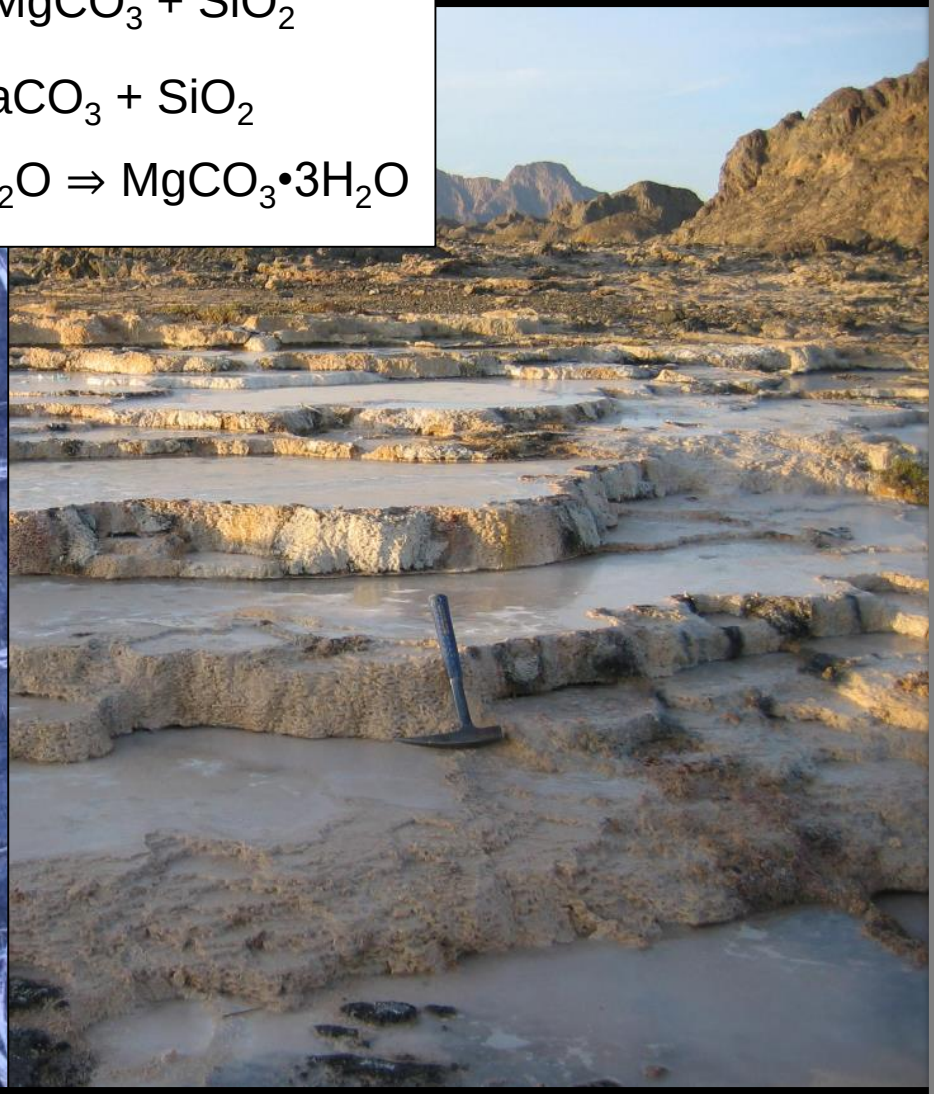
$$Mg(OH)_2 + CO_2 \Rightarrow MgCO_3 + H_2O$$

$$Ca(OH)_2 + CO_2 \Rightarrow CaCO_3 + H_2O$$

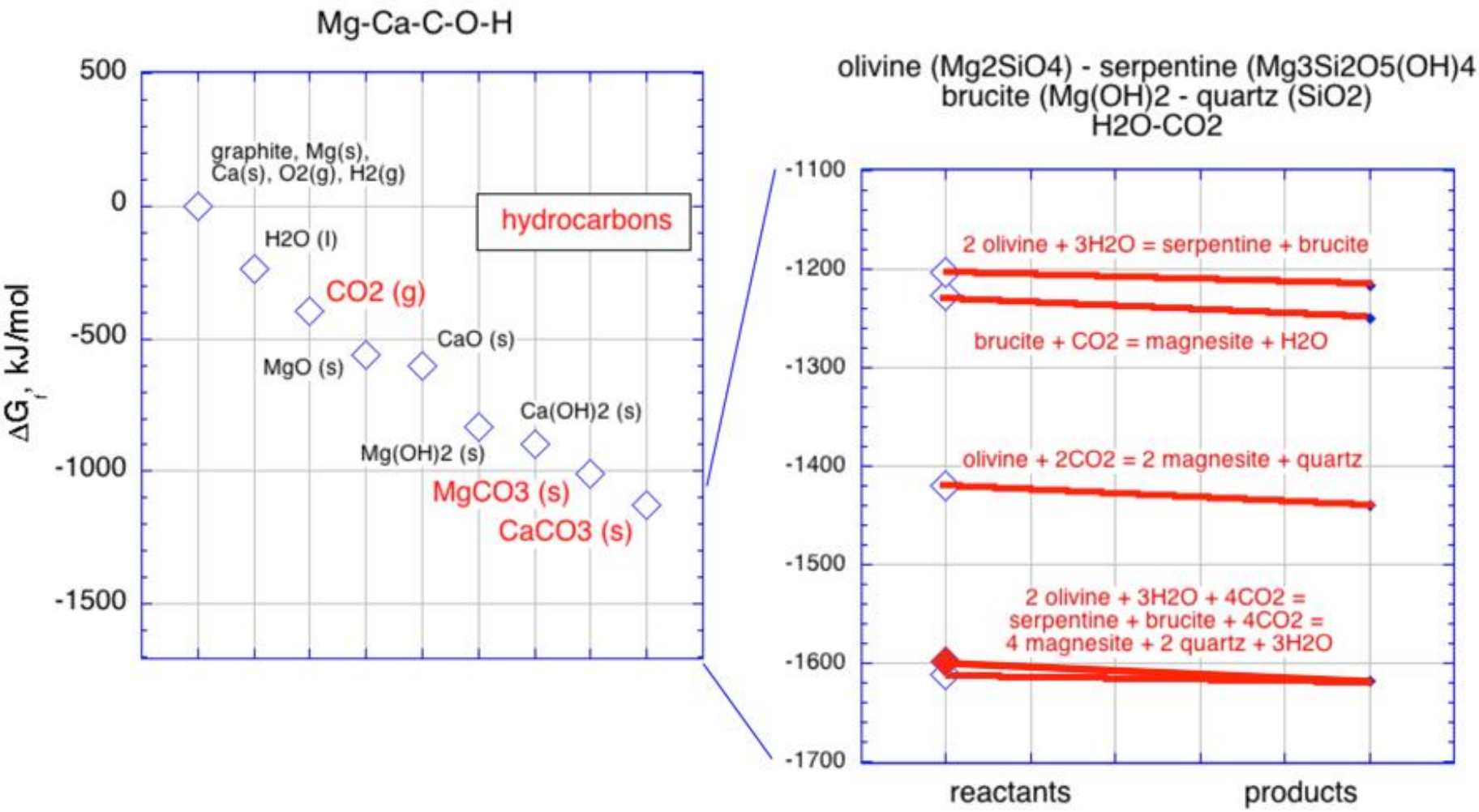
$$Mg_2SiO_4 + 2CO_2 \Rightarrow 2MgCO_3 + SiO_2$$

$$CaSiO_3 + CO_2 \Rightarrow CaCO_3 + SiO_2$$

$$Mg^{2+} + HCO_3^- + OH^- + 2H_2O \Rightarrow MgCO_3 \bullet 3H_2O$$



Mg and Ca carbonates are the "ground state" for C in many near surface geologic systems



National Academies, Negative Emissions 2019
Kelemen et al. Chemical Geology submitted

IPCC 2005 & DOE: expensive

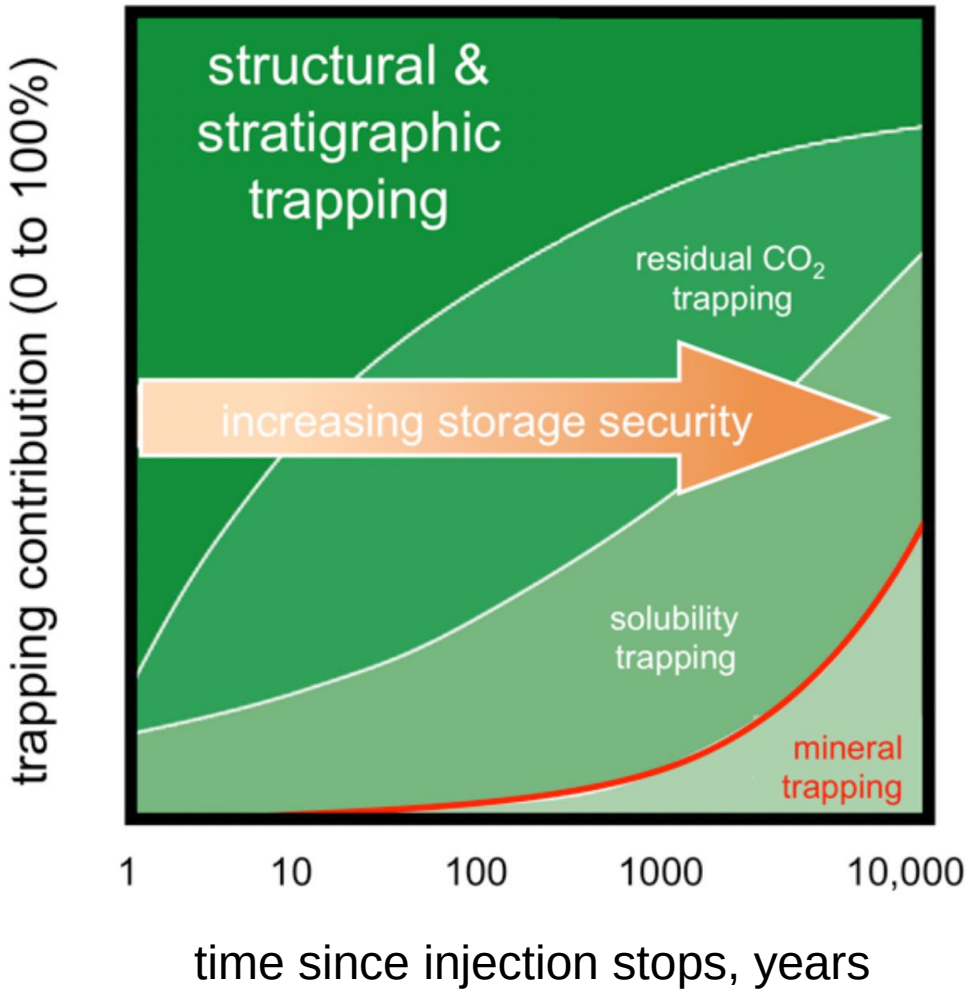
IPCC Report on Carbon Capture & Storage, 2005
Chapter 7: Mineral carbonation and industrial uses of carbon dioxide
Marco Mazzotti et al.

The technology is … not yet ready for implementation.

The best case studied so far is [carbonation of] olivine

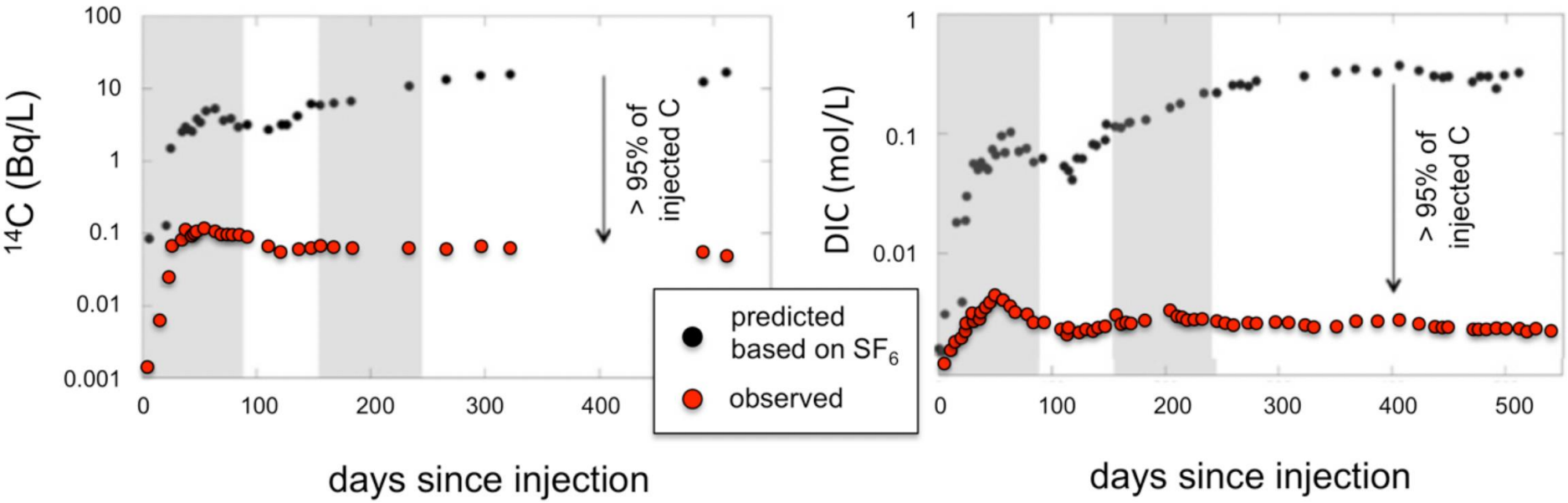
Þ 60-180% more energy
doubles the cost of a power plant
~ \$400/ton CO_2

IPCC 2005 & DOE: slow

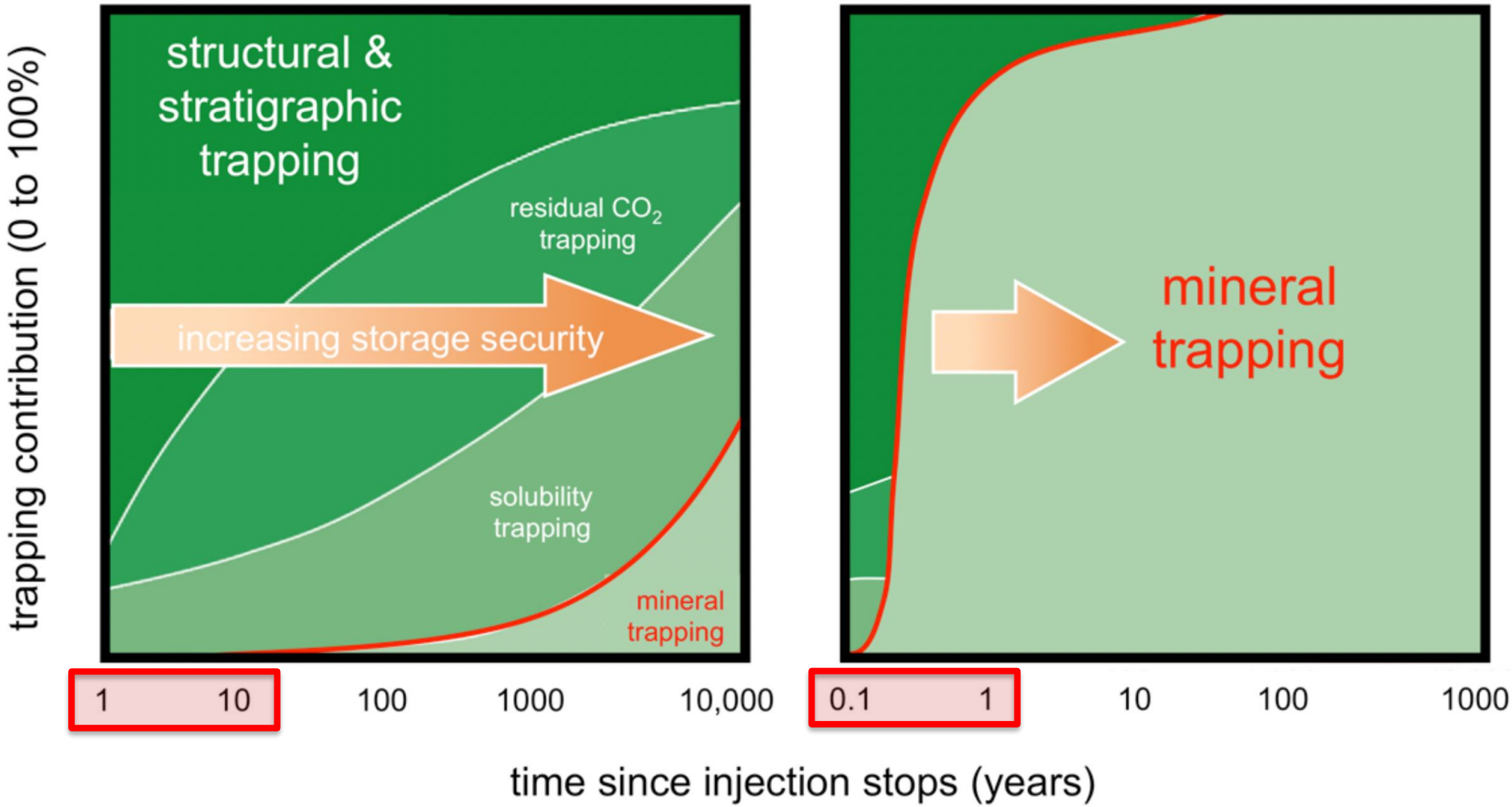


IPCC Report on Carbon Capture & Storage, 2005
Chapter 5: Underground geologic storage

CarbFix, Iceland: fast



Matter et al. Science 2016



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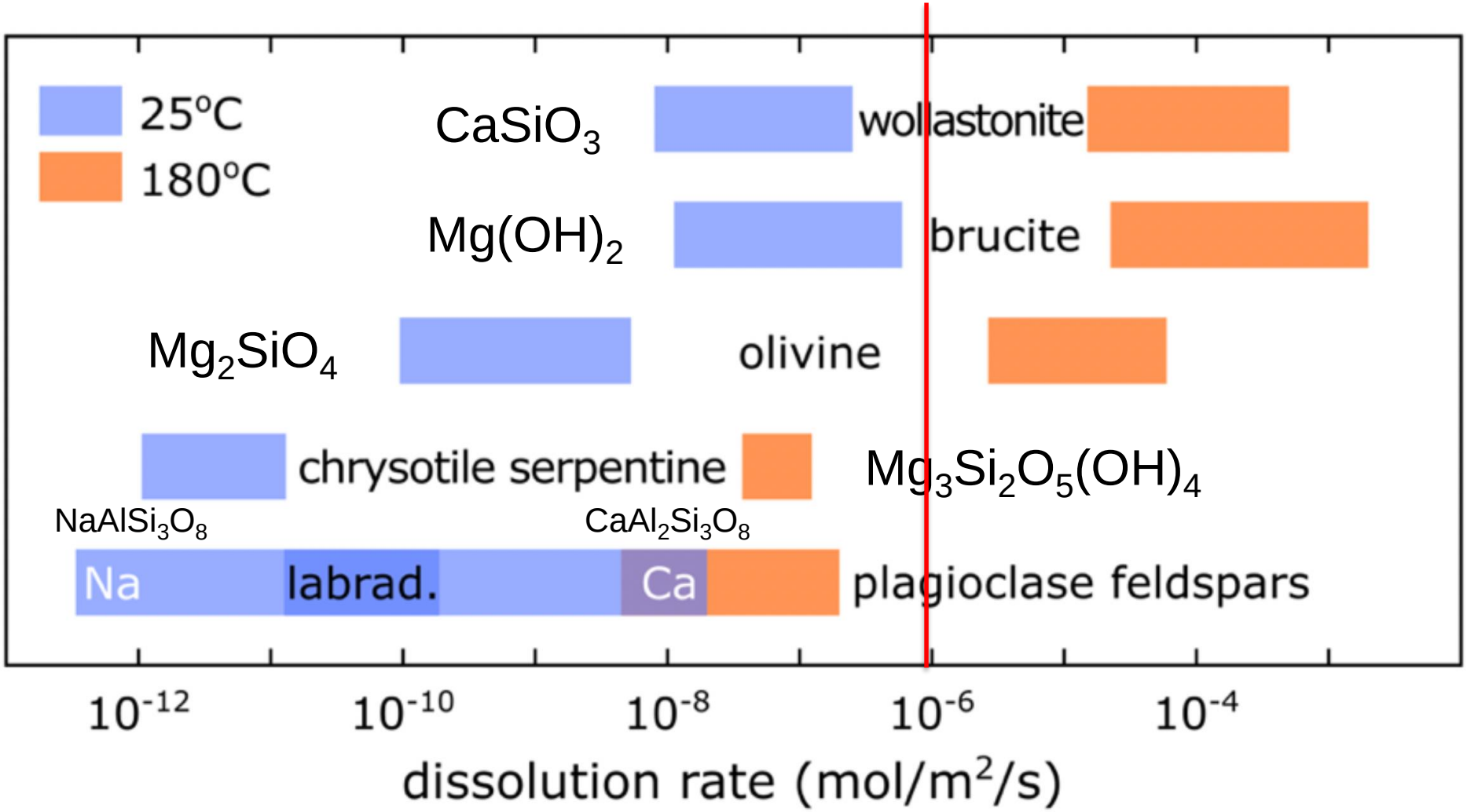


Kelemen et al. Frontiers, in press

carbon mineralization in peridotite max capacity, Gt CO_2

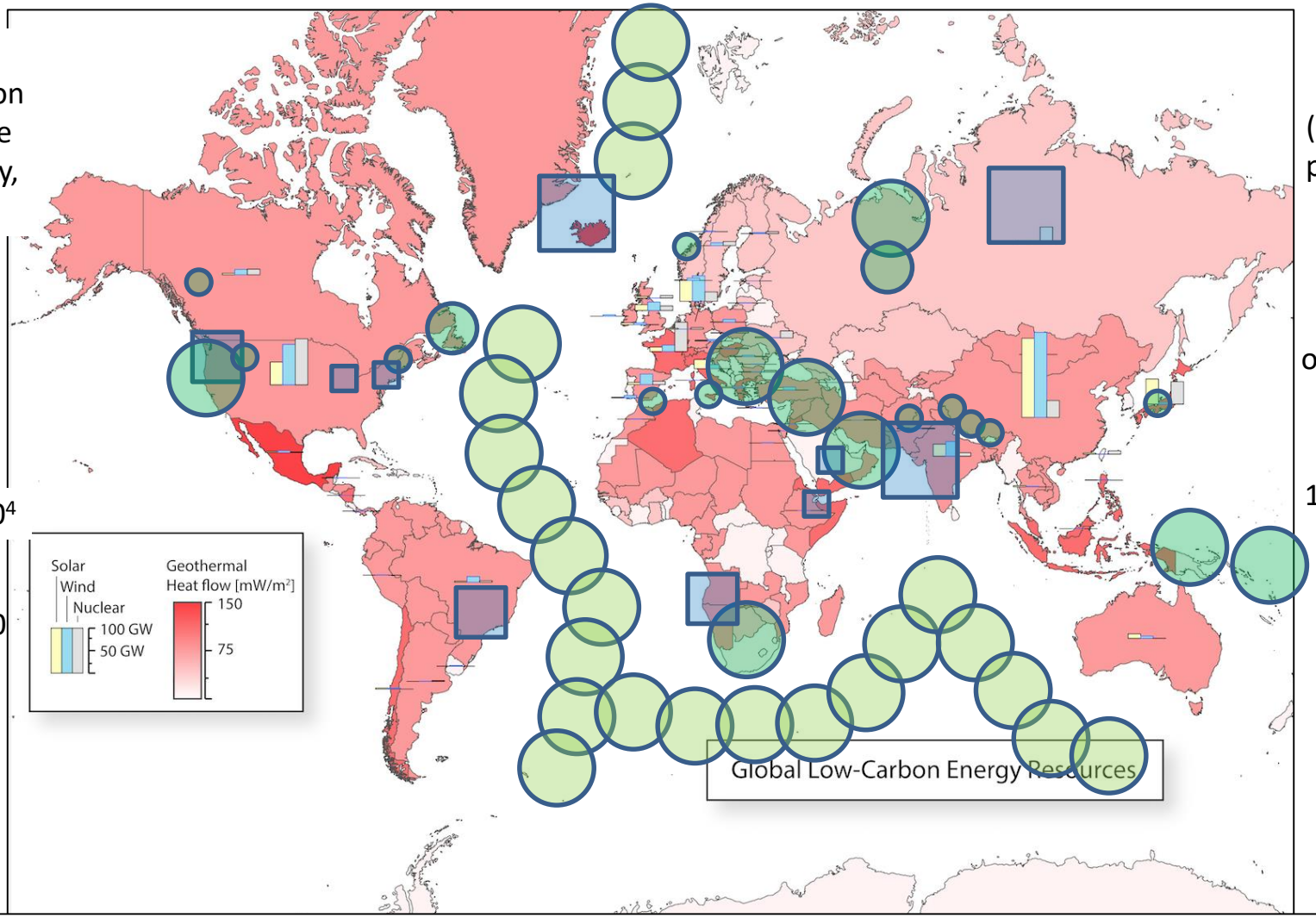
on land

seafloor

$5\ 10^3$ to $5\ 10^4$

500 to 5000

100-500



carbon storage (minerals & pore space) in basalt max capacity, Gt CO_2 on land only

10^5 to $5\ 10^5$

10^4 to 10^5

$1E^3$ to $1E^4$

global CO_2 storage capacity in mafic and ultramafic rocks
100's to 1000's of trillions of tons

(1) cost per ton CO_2 captured:

$/ton = capture process cost / tons CO_2 captured from air

(2) cost per ton CO_2 net removed:

$/ton = total process cost/ [tons CO_2 **captured from air** – emissions to air]

where the total process cost includes the cost of CO_2 capture from calcining, assumed here to be all of the CO_2 produced from the calciner using natural gas

CO_2 captured from process is not included

(3) cost per ton CO_2 produced:

$/ton = total process cost / [tons CO_2 **captured from air + process**]

for all: electricity at $0.06/kWh and gas for heating at $3.25/GJ
maintenance included (not in all NA19 calculations)
no free lunch (waste heat, proprietary power plants)

McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted

Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

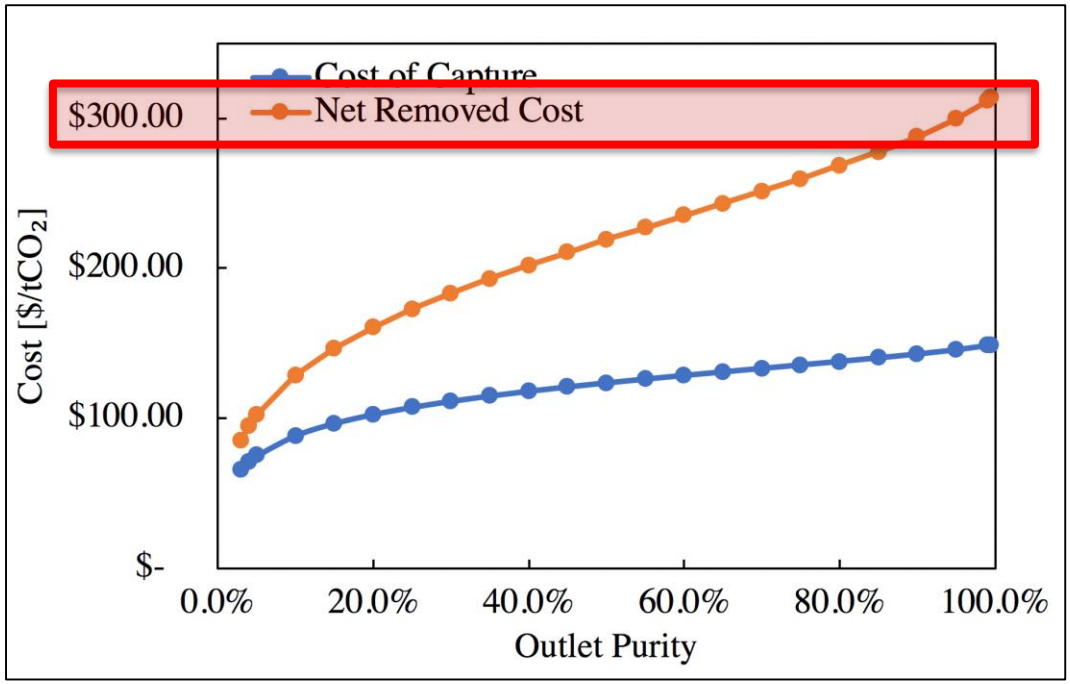
Direct Air Capture System	Capture Cost ($/t CO_2)	
	Captured	Net Removed
Liquid Solvent	147-264	199-357
	147-264	233-419
	141-265	156-293
	145-265	165-294
	154-279	173-310
	317-501	320-506
Solid Sorbent[3]	88-228	89-256
	88-228	89-250
	88-228	113-326
	88-228	113-326
	88-228	124-407
	88-228	166-877

Keith et al. 2018 ≥ $94

$$\text{Cost}\left[\frac{\$}{tCO_2}\right]=\frac{\text{Process Cost [\$]}}{CO_2\text{ Capture from Air [}tCO_2\text{]}}$$

$$\text{Net Removed Cost}\left[\frac{\$}{tCO_2}\right]=\frac{\text{Process Cost [\$]}}{CO_2\text{ Capture from Air [}tCO_2\text{]-}CO_2\text{ Released by Process [}tCO_2\text{]}}$$

$$\text{Produced Cost}\left[\frac{\$}{tCO_2}\right]=\frac{\text{Process Cost [\$]}}{CO_2\text{ Capture from Air [}tCO_2\text{]+Additional }CO_2\text{ Captured by Process [}tCO_2\text{]}}$$



National Academies 2019, McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted

“FastCompany” reported:

“*in 2018, Carbon Engineering published a paper saying that it had dropped costs to around $94 to $232 a ton. Global Thermostat thinks that it can reach $50 a ton.*”

“SingularHub” states:

“Global Thermostat, has already demonstrated that its technology can remove CO_2 for a mere $120 per ton at its facility in Huntsville, Alabama. And at scale, the startup predicts it could achieve DAC for as little as $50 a ton.”

mines:

$10/t to mine & grind, 5 wt% CO_2 = $200/t

200 Mt tailings ⇒ 10 Mt CO2/yr

mining for CDR: prospect for the best rocks,

10% CO_2, $100/t ….

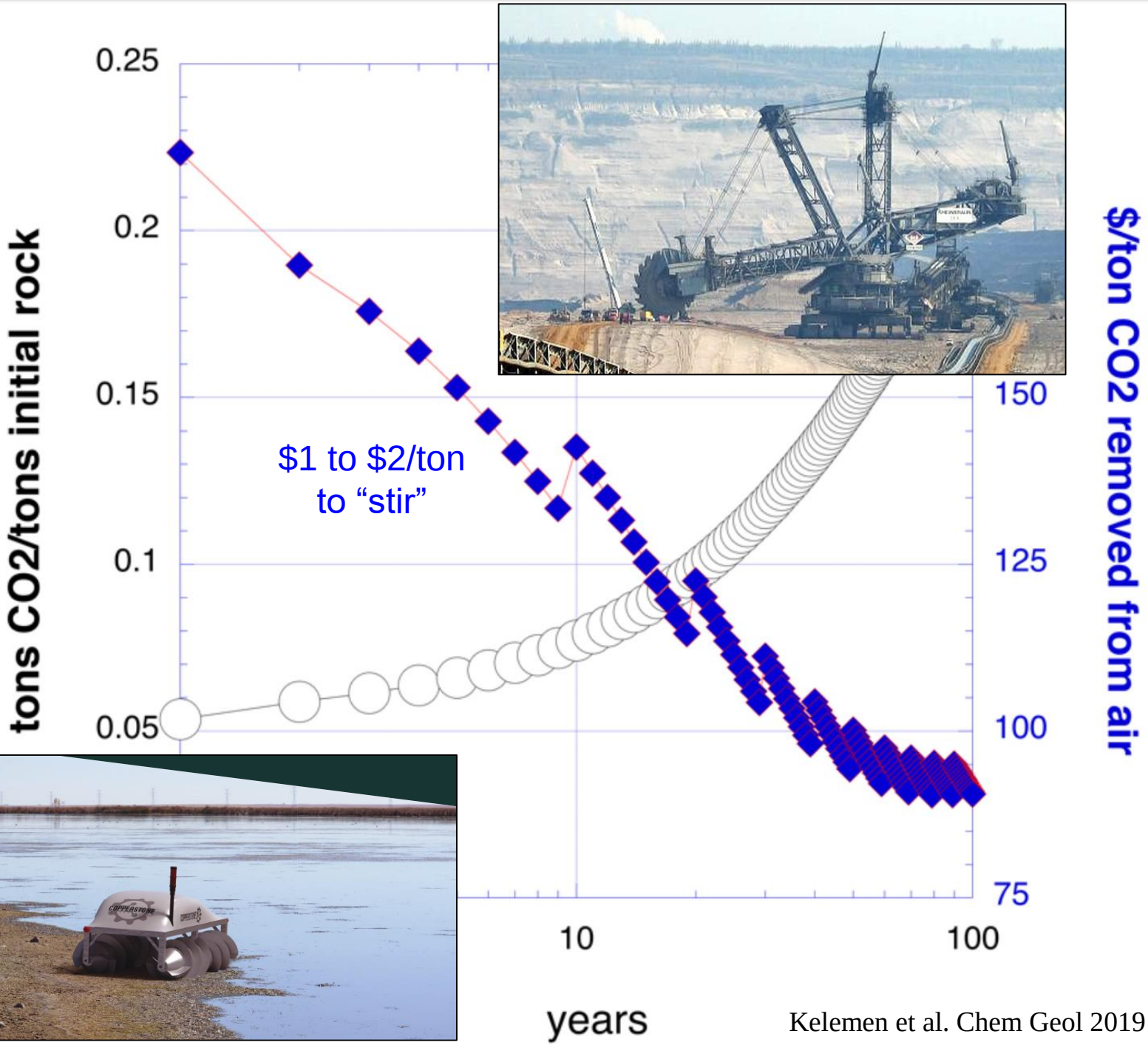
area for 1 Gt CO_2 (10 wt%)

50,000 km^2 x 10 cm deep + mine + power

compare DAC

$100 to $300 per ton …

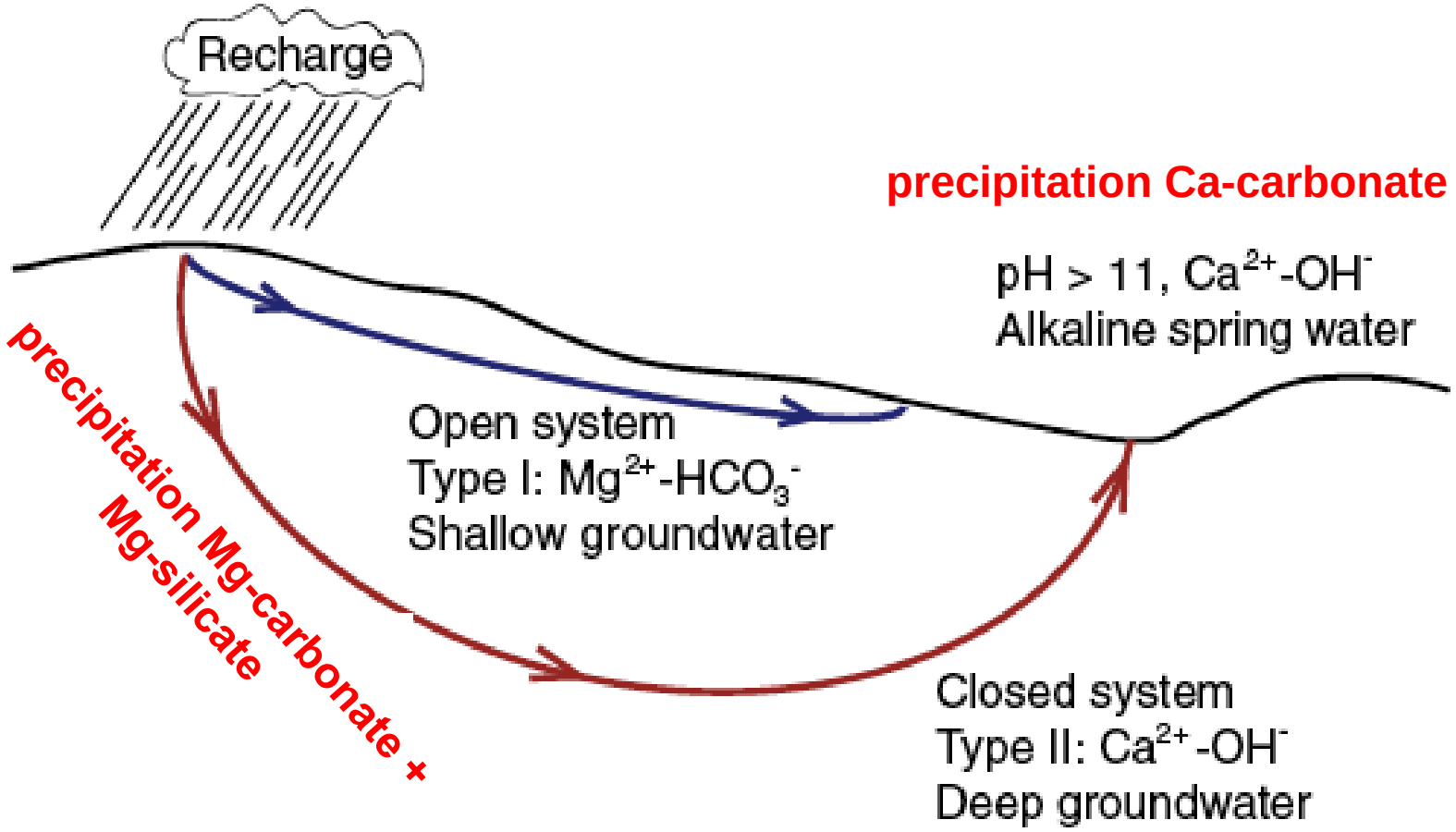
7000 km^2/Gt + 2400 km^2 for power



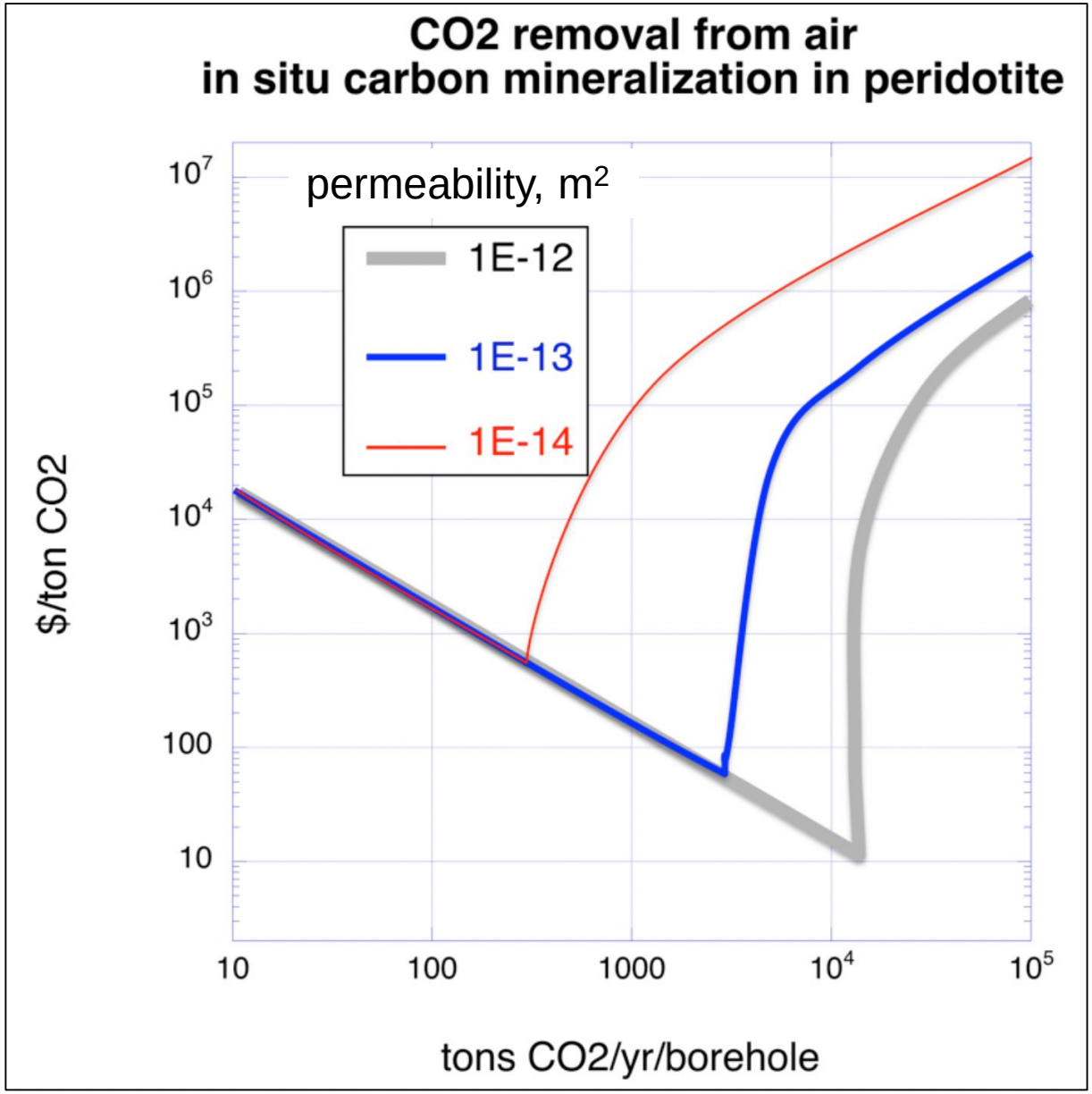
Kelemen et al. Chem Geol 2019 submitted

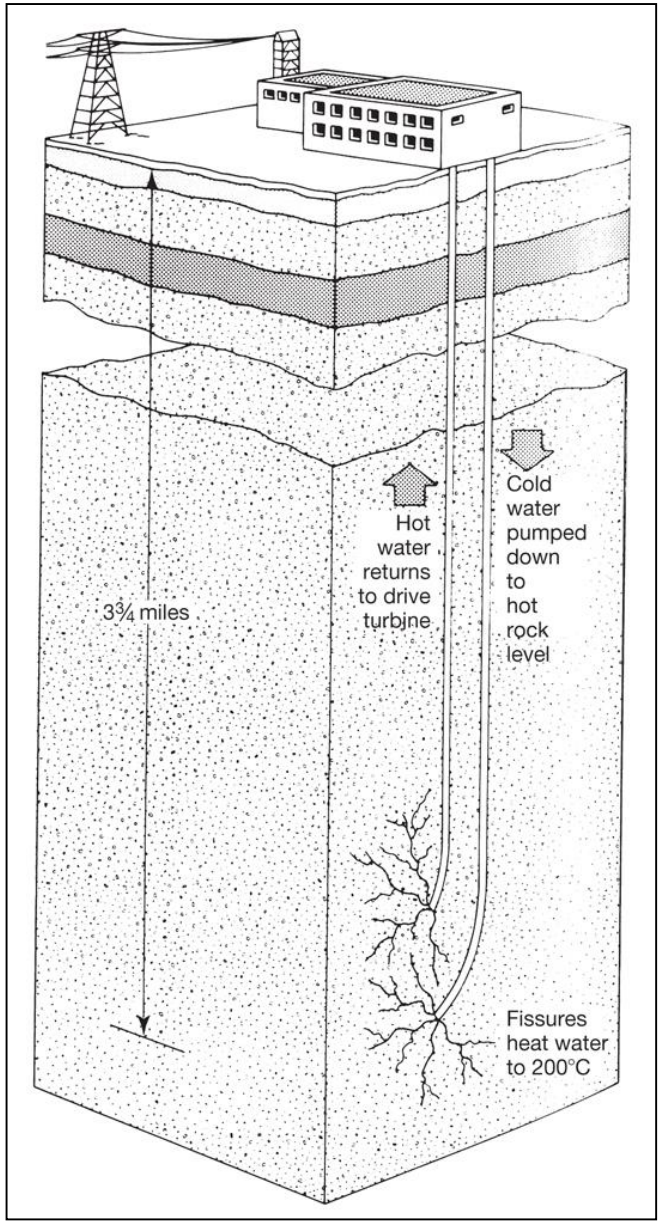
in situ carbon mineralization process

weathering of tectonically exposed mantle peridotite



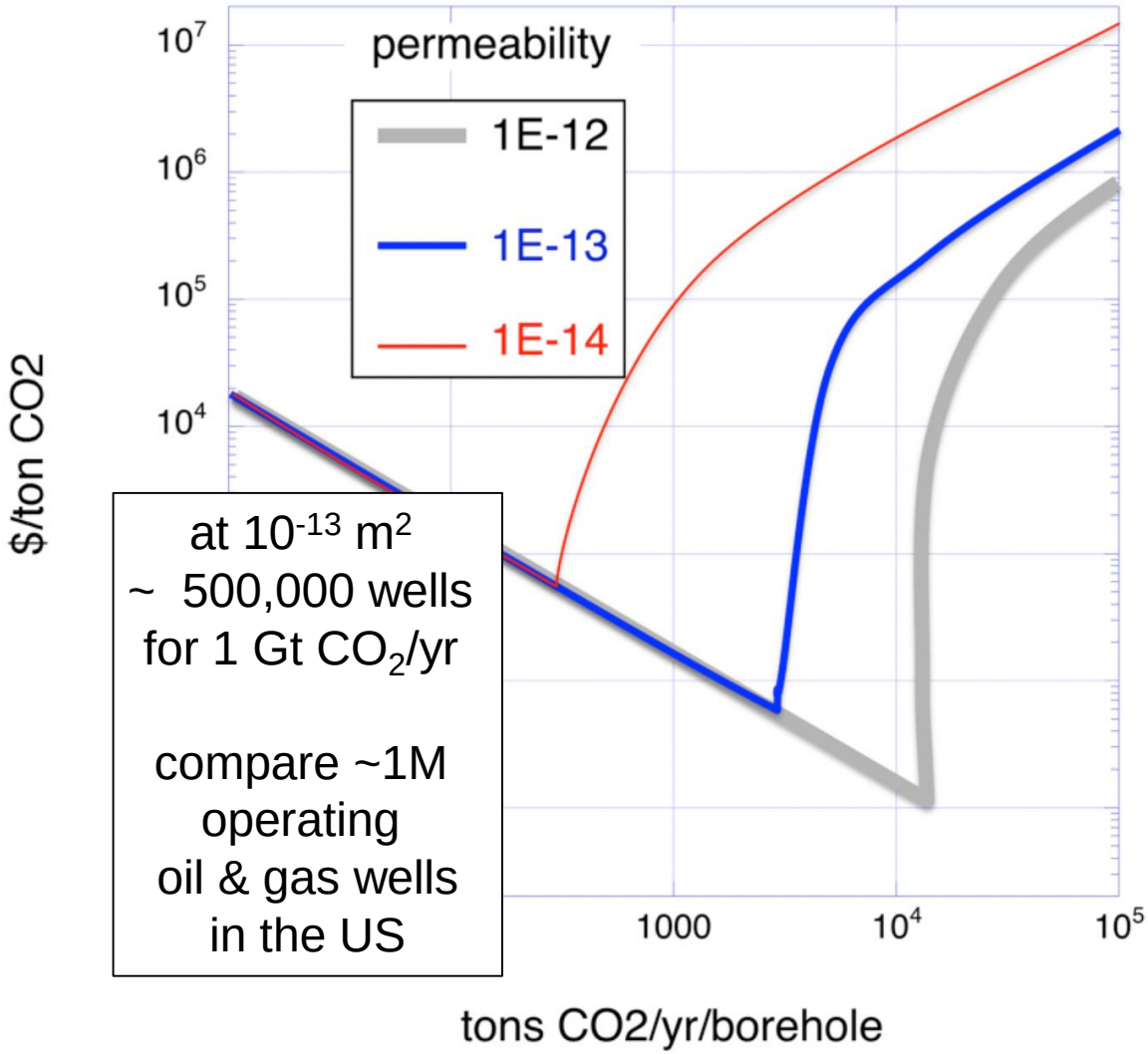
Barnes & O'Neil 1969; Neil & Stanger 1985; Bruni 2002; Paukert et al. 2012





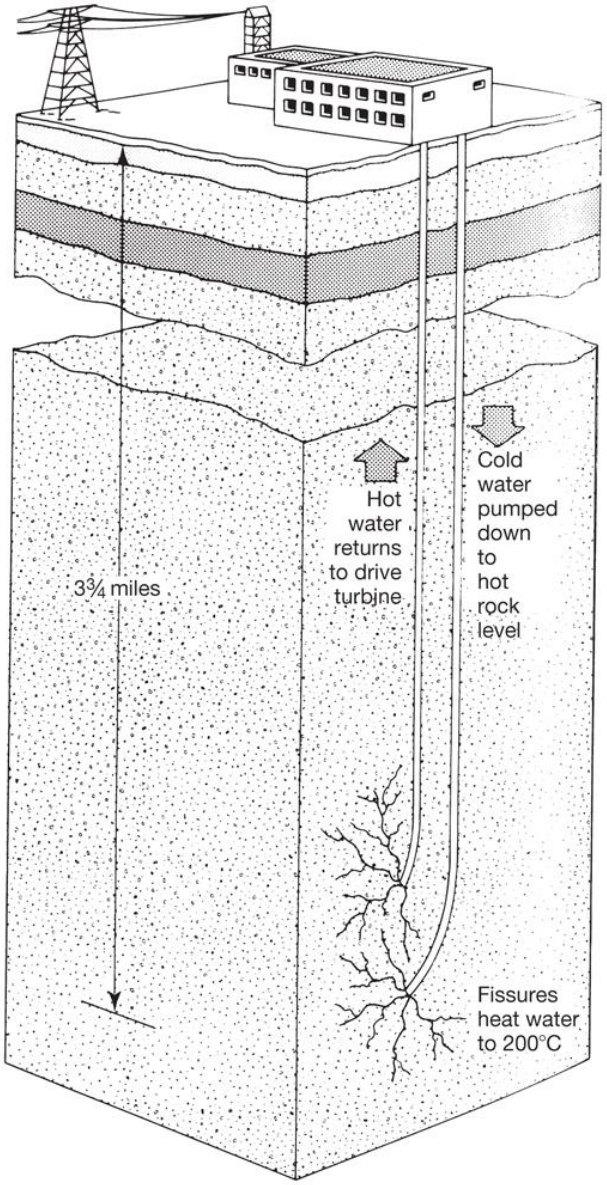
Kelemen et al. Chem Geol 2019 submitted

CO2 removal from air in situ carbon mineralization in peridotite



at 10^{-13} m^2
~ 500,000 wells
for 1 Gt CO_2/yr

compare ~1M
operating
oil & gas wells
in the US



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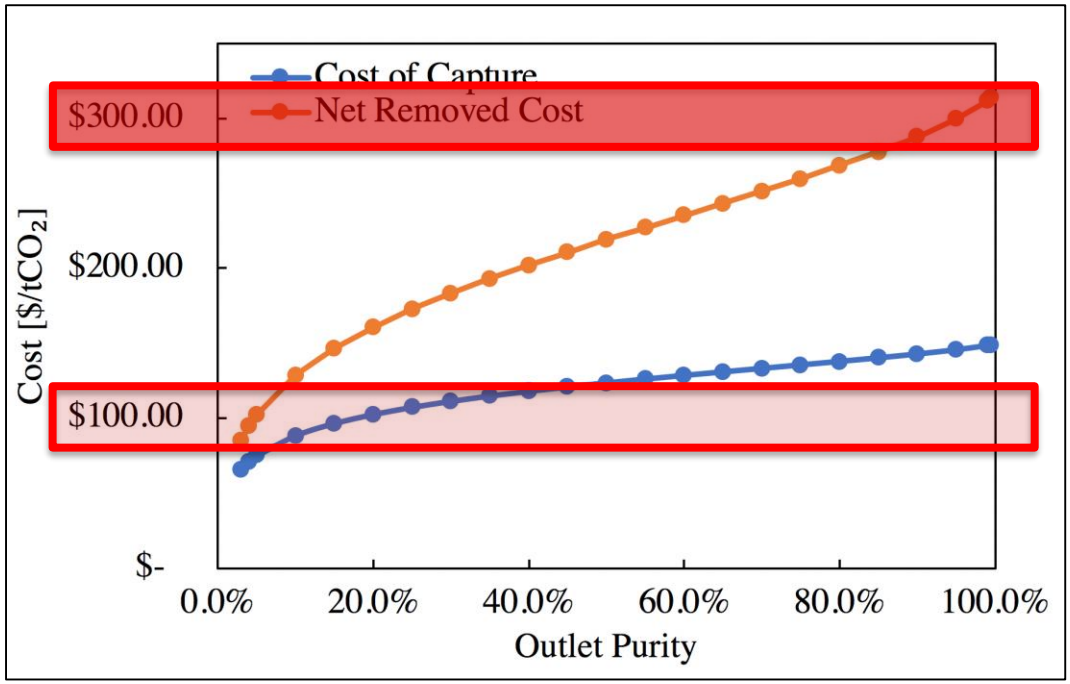
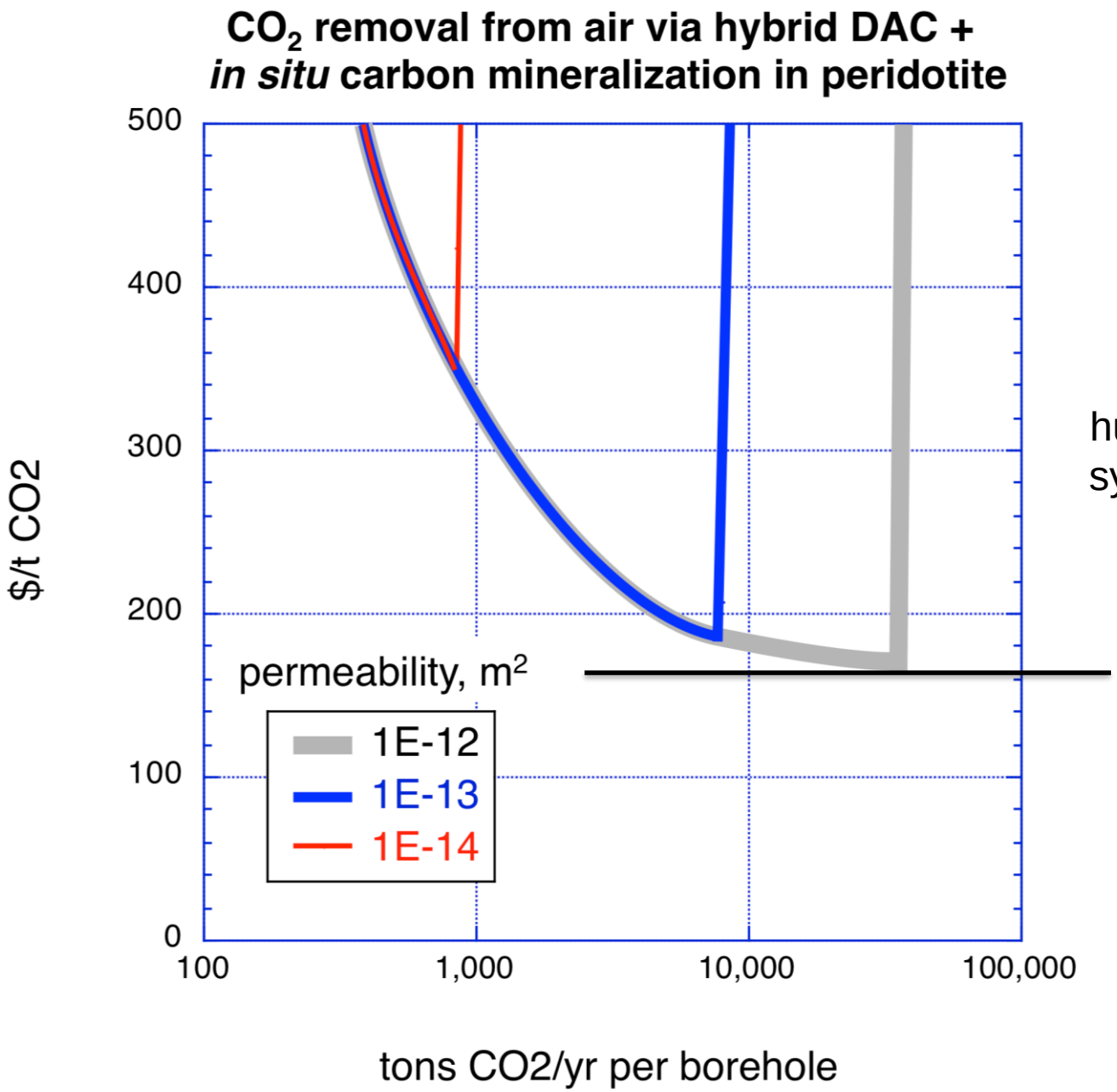


National Academies 2019, McQueen et al. JRSI 2019 submitted
Kelemen et al. Chem Geol 2019 submitted



at 10^{-13} m^2
~ 100,000 wells
for 1 Gt CO_2/yr

wells 250 m apart
6250 km^2
(cows in between!)

huge optimization space
synergy with geothermal

$65 for DACSS to 3%
$100 for compression

Kelemen et al. Chem. Geol. 2019 submitted

compare:

(grid electricity $0.06, natural gas $3.25/GJ)

liquid solvent (Carbon Engineering):

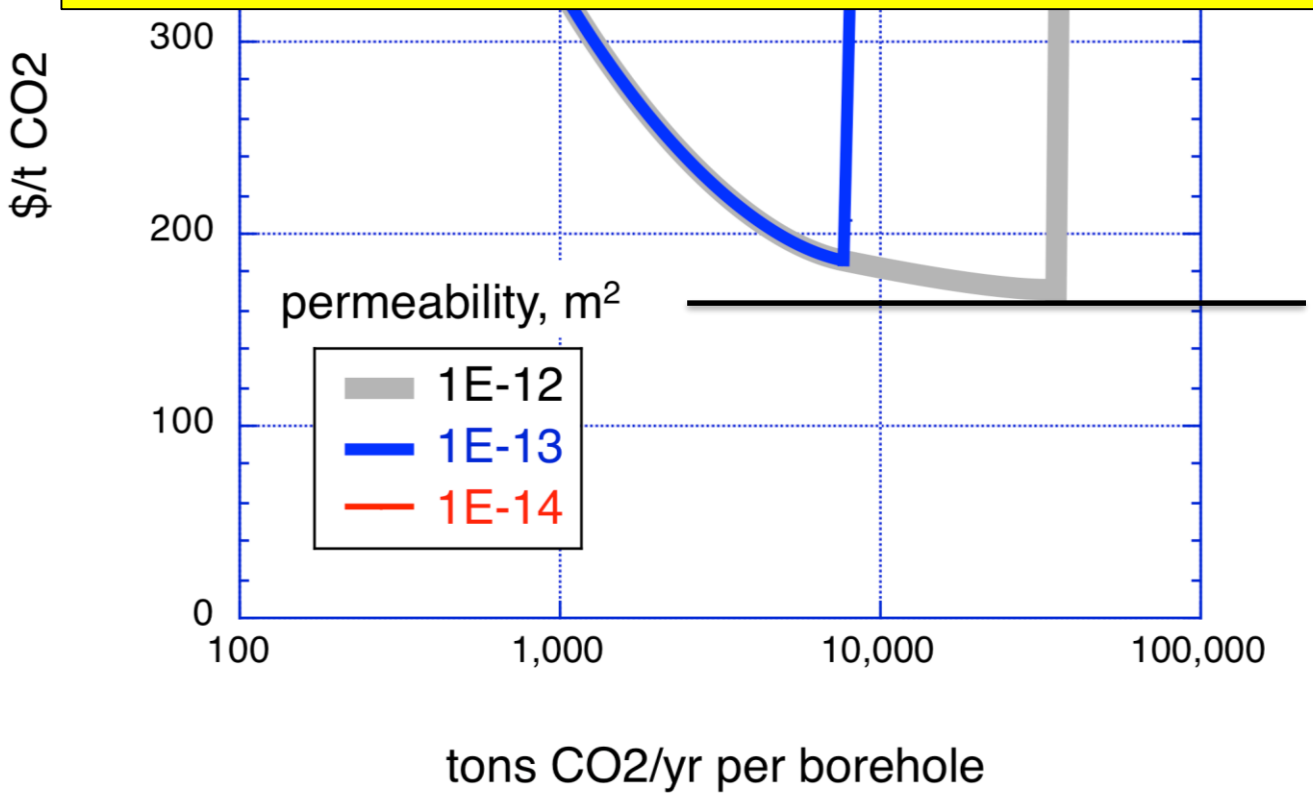
$113-163 net removed (15 MPa output) Keith et al. 2018

$199-357 net removed National Academies 2019

solid sorbent (Global Thermostat)

$124-407 net removed National Academies 2019

comparable area footprint for all; 7000 km^2/Gt CO_2 (2x Nevada Test Site)

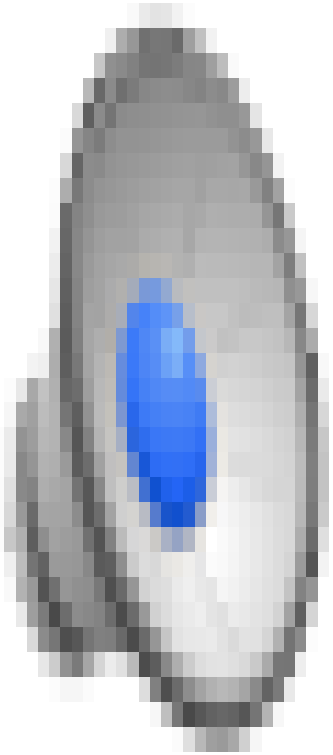


$65 for DACSS to 3%
$100 for compression

Kelemen et al. Chem. Geol. 2019 submitted

cracking
versus
clogging

example
MgO
+
H_2O
=
$Mg(OH)_2$



natural
systems
don't clog,
persist
for 10's to
100's of
thousands
of years

Zheng et al. G-cubed 2018

cracking versus clogging

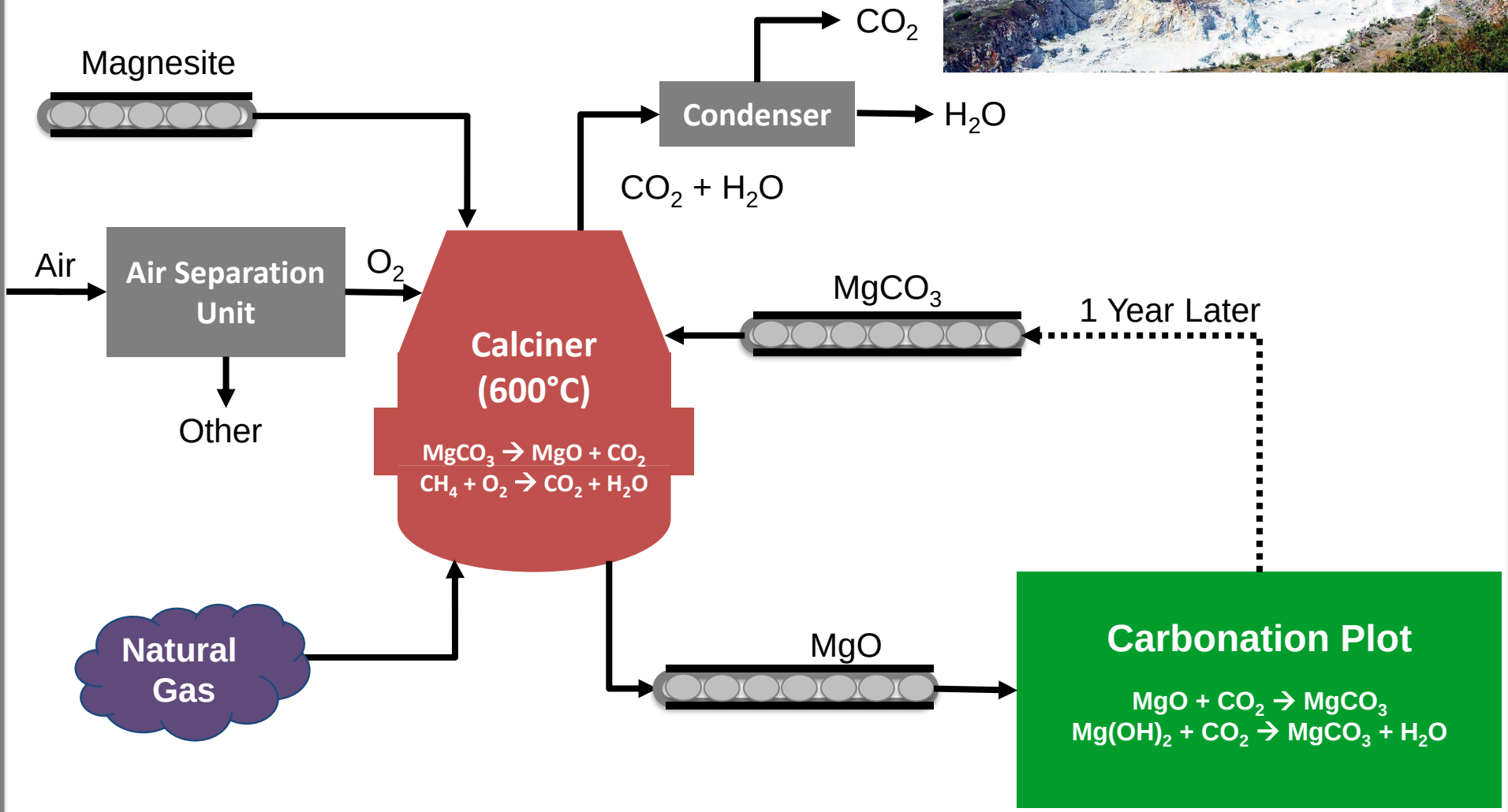
example
MgO
+
H_2O
=
$Mg(OH)_2$

natural systems don't clog, persist for 10's to 100's of thousands of years

Zheng et al. G-cubed 2018

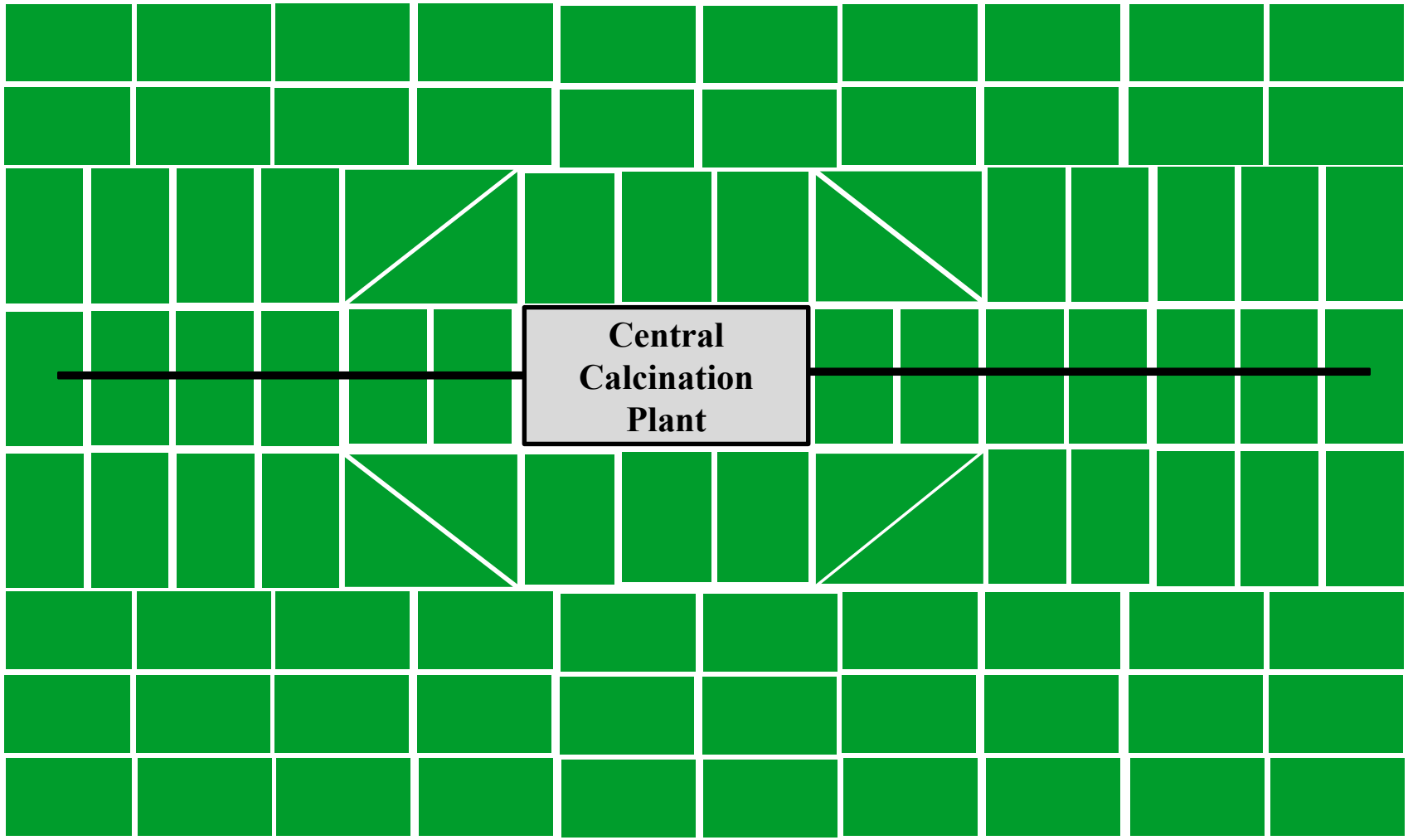
magnesium oxide looping

or $Na(OH)_2$, …



McQueen et al. JRSI submitted 2019
& papers in preparation

enough carbonation plots to keep calciner running 24/7



McQueen et al. JRSI submitted 2019
& papers in preparation

Process Economic Assumptions

Variable	Value	Source/Notes
Natural Gas Cost	$3.25/GJ	Keith et al., 2018
Electricity Cost	$0.06/kWh	Keith et al., 2018
Capacity Factor	90%	Keith et al., 2018
Carbonation Plots	3,405	Continuous Calciner Operation
Environmental Losses	5%	Needs experimental validation
Layer Thickness	10 cm	Needs experimental validation

McQueen et al. JRSI submitted 2019
& papers in preparation

Process Economic Results

Energy Type	Grid Electricity [$0.06/kWh]	Solar Electricity [$0.10/kWh]	Projected Solar Electricity [$0.03/kWh]
Base Cost [$/t$CO_2$]	$47 - $93	$51 - $96	$44 - $90
Net Removed Cost [$/t$CO_2$]	$47- $93	$51 - $97	$44 - $90
Produced Cost [$/t$CO_2$]	$0.32 – $16	$0.32 – $16	$0.32 – $16

McQueen et al. JRSI submitted 2019
& papers in preparation

process cost comparison

Energy Type	Grid Electricity [$0.06/kWh]	Solar Electricity [$0.10/kWh]	Projected Solar Electricity [$0.03/kWh]
Base Cost [$/t$CO_2$]	$47 - $93	$51 - $96	$44 - $90
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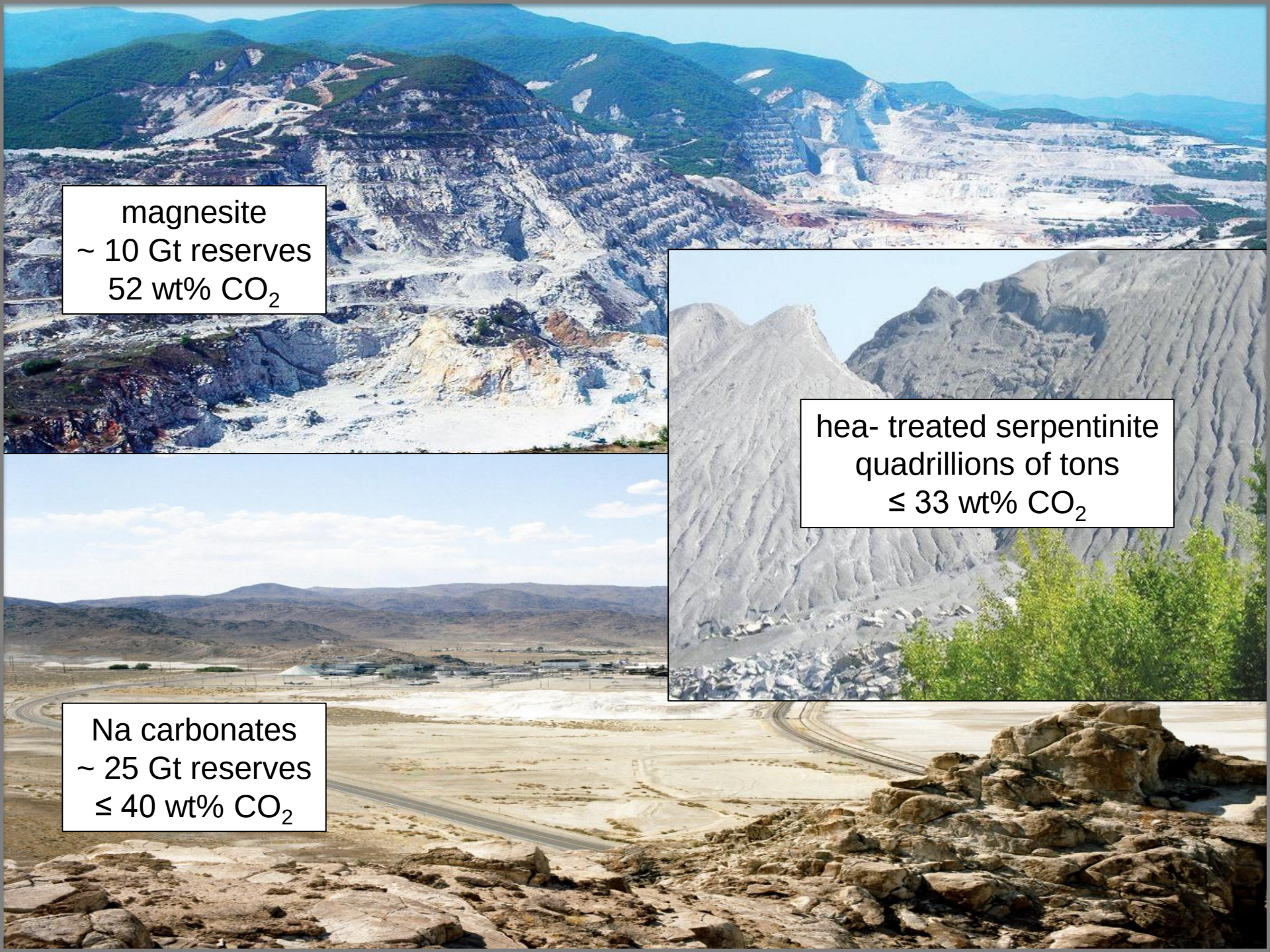
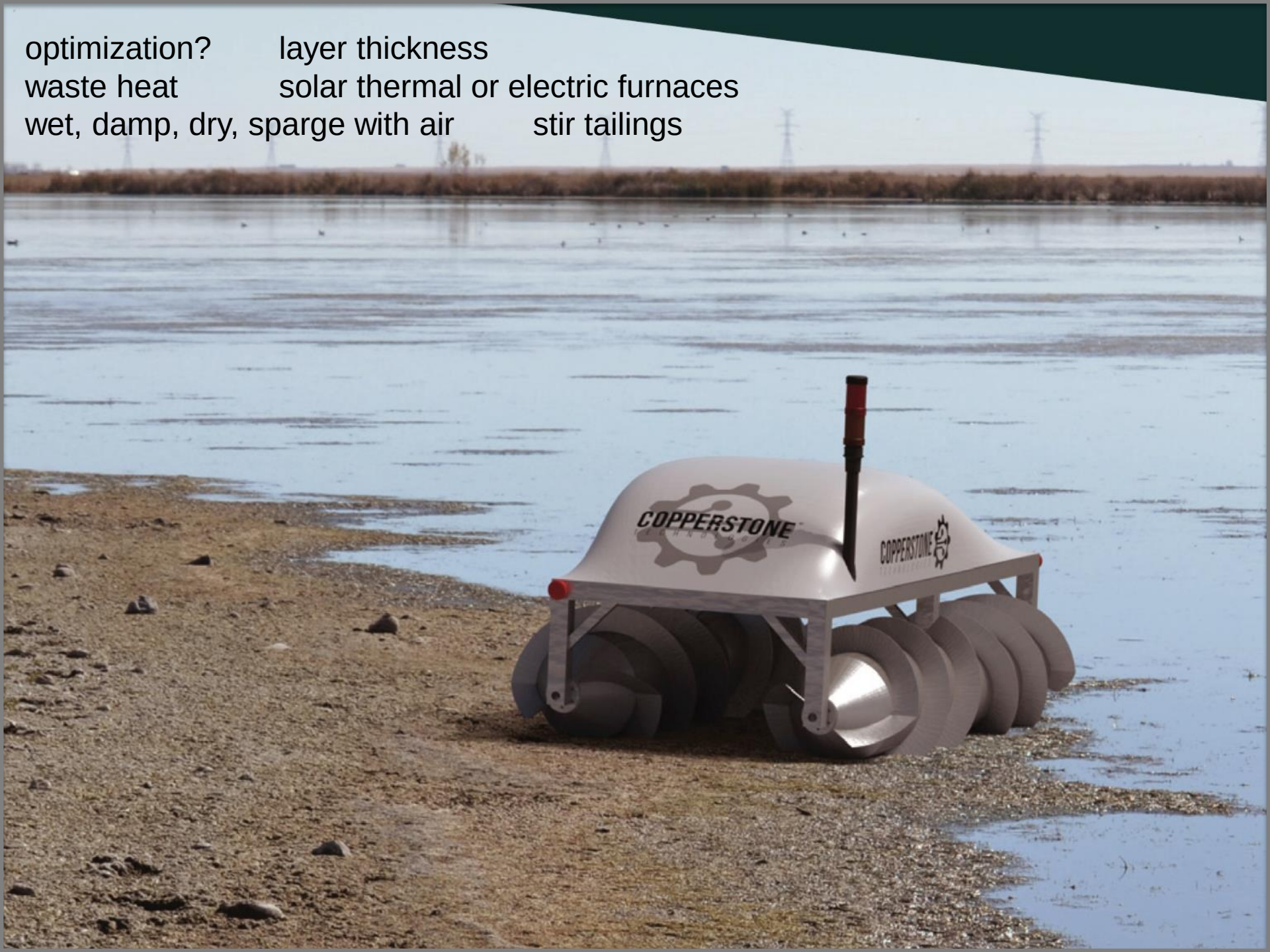

magnesite
~ 10 Gt reserves
52 wt% CO_2
hea- treated serpentinite
quadrillions of tons
≤ 33 wt% CO_2
Na carbonates
~ 25 Gt reserves
≤ 40 wt% CO_2

optimization? layer thickness
waste heat solar thermal or electric furnaces
wet, damp, dry, sparge with air stir tailings



thank you for your attention

References

- D. W. Keith, G. Holmes, D. St. Angelo, and K. Heidel, “A Process for Capturing CO_2 from the Atmosphere,” *Joule*, vol. 2, no. 8, pp. 1573–1594, 2018.
- P. B. Kelemen, N. McQueen, J. Wilcox, P. Renforth, G. Dipple, and A. Paukert Vankeuren, “Engineered Carbon Mineralization in Ultramafic Rocks for CO_2 Removal from Air with Permanent Solid Storage,” *J. Chem. Geol.*, 2019.
- N. McQueen, P. B. Kelemen, G. Dipple, P. Renforth, and J. Wilcox, “Ambient weathering of magnesium oxide for CO_2 Removal from Air (CDR),” *R. Soc. Chem.*, 2019.
- National Academy of Sciences Engineering and Medicine, “Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,” National Academies Press, Washington, D.C., Mar. 2019.
- US Patent Application 62/865,708, "Systems and Methods for Enhanced Weathering and Calcining for CO_2 Removal from Air," filed by Columbia University on June 24, 2019, including inventors Peter Kelemen (Columbia University), Noah McQueen and Jennifer Wilcox (Worcester Polytechnic Institute), Phil Renforth (Heriot-Watt University) and Greg Dipple (University of British Columbia)