

The Comings Foundation

Enhanced Weathering: Is It the Best Method of Removing CO₂ from the Atmosphere?

Table of Contents

CCS, CCUS	5
DCCS	5
What the Ideal CO ₂ removal technique should accomplish.	6
Ocean Alkalinity Enhancement (OAE)	7
Background Information	
A. Alkalinity	9
B. Acidification	10
C. DIC (Dissolved Inorganic Carbon)	12
D. Natural Weathering Stores Huge Amounts of Carbon.	13
Massive Removal of Prehistoric Atmospheric CO ₂ by Weathering	14
E. CaCO ₃ : Aragonite, Calcite, Vaterite and Ω (omega)	15
Aragonite	15
Calcite	16
Vaterite	16
Omega	16
F. RCPs (Representative Concentration Pathways)	18
G. A Short Course in Mineralogy (In Appendix A)	18
US Geological Survey of Methods of Carbon Dioxide Storage	19
<i>In situ</i> CO ₂ sequestration	19
Ophiolites in New Guinea/New Caledonia <i>in situ</i> or <i>ex situ</i>	22
Ophiolites in New Guinea	22
Ophiolites in New Caledonia	24
<i>Ex situ</i> CO ₂ sequestration	28
Enhanced Weathering using Cropland	28
Olivine	30
Effect of pH on Olivine Weathering	35
Where are Mafic and Ultramafic Deposits in the U.S.?	36
Is the supply of olivine too limited for widespread EW?	42
Where to get Commercial Olivine or Basalt	43
Norway	43
Weathering by Type of Land	44
Heavy Metals in Mafic Rocks	47
“Mining” of Nickel from Olivine	48
“Mining” Chromite from Olivine	48
Non-cropland	48
Basalt: Advantages and Disadvantages	48
Use of renewable energy	49

Waste Materials – Tailings	49
Cost estimates for Basalt	50
Silicon Enhancement of Soil	50
Cropland Abandonment and Expansion in the U.S.	50
Carbon Emissions from Cropland Expansion	52
Non-cropland in the US	52
Calcium looping (CaL)	53
Summary of CDR Methods	55
Nitrous oxide N₂O	55
Advantages of Enhanced Weathering on Cropland	58
Costs of EW	60
Soil pH	62
Reducing Emission of CO ₂ from Soil	63
Can a Carbon Capture Apparatus by Married to an Olivine Mine?	65
Use of Tailings for EW	66
Romanov et al (2015)	66
Renforth (2019)	66
Blondes et al, (2019)	67
What About Methane?	68
Removal of Methane by SCPP-PCR	68
Direct Capture of N ₂ O	69
Studies of Enhanced Weathering with Soil	70
O’Conner et al (2004)	70
Map of Ultra Mafic sites in US	71
Schuiling and Krijgsman (2006)	71
ten Berge et al (2012)	72
Renforth, (2012)	71
Moosdorf, N. et al (2014)	73
Soldal (2015)	73
Taylor et al (2016) and Tropical Weathering Hot Spots	73
Oxisols and Ultisols	77
How are Weathering Hot Spots Identified?	80
Renforth et al (2015)	80
Oelkers et al. (2018)	81
Philip, et al (2021)	82
The Basics of CO₂ and Ocean Chemistry	82
Bjerrum Plot	83
Putting Mafic and Ultramafic Rocks in the Ocean	85
Ocean Alkalinity Enhancement and Electrochemistry	86
1. Addition of Carbonate Minerals	86
2. Addition of Silicate Minerals	86
Electrochemistry	87
a. For Carbonate Rocks	87
Rau (2008)	87
b. For Silicate Rocks	88
House et al (2007)	88

Rau et al (2013)	89
Both proposals suggest that specialized boats could be built or retrofitted	91
OTEC Ocean Thermal Energy Conversion	92
Ocean Upwelling (Outgassing) of CO₂	92
Upwelling in the Equatorial Belt	93
Upwelling in the Arctic	94
Upwelling in the Antarctic – Southern Ocea	95
Upwelling in the Arabian Sea	97
c. Electrolysis-GDA (gas diffusion anode)	98
Davies et al. (2018)	98
OTEC	100
d. EW with Hydrogen Gas (H ₂) by Electrolysis vs BECC	101
An Equatorial Project	104
Protecting the Great Barrier Reef	105
Feng et al, (2016)	105
Long Term Effects of OAE	105
Gonzales and Ilyina (2016)	105
Studies of Enhanced Weathering in Oceans (Seawater)	106
Kheshgi, (1995)	106
Lackner (2002)	106
Henry (2008)	107
Hangx and Spiers (2009)	107
Kohler et al (2013); Hauck, et al, (2014)	108
Renforth and Henderson, (2017)	109
Griffioen (2017)	110
Rigopoulos et al (2017)	111
What is ball-milling?	112
Meysman and Montserrat, (2017)	114
Montserrat, et al (2017)	115
Nickel Issues	116
How much of the Problem of Removing CO₂ from the Atmosphere can be solved by Enhanced Weathering?	117
A. What are the Annual CO ₂ Emissions due to Fossil Fuels?	117
B. Estimates of the Amount of CO ₂ that could be removed by EW	118
a. Beerling et al. (2020)	118
b. Renforth (2012)	118
c) Strefler et al (2018)	119
d) Hartmann & Kempe (2008)	119
e) Moosdorf et al (2014)	119
Who can serve as advisors to answer the listed questions?	119
Negative Thinking About EW Negative Emissions Technology	119
EFI (2019)	120
Ciais, et al. (2013)	120
Editorial in Nature (2018)	120
Schuiling and Krijgsman (2006)	120

Hartmann and Kempe (2008)	120
Kohler et al (2010)	121
Kohler et al (2013)	121
Anderson and Peters, (2016)	121
Nemet et al, (2018)	121
Taylor et al, (2015)	122
These costs are enormous!!!	122
Federal involvement	123
Perhaps Not Hopeless	123
In Conclusion	124
More Realistic Comings Foundation Projects	124
1. EW in South America Hot Spots	
Research Plan for Comparing Efficacy of Weatherization in Hot Spots to US Croplands	130
2. Adding finely ground olivine to standard fertilization practices in the US	131
3. Improving the Yield of Rice Farms	132
4. Saving the Great Barrier Reef in Australia	132
5. Decrease Atmospheric Methane	132
6. Develop blueprints for ships designed to distribute ultramafic rocks in the ocean using electrolysis techniques and renewable power	132
An OAE Research Ship	133
7. The Grand Plan – World-wide Cooperation for EW	134
Questions Section	135
A. Questions about mafic rock weathering on cropland	135
B. Questions about putting mafic rocks directly into the ocean.	141
C. Questions Relating to the Grand Plan and New Caledonia	138
Appendices	139
Appendix A A Short Course in Mineralogy	139
Appendix B Conversion Factors	141
Appendix C Ophiolite Sites around the World	142
Appendix D Musk X-prize (see Appendix D on web site)	145
Appendix E Bay Engineering Inc	145
References	146-172

Enhanced Weathering: Is It the Best Method of Removing CO₂ from the Atmosphere?

All of the premier organizations dedicated to combating climate change have concluded that in addition to reducing CO₂ emissions, it will be necessary to also remove CO₂ from the atmosphere to avoid an excessive rise in the earth's temperature (NAS 2015). For example, the

2018 Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR1.5) outlined the importance of reaching net-zero emissions by 2050 in order to limit warming to 1.5 degrees. SR1.5 and the National Academies of Science (NAS) estimated that **3 to 10 billion metric tons (gigatons, or Gt) of CDR (Carbon Dioxide Removal) per year would be required globally by 2050 and up to 15 - 20 Gt per year by the end of the century.** (IPCC, 2019; NAS 2018b)

CDR is not meant to minimize the need to cut emissions. Both approaches are needed. The concepts involved are called NET's or **Negative Emission Technologies**. Various NETs have been proposed so far but only a few have developed beyond the laboratory and there is as yet little public funding (Bach et al, 2019). That is where private foundations such as the Comings Foundation, might come in. We propose to support research, development and implementation of one of these technologies – **Enhanced Weathering**.

The following review mentions many different types of minerals and mineral concepts. A **Brief Primer on Mineralogy** has been placed in **Appendix A**.

CCS, CCUS. One of the most common NET proposals is **Carbon Capture and Storage (CCS)**. This involves the capture of CO₂ produced in association with the burning of fossil fuels involved the production of electricity, especially coal-based power plants followed by the sequestration of the CO₂ into various underground storage sites. A modification of this approach is **CCUS (Carbon Capture Use and Storge)** where the captured CO₂ is put to a variety of uses and the excess sequestered. There are some major problems with these approaches. First, if the carbon capture is limited to the output of power plants that will only mitigate emissions and not reduce the total amount of CO₂ in the atmosphere. Second, is that there are serious concerns about the permanence and safety of the sequestered CO₂. Some sites may be ideal, but others may leak, resulting in the sudden release of massive amounts of CO₂ back into the atmosphere. This is reminiscent of the release of many tons of CO₂ from Lake Nyos in Cameroon in 1986 that killed 1200 people. This was possible because CO₂ is heavier than air and spreads over land like a carpet of death. In addition, it is doubtful that there are sufficient geologically suitable sites to bury the billions of tons of CO₂ produced by coal burning power plants each year.

As pointed out by Mann (2020) a common place for sequestering the CO₂ recovered from power plants is oil wells, i.e., Enhanced Oil Recovery (EOR). He stated that the recovered oil, when burned, would yield several times as much CO₂ as was sequestered in the first place. Also, this process is only about 90% effective in removing the CO₂ produced, leaving millions of tons still being released (Mann, 2020). However, see also EFI (2019) which proposed that more CO₂ can be stored in this fashion than produced by the burning the oil, resulting in carbon negative oil.

Finally, and possibly most seriously, is a study by Bartholomew and Mauter (2021). They point out that one of the major proposed sites for sequestering CO₂ is the large salt reservoirs underneath basalt domes, and here the problem is cost. The brine in these reservoirs is three times more concentrated than seawater. These brines will either need to be disposed of via deep well injection or desalinated for beneficial reuse. Pumping it underground—an approach that has been used for oil and gas industry wastewater—has been linked to increased earthquake frequency and has led to significant public backlash. But **desalinating the brines is significantly more costly and energy intensive** due, in part, to the efficiency limits of desalination technologies. It's a complex step with a potentially huge price tag.

DCCS A second major approach is **Direct Carbon Capture and Storage**. This approach is to directly remove CO₂ from the atmosphere using one of several recent technologies such as Climeworks, Carbon Engineering, Global Thermostat, Lackner, and others. This has the advantage that the source of the CO₂ is virtually unlimited and equal to the total amount in the atmosphere and not tied to power plants. However, this has some major disadvantages of its own.

First, the storage part has the same disadvantages as above, with CCS and CCUS, namely concerns about the safety and permanence of the CO₂ storage. Injection of CO₂ directly into mafic rocks (see *in situ* sequestration below) may be a way around this. Second, most of these techniques are very expensive. A review of different aspects of these techniques can be found in Ballerat-Busserolles, K et. al., (eds) (2018). Finally, both **CCS**, **CCUS** and **DCCS** have the disadvantage that they do not address three other serious problems with climate change and greenhouse gases:

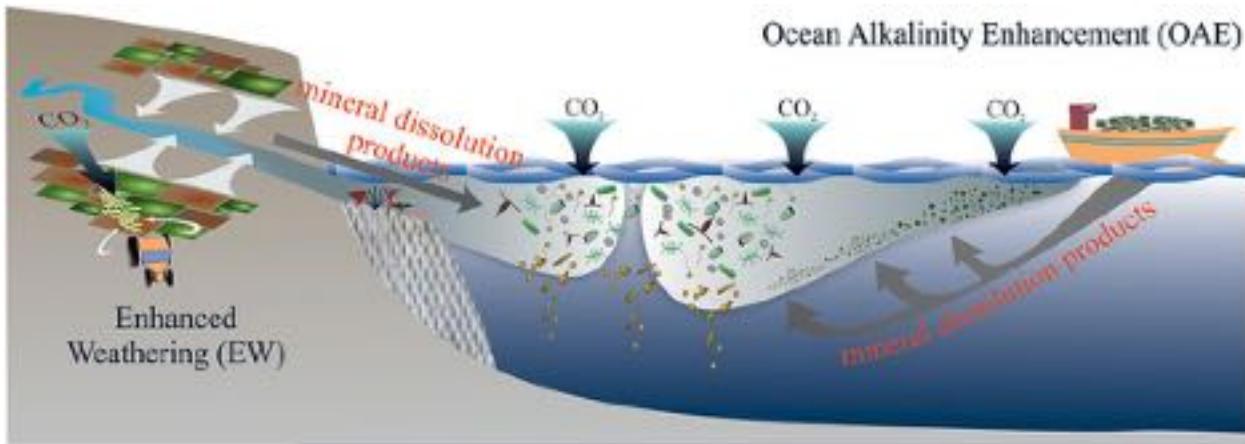
- Ocean acidification. • Atmospheric N₂O • Atmospheric Methane

What the Ideal CO₂ removal technique should accomplish.

The following are the characteristics of an ideal method of removing CO₂ from the atmosphere. It needs to:

- Solve the problem of the **permanent and safe** long-term storage of captured CO₂, i.e., for thousands or millions of years.
- Help decrease ocean acidification.
- Decrease marine production of N₂O.
- Decrease the soil production of N₂O.
- Have the potential of removing the third serious greenhouse gas – methane.
- Be relatively cheap.
- Avoid the restrictions of regulatory groups compared, for example, to ocean fertilization and SRM (solar radiation management).
- If land based it should
 - a) not compete with regular croplands.
 - b) actually, improve existing croplands.

We believe that the NET that satisfies all of these conditions is: **Enhanced Weathering (EW) using Croplands, Non-croplands, and Oceans**. Acceleration of weathering could be realized by pulverizing and distributing gigatons of Mafic and Ultramafic Mg, Ca and Fe oxides onto land (termed “**Enhanced Weathering (EW)**”) or sea (termed “**Ocean Alkalinity Enhancement (OAE)**.” The following diagram illustrates these two approaches (Bach et al, 2019).



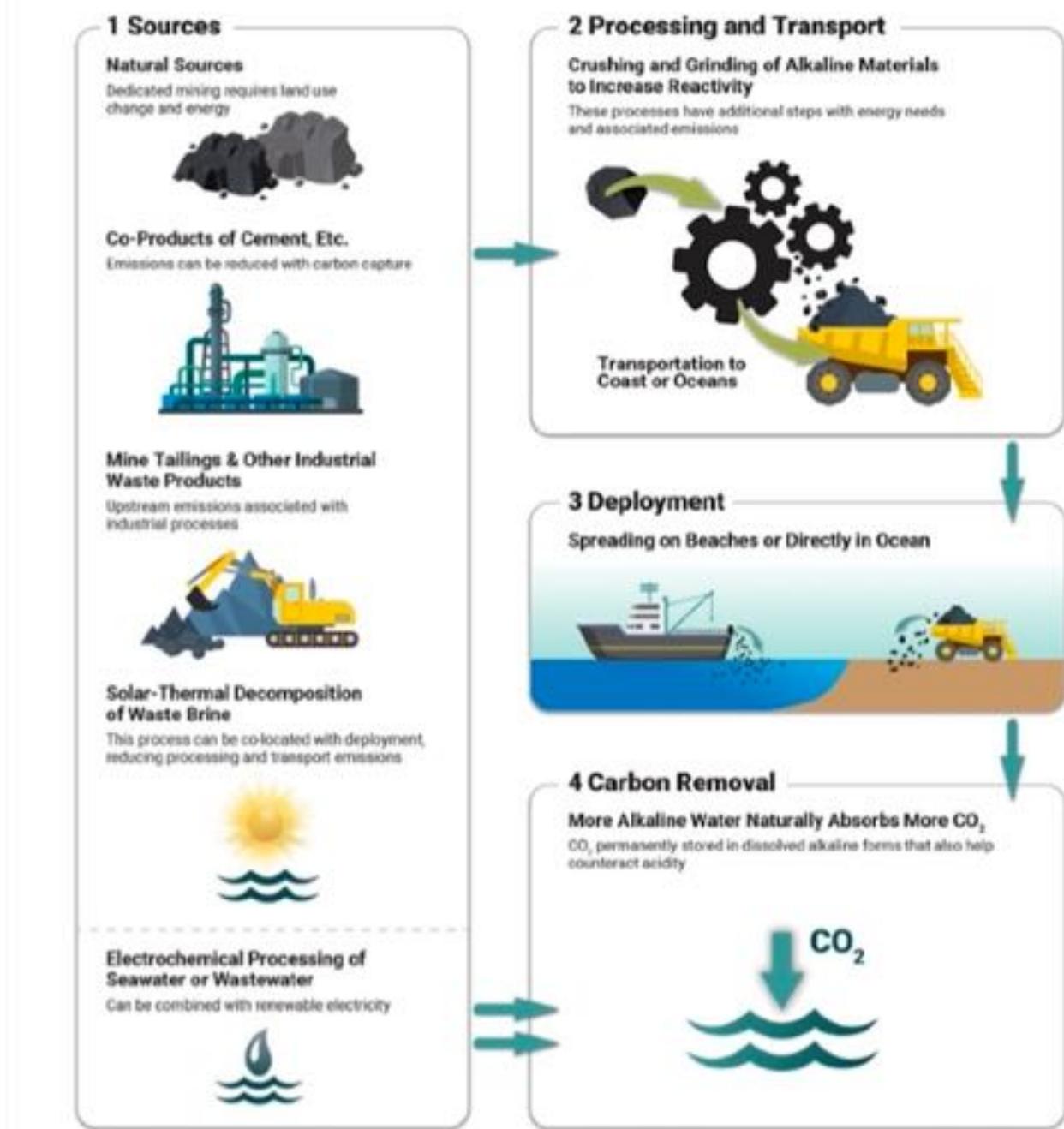
During EW, mineral dissolution products enter the ocean mostly via rivers so that perturbations first occur in estuarine and coastal regions. In the case of OAE, cargo ships could transport the minerals to coastal regions or further offshore and the distribution sites would be impacted most strongly.

Not only do we believe that Enhanced Weathering, both *in situ* and *ex situ*, is the best NET, we believe there should be an international effort in which most nations participate.

Ocean Alkalinity Enhancement (OAE)

The following diagram illustrates the details of OAE (EFI 2000b *Uncharted Waters*.)

Ocean Alkalinity Enhancement Approaches and RD&D Needs



Before progressing, we first present some **Background Information** on critical concepts. See **A through G**.

A. Alkalinity

Since the concept of alkalinity is central to many issues relevant to EW, we will explain it now in some detail. The following is from the paper by Bach et al (2019).

“Total alkalinity (TA) is a complex chemical quantity composed of several ions and molecules (Zeebe and Wolf-Gladrow, 2001). TA is defined as the excess of proton (H^+) acceptors over proton donors with respect to a certain zero level of protons (Dickson, 1981; Wolf-Gladrow et al., 2007). In terms of chemical concentrations this reads in equation

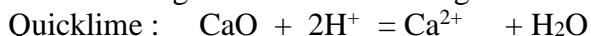
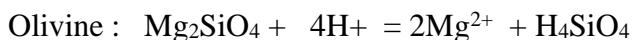
$$(1) \text{TA} = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{B(OH)}_4^-] + [\text{OH}^-] + [\text{HPO}_4^{2-}] + 2[\text{PO}_4^{3-}] \\ + [\text{H}_3\text{SiO}_4^-] + [\text{NH}_3] + [\text{HS}^-] - [\text{H}^+] - [\text{HSO}_4^-] - [\text{HF}] - [\text{H}_3\text{PO}_4]$$

H^+ is removed by OAE -> increased TA

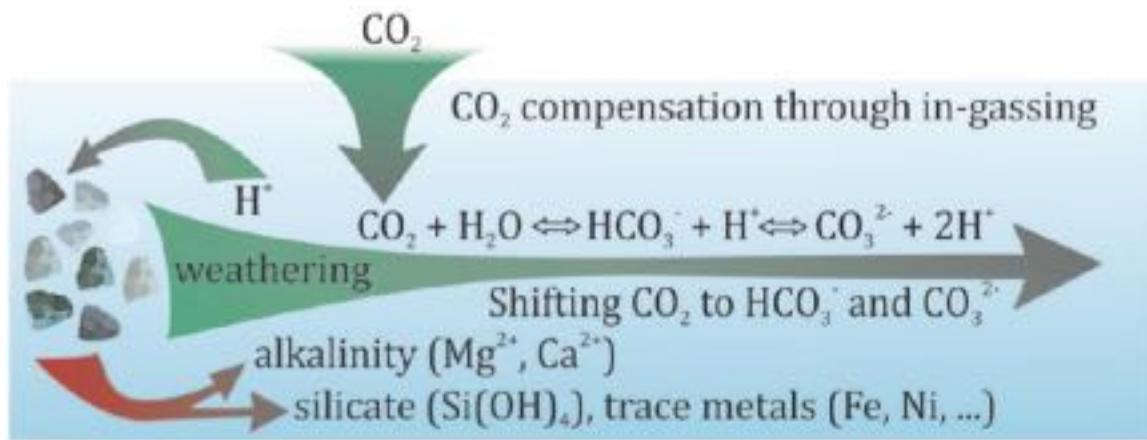
The dissolution of CO_2 in seawater and the subsequent reaction with H_2O have no effect on TA because the formation of proton donors and acceptors is balanced.



A shift of the carbonate chemistry equilibrium (Equation 2) toward HCO_3^- and CO_3^{2-} would coincide with decreasing CO_2 concentration so that additional CO_2 from the atmosphere could be absorbed and stored permanently. Such a shift toward HCO_3^- and CO_3^{2-} can be induced through the dissolution of minerals like **olivine** (Mg_2SiO_4) or **quicklime** (CaO). H^+ is consumed during the dissolution of these minerals and replaced by conservative ions with positive charges (in our cases Mg^{2+} or Ca^{2+}) (Pokrovsky and Schott, 2000; Wolf-Gladrow et al., 2007; Oelkers et al., 2018):



The positive charges from Mg^{2+} and Ca^{2+} must be balanced by negative ones due to the constraint of electroneutrality (Wolf-Gladrow et al., 2007). The law of **electroneutrality** states that in any single ionic solution a sum of negative electrical charges attracts an equal sum of positive electrical charges. This ultimately forces the shift from CO_2 to HCO_3^- and CO_3^{2-} (figure below) and is measurable as an **increase in TA which is called “ocean alkalinity enhancement or modification.”**



The above is a graphical summary of CDR through chemical weathering in aqueous media (e.g., soil pore water or seawater). When EW/OAE-relevant minerals (e.g., quicklime or olivine) dissolve **they consume protons, H^+ , which shifts the carbonate chemistry equilibrium away from CO_2 to HCO_3^- and CO_3^{2-}** . Additional CO_2 can subsequently be absorbed by the aqueous media because the shift can cause CO_2 undersaturation relative to the surrounding atmosphere. For EW/OAE it is important that the dissolution occurs as long as the aqueous media is in contact with the atmosphere (e.g., in the surface mixed layer of the ocean) so that the under-saturated medium can be replenished with atmospheric CO_2 .

The minerals appropriate for EW/OAE comprise, for example, naturally occurring Mg-rich olivine-type silicates (Mg_2SiO_4) (Schuiling and Krijgsman, 2006). These may absorb 1 Gt of CO_2 for every 1–2 Gt of olivine-rich rocks. Dissolving one mole of olivine leads to an increase in total alkalinity by 4 moles and in silicic acid (H_4SiO_4) by one mole (Köhler et al., 2013). The energy expenses are due to mining, mineral grinding, and distribution (Moosdorf et al., 2014).

B. Acidification

The cause, effects and treatment of ocean acidification were so well covered by EFI (2019) *Clearing the Air* they will be presented verbatim by presenting their Box 5-1.

Box 5-1

Ocean Acidification

The oceans currently absorb approximately a quarter of anthropogenic CO₂ emissions.¹⁷ As CO₂ dissolves in the ocean, it reacts with water to form bicarbonate ions (HCO₃⁻) and hydrogen ions (H⁺). Most of the hydrogen reacts with existing carbonate ions (CO₃²⁻) to form additional bicarbonate, but some remains, acidifying seawater. This has led to a 30 percent increase in ocean acidity since the beginning of the industrial era, faster than any acidity change in the oceans over the last 20 million years.¹⁸

The reaction between hydrogen and carbonate ions depletes the amount of carbonate that is available for marine organisms such as shellfish and coral to form calcium carbonate (CaCO₃) for shells and skeletons (Figure 5-2).^{19,20} This problem is compounded by the fact that if acidification trends continue, seawater will become corrosive to these shells by the end of the century. Increased acidification also threatens corals, and bleaching events are becoming more common.²¹ Increased ocean acidification will also have major impacts on phytoplankton, the foundation of the entire marine food web.²²

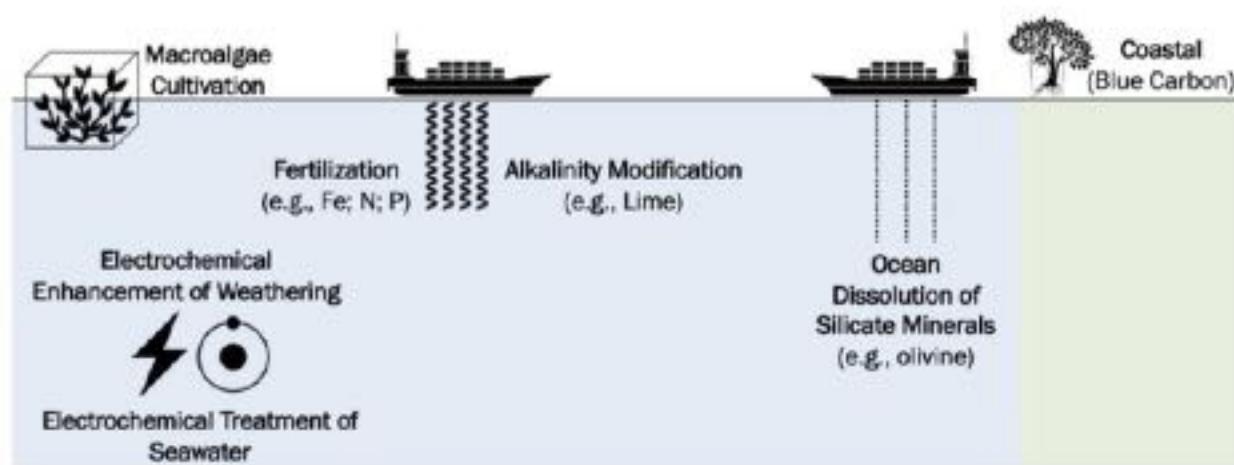
The relationship between CO₂ and ocean acidification may make it seem counterintuitive to actively store CO₂ in the oceans as a CDR technique. However, proposed CDR techniques such as ocean alkalinity modification (OAM) focus on storing carbon in the form of bicarbonate, chemically balanced by sources of alkalinity such as lime (CaO). These approaches would leave the pH of seawater unchanged or act to counter increasing acidification on a local basis. This can be an important co-benefit of these pathways in addition to their climate impact.

Some of the negative impacts of acidification are illustrated below.



Left: A healthy shell. Right: A shell affected by increased ocean acidity at pH and carbonate levels projected for the year 2100. Source: National Oceanic and Atmospheric Administration.

The following is an additional diagram of treatment options from EFI (2019) *Clearing the Air*.



Several opportunities exist to pursue CDR in coastal and deep oceans environments. Source: EFI, 2019. Compiled using data from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Graphics from Noun Project.

Some of these approaches are covered later.

C. DIC (Dissolved Inorganic Carbon)

The dissolved CO₂ can take several forms, including dissolved gaseous CO₂, carbonic acid (H₂CO₃), bicarbonate ions (HCO₃²⁻), and carbonate ions (CO₃²⁻). These are collectively known as **dissolved inorganic carbon (DIC)**, and the relative amount of each one is determined by pH (see Bjerrum Plot, p79). At normal seawater pH values, most DIC is in the form of bicarbonate ions HCO₃²⁻.

Of the three forms dissolved CO₂ (non-ionic), is about 1% of the total, which can be exchanged with the atmosphere until the partial pressure in surface water and air are equal. Bicarbonate ion (HCO₃²⁻) is about 91% and carbonate ion (CO₃²⁻) is about 8%. As atmospheric CO₂ increases, the dissolved CO₂ content of surface seawater increases at a similar rate, but most of the added CO₂ ends up as HCO₃²⁻. Meanwhile, the CO₃²⁻ content decreases, since the net effect of adding CO₂ is a reaction with CO₃²⁻ to form HCO₃²⁻ (Prentice, et al., 2001). Since this carbon is out of contact with the atmosphere, it is sequestered for the purposes of climate, and **it can remain in this form for millennia**. The net result of increasing ocean alkalinity is a decrease in atmospheric CO₂.

The uptake capacity for CO₂ also varies significantly due to additional factors, most importantly seawater **temperature, salinity and alkalinity** (the latter being a measurable quantity approximately equal to [HCO₃²⁻] + 2 × [CO₃²⁻]).

An important feature of DIC is that it is larger in the deep oceans than on the surface because of several “pumps,” including upwelling/circulation (the “**solubility pump**”), phytoplankton photosynthesis (the “**soft-tissue pump**”), and the formation of hard shells (the “**carbonate pump**”). **These pumps export carbon to the deep ocean and ocean sediments, separating it from the atmosphere for thousands of years or longer.** They also keep the concentration of CO₂ in ocean surface waters lower than it otherwise would be, leading to continued removal of CO₂ from the atmosphere.

D. Natural Weathering Stores Huge Amounts of Carbon.

Before reviewing Enhanced Weathering what about regular, natural, non-enhanced weathering? The following table shows the relative amounts of carbon stored by different natural sinks (serc.carleton.edu).

Major stores of carbon on the earth

Sink	Amount in billions of Metric tons
Atmosphere	578 (as of 1700)- 766(as of 1999)
Soil organic matter	1500 to 1600
Ocean	38,000 to 40,000
Marine sediments and sedimentary Rocks	66,000,000 to 100,000,000
Terrestrial Plants	540 to 610
Fossil Fuel Deposits	4000

This shows that massive amounts of carbon are stored for eons by natural weathering processes that involve marine sediments and sedimentary rocks. One of the most famous examples of this is the White Cliffs of Dover.



White Cliffs of Dover

The **White Cliffs** date back over **136 million years**, having been formed during the Cretaceous period in the Mesozoic era as the shells and skeletons of billions of tiny sea creatures fell to the bottom of the sea. They are composed of calcite (CaCO_3) from algae plankton called coccolithophores. When using silicates, such as olivine, the release of additional Si, Fe and Ni could benefit silicifiers and N₂-fixers such as cyanobacteria, diatoms, foraminifera and coral) and increase ocean productivity. CO₂ consumed by silicate minerals (mafic rocks) is expected to be bound for millions of years, in part, due to carbonate precipitation in the oceans (Berner and Kothavala 2001).

This shows the immense duration of time that carbon is stably stored from natural weathering processes in which products of weathering are washed into the sea and taken up by various organisms which sink to the bottom and sequester carbon for eons. Enhanced weathering is simply the use of these methods but rapidly speed up this natural weathering process.

Massive Removal of Prehistoric Atmospheric CO₂ by Weathering

An indication of the immense ability of weathering to remove CO₂ from the atmosphere can be seen in geologic history. Oceanic anoxic events (OAEs) were times of abrupt carbon-cycle perturbations, driven by increases in atmospheric CO₂ largely the result of volcanic eruptions, as evidenced by the emplacement of large igneous provinces (LIPs). The cause of oceanic hypoxia following marked increases in atmospheric CO₂ is complex (Wignall, 2015), but an increase in the metabolism of ocean organisms due to warming plays an important role.

Between 55 and 200 million years ago there were 9 OAEs (Percival et al, 2016). Sequestration of CO₂ in organic-rich black shales and by reaction with silicate rocks exposed on continents would ultimately restore climatic equilibrium but at the expense of significant

chemical change in the oceans and over time scales of tens to hundreds of thousands of years. This long duration is a reflection of the amount of CO₂ spewed into the atmosphere amounting to upwards of 2000 ppm. The fact that CO₂ levels were brought back to current levels indicates the **immense capacity of weathering to remove atmospheric CO₂** even though this took many thousands of years.

Since the current CO₂ levels are 414 ppm, a decrease in atmospheric CO₂ by weathering would not take as long. In addition, the process can be markedly accelerated by the fine grinding and dispersal of the basalt and olivine.

E. CaCO₃: Aragonite, Calcite, Vaterite and Ω (omega)

Alkalinity, above, required a special explanatory section because it is an important concept in understanding the use of EW in the oceans. The same is true of various aspects of calcium carbonate, CaCO₃.

CaCO₃ occurs in three forms: aragonite, calcite and vaterite. The shells and skeletons of many marine organisms are made from either calcite or aragonite. Aragonite is of particular interest because it is produced by many tropical corals, cold-water corals, pteropods and some mollusks. It is more soluble than calcite. **Pteropods** are a group of **planktonic** gastropods that are widely regarded as biological indicators for assessing the impacts of ocean acidification.

Aragonite is formed by biological and physical processes, including precipitation from marine and freshwater environments. The crystal lattice of aragonite is an orthorhombic crystal system. It is more soluble than calcite.



Aragonite crystals Wikipedia

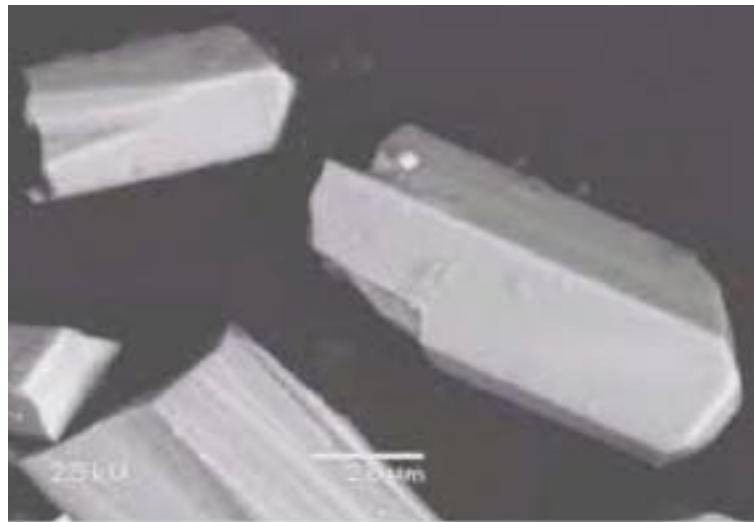
Aragonite is considered essential for the replication of reef conditions. It provides the materials necessary for much sea life and also keeps the pH of the water close to its natural level to prevent the dissolution of biogenic calcium carbonate.

Calcite the most stable polymorph of calcium carbonate. It has a trigonal crystal shape.



Calcite Wikipedia

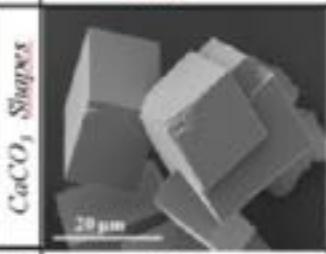
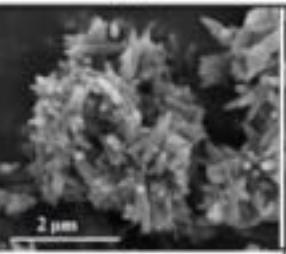
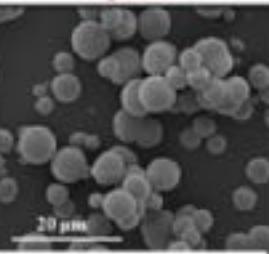
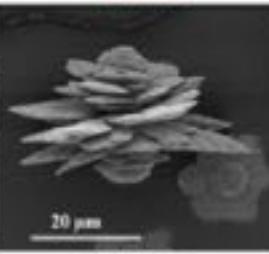
Vaterite was named after the German mineralogist Heinrich Vater. It is also known as mu-calcium carbonate ($\mu\text{-CaCO}_3$) and belongs to the hexagonal crystal system.



Vaterite Wikipedia

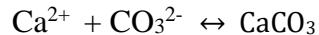
Recently, vaterite was found to have a huge potential for use as drug delivery carriers.

The following figure shows the different crystalline forms of CaCO_3 .

	Cubic	Rod	Sphere	Flower
<i>CaCO₃ Shape</i>				
A	2-20 μm	2.1-3 μm	0.2-5 μm	20-100 μm
B	Calcite (β -CaCO ₃)	Aragonite (γ -CaCO ₃)	Vaterite (μ -CaCO ₃)	Vaterite (μ -CaCO ₃)
C	Rhomboedric	Orthorhombic	Hexagonal	Hexagonal

Crystalline forms of CaCO₃ Medcraveonline.com

Omega The saturation state omega (Ω) describes the level of calcium carbonate **saturation in seawater**. The precipitation and dissolution of aragonite in seawater is shown by the following equation.



$$\Omega = [\text{Ca}^{2+}] \times [\text{CO}_3^{2-}] / [\text{CaCO}_3]$$

If the saturation state for aragonite is less than 1 ($\Omega < 1$), conditions are corrosive (undersaturated) for aragonite-based shells and skeletons and the direction of the above equation is toward the left. If the saturation state is above 1 ($\Omega > 1$), waters are supersaturated with respect to calcium carbonate and conditions are favorable for shell formation with the direction of the above equation to the right. Coral growth benefits from a saturation state of 3 ($\Omega \geq 3$). The level of Ω calcite in the world's oceans are shown in the following figure.

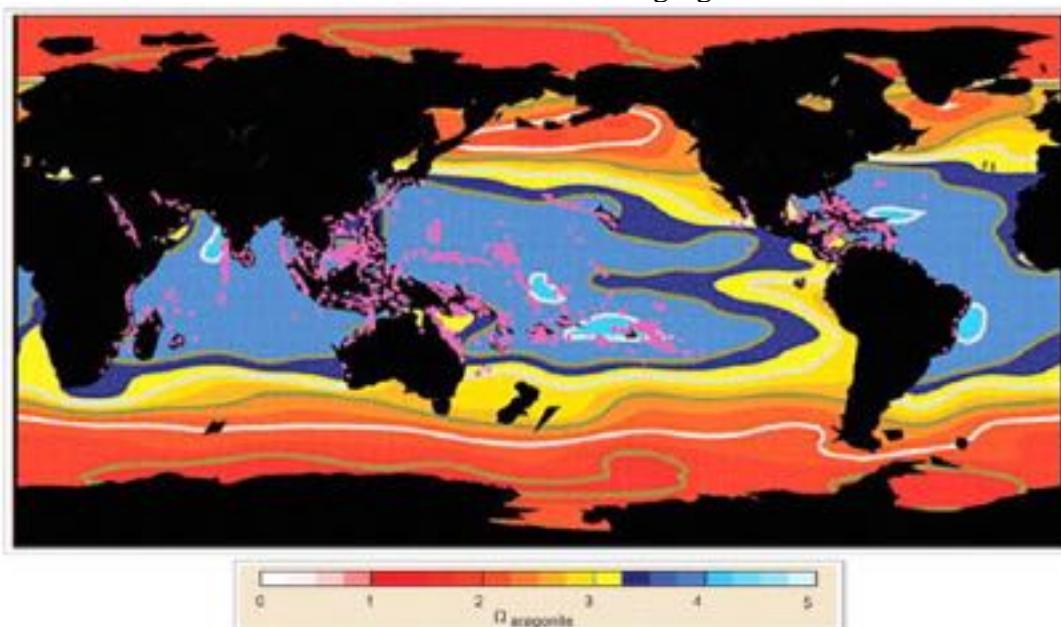


Figure adapted from Hoegh-Guldberg et al., (2007)
Coral reef locations are indicated by pink dots.

Ω values are highest at low latitudes (straddling the equator). The majority of this region has Ω around 4, with a few pockets having $\Omega > 4.0$. The waters along the western coast of South America are the only exception, having Ω values around 3.0. The locations of the pink dots representing coral reef locations are consistently found in the regions with higher Ω values. Conditions for coral reef growth are:

- $\Omega > 4.0$: optimal
- $3.5 < \Omega < 4.0$: adequate
- $3.0 < \Omega < 3.5$: marginal
- $\Omega < 3.0$: poor

A decrease in Ω calcite is occurring due to anthropogenic CO₂ emissions, contributing to the loss of coral reefs.

F. Units of Weight

Before progressing further, it is informative to know the meaning of various metric terms.

Unit	Symbol	Order of Magnitude	Amount
peta	P	10^{15}	quadtrillion
tera	T	10^{12}	trillion
giga	G	10^9	billion
mega	M	10^6	million
kilo	k	10^3	thousand
milli	m	10^{-3}	thousandth
micro	u	10^{-6}	millionth
nano	n	10^{-9}	billionth
picro	p	10^{-12}	trillionth

In general use of the term picro refers to trillionth (10^{-12}) and the use of the term giga refers to billions (10^9). The variable use of grams versus tons can also be confusing. One metric ton = one million 10^6 grams.

So, how much is a PgCO₂?

As shown below, we often see a statement like “could perhaps extract 0.5–4 PgCO₂/yr, by 2100.” It is not immediately obvious how much a PgCO₂ is. Did the P stand for pentagram (10^{15})? The table above indicates that the symbol for a pentagram is P. The definitive answer came from Canadell and Schulze (2013). They stated that:

“PgC per year (petagrams of carbon per year equals 10^{15} g equals a billion (giga) (10^9) metric tons” Finally, an author (or editor?) made this term clear.

So how much is a ton of C?

The atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44, because it includes two oxygen atoms that each weigh 16. So, to switch from one to the other, use the formula: One ton of carbon equals $44/12 = 11/3 = 3.67$ tons of carbon dioxide.

One ton of carbon (C) = 3.67 tons of carbon dioxide

G. RCPs (Representative Concentration Pathways)

Different numbered RCPs may be mentioned in the climate change literature. RCP refers to **Representative Concentration Pathways**. They represent different emissions, concentration and radiative forcing projections leading to a large range of global warming levels, from continued warming rising above 4 °C by the year 2100 to limiting warming well below 2 °C as called for in the Paris Agreement. The following table summarizes what the different numbers mean.

RCP	Forcing	Temperature	Emission Trend
1.9	1.9 W/m ²	~1.5 °C	Very Strongly Declining Emissions
2.6	2.6 W/m ²	~2.0 °C	Strongly Declining Emissions
4.5	4.5 W/m ²	~2.4 °C	Slowly Declining Emissions
6.0	6.0 W/m ²	~2.8 °C	Stabilising Emissions
8.5	8.5 W/m ²	~4.3 °C	Rising Emissions

When combined with the **Socioeconomic Pathways (SSPs)** they provide a powerful framework to explore the space of future pathways in terms of different levels of mitigation stringency and different assumptions about socioeconomic development.

G. A Short Course in Mineralogy

This is the final section of background information and is in [Appendix A](#).

End of Background Information.

US Geological Survey of Methods of Carbon Dioxide Storage

The emphasis in the present review is on the potential role of EW using cropland, non-cropland and oceans. The US Geological Survey published two important documents: USGS (2019) and Blondes et al, (2018). These documents reviewed techniques for CO₂ storage in the United States. Based on those and current literature there are five approaches.

1. CO₂ Storage: Injection of CO₂ **underneath rock formations** deep underground without mineralization. As noted above, these are potentially dangerous.

The next four types of CO₂ Mineralization **are all versions of Enhanced Weathering**.

In situ storage

2. CO₂ Mineralization: Injection of CO₂ **into rock formations** deep underground for underground *in situ* mineralization.

Ex situ storage

3. CO₂ Mineralization: Exposure of CO₂ to **broken or pulverized pieces of rock at the surface**, using leftovers from mining, called mine tailings.

4. CO₂ Mineralization: Spreading **pulverized mafic rocks onto croplands and non-croplands**. Also, ex-situ storage.

5. CO₂ Mineralization: Spreading **pulverized mafic rocks onto the beaches or ocean**.

Because of the potential danger of the escape of the CO₂ for #1, and the fact that several companies are already doing #2 (see below), our emphasis will be on #3, #4 and #5. But first we will discuss *in situ* sequestration.

In situ CO₂ sequestration

The *in-situ* sequestration of CO₂ involves injecting captured CO₂ into mafic or ultramafic rocks underground. The first large scale effort to examine *in situ* CO₂ sequestration was in Iceland by Reykjavik Energy. The experiment called **Carbfix** took place at Iceland's Hellisheiði geothermal power plant. Starting in 2012, machines separated CO₂ and hydrogen sulfide gas—natural products of the geothermal sites—from the plant's exhaust and injected them through wells 400 to 800 meters back down into the basalt. Over eight months engineers injected about 250 tons of CO₂. Monitoring at nearby wells showed that 95 percent of it was locked into carbonate minerals within two years. The project has operated ever since, storing roughly 10,000 tons of CO₂ per year. In 2019 Carbfix was spun off as an independent company with the goal of locking a billion tons of CO₂ into basalt by 2030.

Since then, another team at Pacific Northwest National Laboratory in Richland, Wash., has also mineralized CO₂ in basaltic rocks—the **Wallula Basalt Pilot Demonstration**. Mafic mantle rocks could be more potent than basalts because they contain three times as much reactive magnesium and calcium.

One of the places in the world where *in situ* sequestration is believed to have great promise is in **Oman on the Arabian Peninsula**.



A recent report provides an update on this work (Fox, 2021). Peter Kelemen a geologist at the Lamont-Doherty Earth Observatory at Columbia University and his colleagues estimate that Oman's exposed mafic rocks are absorbing 100,000 metric tons of CO₂ every year by natural mineral carbonation. How far down does this carbonation occur? Drilling cores showed that it **does not go deeper than about 100 meters**. Since Oman's mantle rocks are on average about three kilometers thick, they realized there was a huge potential for carbonation if they could reach deeper down.

The plan by Kelemen, Matter and Lackman (Kelemen & Mater, 2008; Metter and Kelemen, 2009; Lackner and Matter, 2008; Paukert, et al, 2012; Kelemen, et al.2019; Fox, 2021) was to utilize CO₂ **direct-air capture** machines, pressurize the CO₂ gas, mix it with water and send it down a borehole 1,000 to 3,000 meters deep into the surrounding mantle rocks. The water would seep through the rock's pores, eventually reaching a second hole as much as 1,000 meters away that would act as a return chimney where more gas could be concentrated in it again, for a return journey. Rock temperatures three kilometers down are about 100 degrees C. That heat would accelerate the reactions. Additional heat generated by the reactions themselves would help drive the circulation of warmed water back up the chimneys.

With sufficient increase in effort, they calculated that upwards of a **billion tons of CO₂ could sequestered per cubic kilometer of rock per year**. It is estimated there are 15,000 cubic km of relevant underground rock. There are similar outcrops in Alaska, Canada, California (Dickinson et al, (1996), New Zealand, Japan, and other places. The worldwide storage capacity

of these rocks, including Oman's, is estimated to be **able to sequester 60 trillion to 600 trillion tons of CO₂ - roughly 25 to 250 times the amount that humans have added to the atmosphere since 1850.** Compared to Oman, there are almost equally large massifs in New Caledonia and Papua New Guinea. The contiguous 48 US States contain relatively small bodies of peridotite that cumulatively have about the same mass as the Samail ophiolite (Krevor et al., 2009). One current problem with Oman is its political instability.

For this vision to materialize, it would be necessary to build an extensive, global infrastructure of machines that pull CO₂ from the atmosphere and inject it down wells drilled into mantle rock. A team of workers was scheduled to arrive in Wadi Lawayni Valley in Oman to conduct the world's first test of injecting and mineralizing CO₂ deep into mantle rock. If that experiment succeeded, it could be the first step toward transforming Oman, or even the greater Arabian Peninsula, into a major industrial center for managing the climate emergency.

Any down sides? Ballpark estimates suggest that trapping a billion tons of CO₂ in carbonate minerals could potentially increase the volume of the rock by up to a tenth of a cubic kilometer, equal to about 35 Empire State Buildings. This could conceivably cause the ground to rise by up to 30 centimeters a year. Kelemen thinks that to reckon with this issue, any gigaton-scale injection in Oman should occur near the shores of the Gulf of Oman, where engineers could drill diagonally into mantle rocks that sit below the shallow seafloor. Any bulging would probably occur on the seafloor, where it would likely be benign. And the site would obviously provide plentiful seawater to carry concentrated CO₂, important because groundwater tends to be scarce in this desert nation.

What next? An Oman-based company named 44.01 (after the average molecular weight of CO₂) has received government approval to run the world's first pilot test of mineral carbonation in mantle rocks. They will start injecting freshwater containing CO₂ and an inert tracer chemical into a borehole. Researchers would monitor the levels of tracer, CO₂ and dissolved minerals in a second borehole around 100 meters away to determine how quickly water is traveling through the intervening rock and how much CO₂ is being stripped from it. If this experiment shows that CO₂ is mineralizing quickly the company plans to begin its first commercial injection operation in 2022. It would use freshwater or possibly treated wastewater to carry 10,000 tons of the gas a year down a single well, with hopes of eventually expanding to 100,000 tons a year. The company also plans further expansion.

Advantages of *in situ* CO₂ sequestration. There are some major advantages of *in situ* hybridization.

- It avoids the cost of mining, crushing and transportation of mafic and ultramafic rocks.
- It has huge potential for sequestering massive amounts of CO₂.
- The CO₂ is safely sequestered for very long periods of time.

The **disadvantages** are that

- A variety of many machines are needed to extract CO₂ from the air and these processes are expensive, estimated at \$120 to \$220 or more per ton.
- Very large amounts of energy are required.
- It will require a massive infrastructure.
- The problem of elevation of the land over the injection sites needs to be addressed.

Since the rocks do the extraction from the air, *ex situ* CO₂ sequestration, as with enhanced weathering using crop land, non-crop land or the oceans, avoids the cost of CO₂

extraction from the air, as well as the side effect of the ground rising. However, *ex situ* in turn has the cost of mining, grinding and transportation. When using the ocean, there are two transportation costs, getting the rocks to the shipping ports, and the shipping itself. Hopefully, much of the latter can be done with renewable energy.

Since one or more private companies are already involved in *in situ* sequestration, the Comings Foundation will emphasize *ex situ* enhanced weathering.

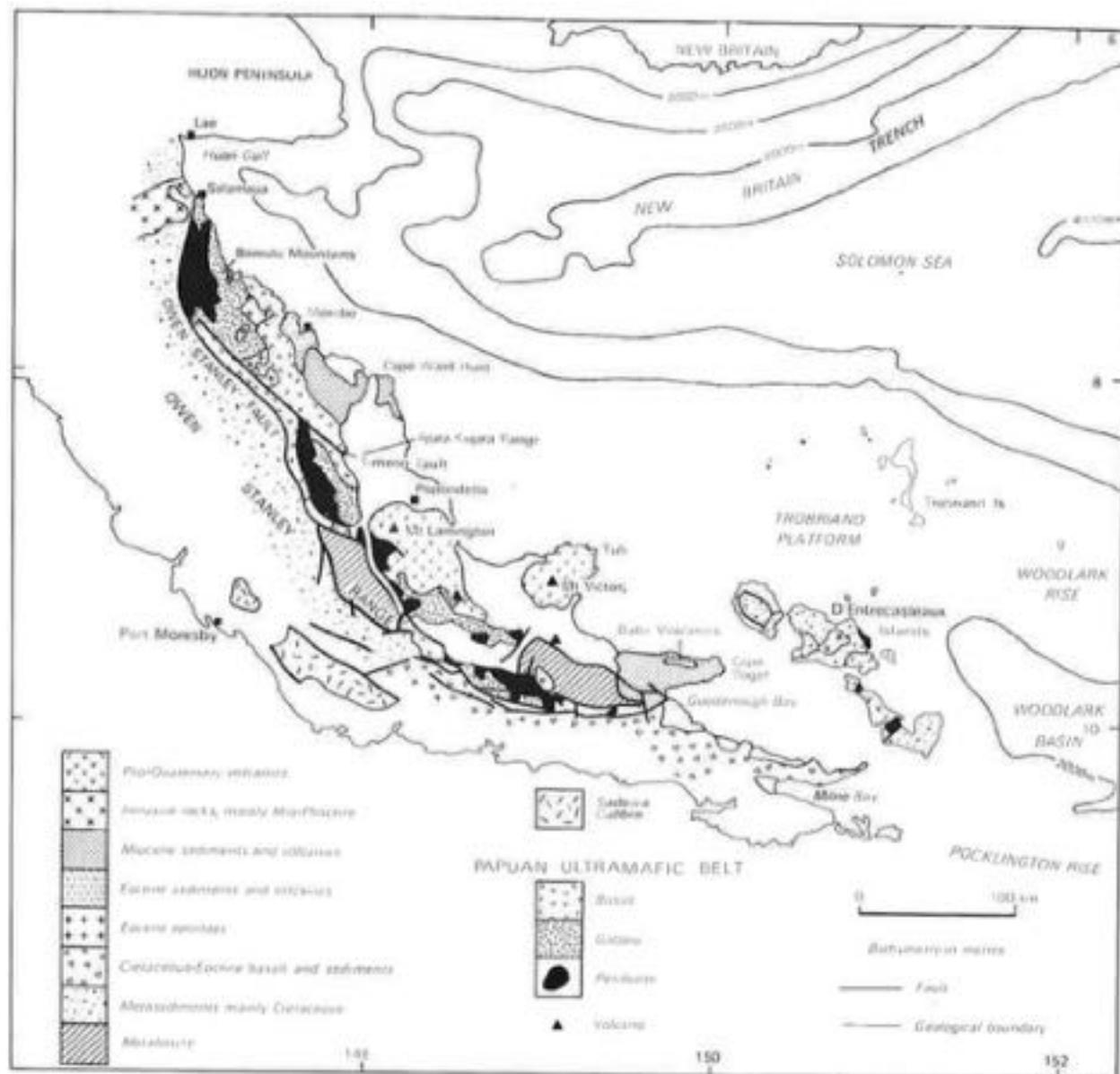
Ophiolites in New Guinea/New Caledonia - *in situ* or *ex situ*

As stated above, there are also large massifs of ultra-mafic rocks in New Caledonia and Papua New Guinea comparable to those in Oman. The following explores where these deposits are.

Ophiolites in New Guinea.

The **Papuan Ultramafic Belt** marks a well-documented collision between continental crust and a subduction system (Smith 2013). To the southeast, there is an extensive sequence of basaltic rocks known as the Milne Terrain. Geochemical data indicate that these upper Cretaceous and Eocene rocks have MORB-type (Mid-Ocean Ridge Basalt) affinities, and their most likely tectonic association is with the opening of the Coral Sea Basin. Milne Terrain rocks represent the lower plate in the obduction system along which the Papuan Ultramafic Belt was emplaced, and thus they are the structural equivalent of the continental crust which was separated from the Australian continental block by the opening of the Coral Sea.

The following map shows the location of the **Papuan Ultramafic Belt** and Milne Terrain.



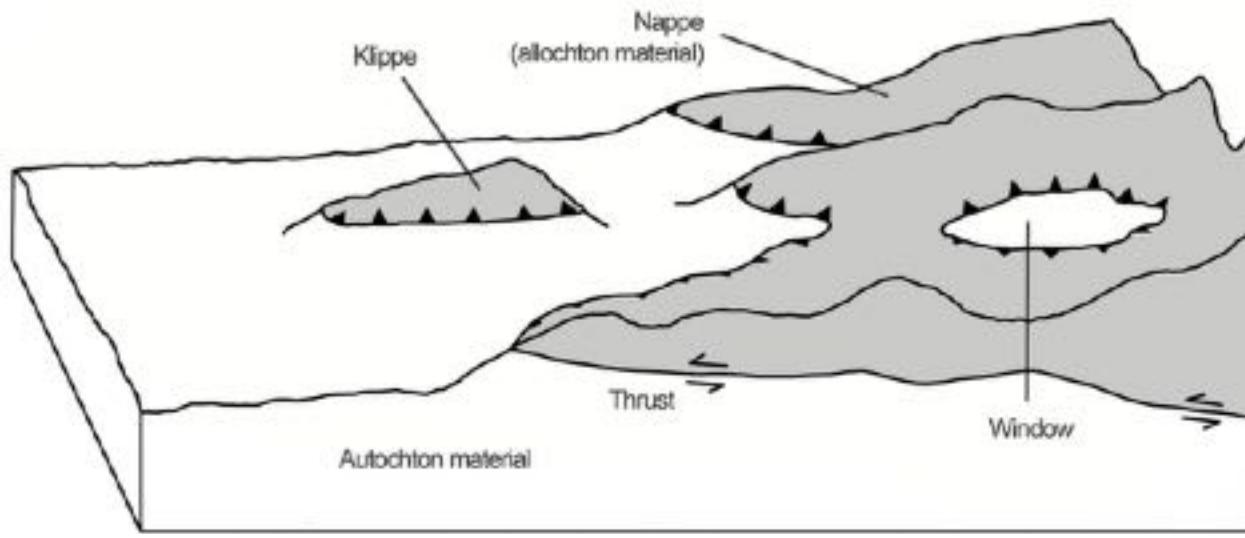
Papuan Ultramafic Belt (Davies and Jaques, 1984)

This map suggests that the northern coast of the Papuan Peninsula, near the town of Salamaus, where the ultramafic belt is closest to the ocean could a suitable site for mineable ultramafic rocks and research. The following shows this area on a relief map.

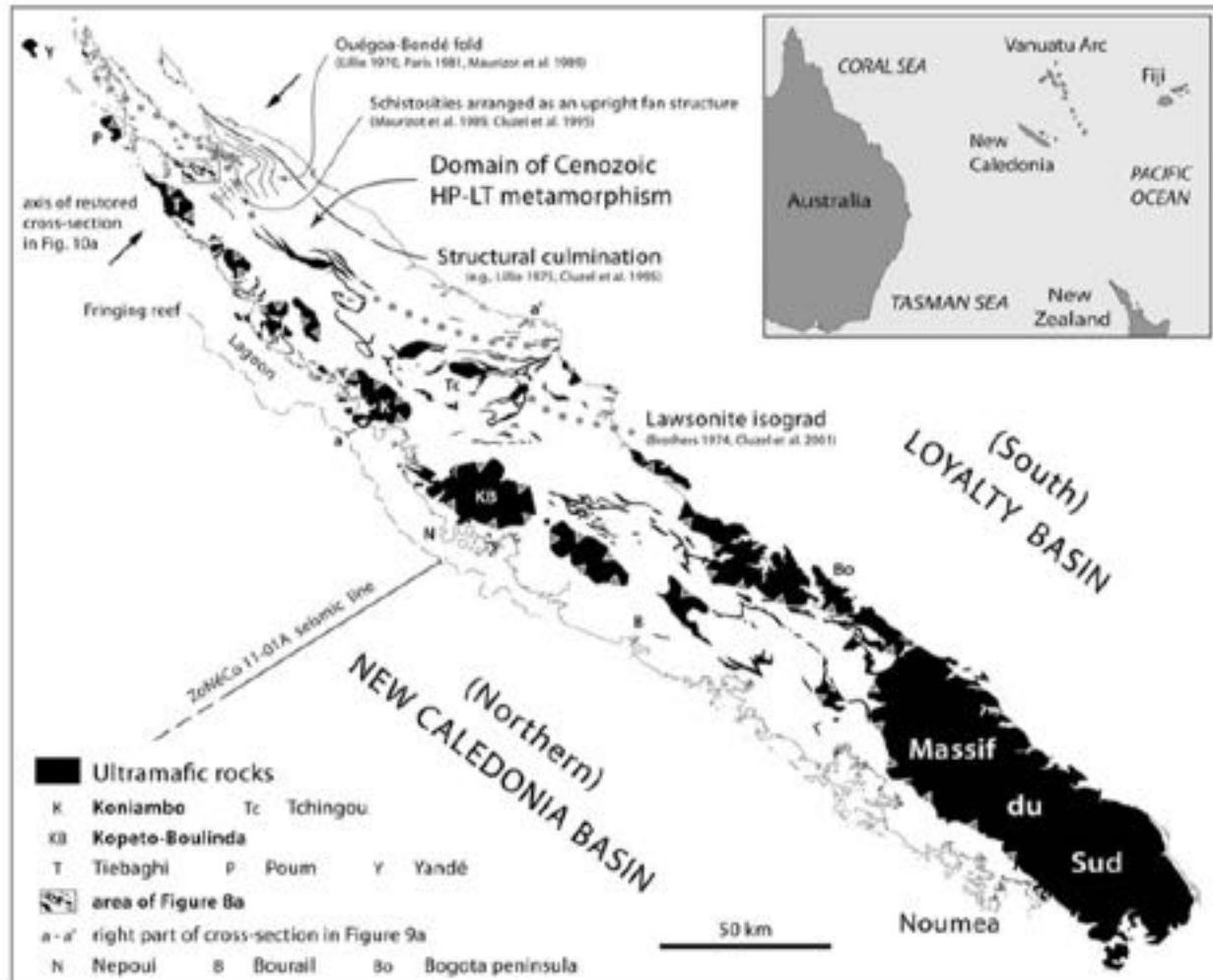


Ophiolites in New Caledonia

The **Peridotite Nappe** of New Caledonia is one of the few ophiolites worldwide that escaped collisional orogeny after obduction. (Gautier, et al 2016). **Orogeny** refers to a process in which a section of the earth's crust is folded and deformed by lateral compression to form a mountain range. **Obduction** refers to the sideways and upwards movement of the edge of a crustal plate over the margin of an adjacent plate. Gautier et al (2016) described the deformation associated with **serpentization** (see Appendix A) in two klippes of the nappe in northwestern New Caledonia. A **klippe** (German for cliff or crag) is a geological feature of thrust fault terrains. A **klippe** is the remnant portion of a nappe after erosion has removed connecting portions of the nappe. A **nappe** is a large mass of rock thrust over other rocks. The following figure illustrates these terms.



A map of the location of ultramafic rock formations in New Caledonia is shown below. The Peridotite Nappe is mainly exposed in the “Massif du Sud,” covering much of the southeastern third of the Grande Terre and in a series of klippes along the northwestern coast. In the Massif du Sud, the thickness of the nappe is **at least 1.5 km** but locally may reach 3.5 km. The nappe is mostly composed of harzburgites. In the harzburgites, compositional layering is represented by 1 to 100 m thick layers of dunite.



Structural map of the Grande Terre, New Caledonia. The distribution of ultramafic rocks is slightly modified from Maurizot and Vendé-Leclerc (2009). Most of these rocks are originally part of the **Peridotite Nappe**.

The following is a relief map of the southern part of New Caledonia.



It is a mixture of moderate hills and flat places.

New Caledonia is an archipelago located in the Pacific Ocean to the south of the Equator. It is located in the southwest Pacific Ocean, 1300 km east of Australia. The **climate is tropical**, influenced by the trade winds, with a hot and rainy season, a cool and drier season, and two intermediate periods. The hot season is humid and rainy and runs from late December to late March. The temperatures in this season are high, around 30/32 °C (86/90 °F) during the day, but with peaks of 35 °C (95 °F). The humid heat is unpleasant, although the breezes make it more bearable; rain showers and thunderstorms are frequent. Rainfall is more abundant in inland elevations and on the north-eastern coast of the main island, where it exceeds 300 millimeters (12 inches) in the wettest month (March), while on the west coast, it ranges from 200 mm (8 in) in the north to 150 mm (6 in) in the south (see Nouméa).

Multiple features make New Caledonia an almost ideal site for supply of ultramafic rocks for enhanced weathering both on land and in the ocean. It is one of the only ophiolite areas in the world that has not been converted to mountains by orogeny and thus has plenty of surface ultramafic rock. Its tropical weather is consistent with it being a weathering hot spot (see below). Large amounts of ultramafic rock could be spread on flat land of the Grande Terre region. Kelemen and associates showed that natural carbonation of ultramafic rocks extended downward for 100 meters. This suggests that ground ultramafic rocks could be layered quite deeply, given that there is adequate rainfall.

In addition to these *ex-situ* uses of ophiolites New Caledonia could also support *in-situ* use as in Oman. Alternatively, it could be an excellent site for supplying ultramafic rock to be spread in the ocean to reverse the acidification at the nearby Great Barrier Reef and the rest of the ocean. In addition, it has an excellent port - Port Noumea.

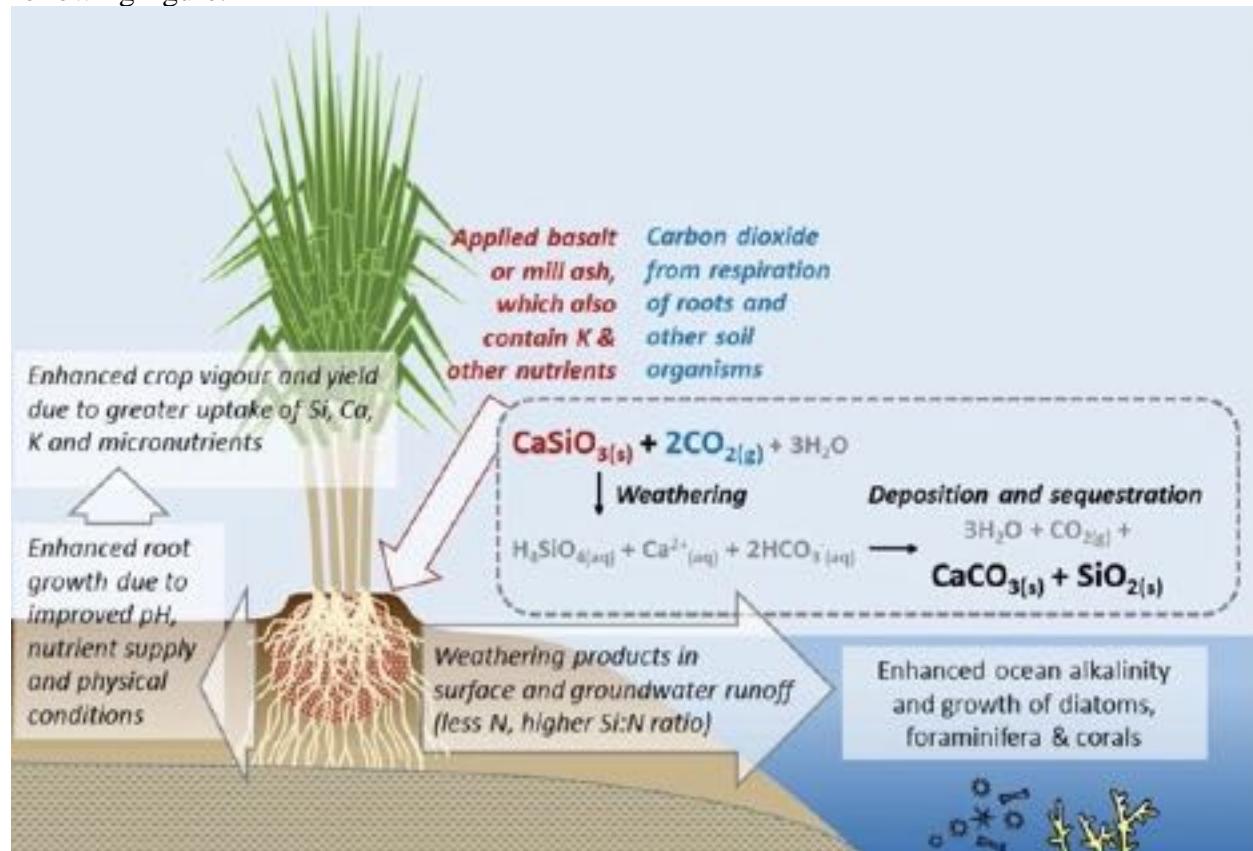
Ex situ CO₂ sequestration #3 to #5

The following review of this technology is based on the work of many scientists. A thorough review for both land and the ocean was published by Hartmann et al (2013). Several parts of this report were drawn from that report and are so credited where relevant. Other excellent reviews were EFI (2019, 2020a-c).

Before finalizing how the Comings Foundation might help, we propose to seek the assistance of number of experts in the field to answer a long list of questions we have about different aspects of Enhanced Weathering on crops, non-cropland and the oceans. These questions are listed at the end of this review in **The Questions Section**.

Enhanced Weathering using Cropland

A form of accelerated weathering that also improves cropland is an NET consisting of spreading ground-up mafic and ultramafic rocks onto farmlands. This was proposed by Beerling et al (2018) and others (Hartman, et al 2008, 2012, 2013, Schuiling & Krijgsman 2006; Kohler et al, 2010; Taylor, et al, 2016, 2017; NAS 2018, 2019). EW using cropland is outlined in the following figure.



Concept of farming with crops and rocks by Beerling et al (2018) especially using olivine.

In soils, chemical breakdown of silicate rocks is accelerated during **aqueous reactions** with the elevated soil CO₂ environment, releasing base cations (Ca⁺⁺ and Mg⁺⁺) and delivering bicarbonate (HCO₃⁻) anions via runoff to surface waters and eventually the ocean. Enhanced weathering, therefore, also uses both the oceans and soil to store atmospheric CO₂ as these stable dissolved inorganic alkaline forms. Currently the oceans worldwide store around 38,000 Pg* C (38,000 gigatons) >45 times the mass of C in the current atmosphere.

* Pg = pentagrams = 10¹⁵ grams = 10⁹ tons or one gigaton.

The residence time of dissolved inorganic carbon in the global ocean is around 100,000 to 1,000,000 years, making it essentially a permanent C-storage reservoir on human timescales. Thus, the residence time for enhanced weathering using croplands is many, many years.

There are two potential types of mineral for this use: **carbonates** and **silicates**. Silicates are best because carbonate weathering on acidic agricultural soils can lead to a net CO₂ flux to air and carbonate minerals lack silica (Si) and other plant nutrient elements. Thus, the process of carbonate weathering on land delivers fewer benefits to climate, soils and crops.

The silicate rocks are igneous, which means that they formed from cooled volcanic magma. Granite and basalt are the most common igneous rocks. Basaltic magma is what comes out when the earth's crust is cut through. As an eruption ends, the basalt "scab" heals the wound in the crust. Since it cools very quickly, the minerals have very little opportunity to grow and are very fine grained. Most of the ocean floor is basalt, and most of the continents are granite but there are continental areas (Deccan traps) where the basalt is on the surface. Carbonates have some distinct disadvantages (see below).

Ma = magnesium **fic** = ferric iron.

Mafic relates to a group of usually dark-colored minerals rich in magnesium or iron. Common mafic rocks include basalt, diabase and gabbro.

Ultramafic rocks have lower silica content (less than 45%). They are dominated by **olivine, plagioclase and pyroxene**. They are also known as **ultrabasic rocks**.

Peridotites have a high concentration of olivine and other silicate minerals.

Plagioclase is the name of a group of feldspar minerals that form a solid solution series ranging from pure albite, Na(AlSi₃O₈), to pure anorthite, Ca(Al₂Si₂O₈).

Pyroxene minerals are defined by their chemical composition and crystal structure. Their generalized chemical composition is described by the formula **XYZ₂O₆** where **X** can be Ca, Na, Fe⁺⁺, Mg, Zn, Mn or Li. **Y** can be Mg, Fe⁺⁺⁺, Cr, Al, Co, Mn, Sc, Ti or Vn. **Z** can be Si, Al or a combination of both. A wide range of cation substitutions can occur in the X and Y positions.

The following figure from Hills et al (2020) shows that many other rocks can be used.

TABLE 1 | Common minerals and their reactivity with carbon dioxide.

Mineral	Formula	Reaction pathway	Potential CO ₂ uptake (% w/w total weight)
Olivine (Festikid)	Mg ₂ SiO ₄	Mg ₂ SiO ₄ + 2H ₂ CO ₃ → 2MgCO ₃ + H ₄ SiO ₄	63
Serpentine polytype	Mg ₃ Si ₂ O ₅ (OH) ₂	Mg ₃ Si ₂ O ₅ (OH) ₂ + 3H ₂ CO ₃ → 3MgCO ₃ + 2H ₄ SiO ₄ + H ₂ O	48
Portlandite	Ca(OH) ₂	Ca(OH) ₂ + H ₂ CO ₃ → CaCO ₃ + 2H ₂ O	59
Brucite	Mg(OH) ₂	Mg(OH) ₂ + H ₂ CO ₃ → MgCO ₃ + 2H ₂ O	76
Lambe	Ca ₂ SiO ₄	Ca ₂ SiO ₄ + 2H ₂ CO ₃ → 2CaCO ₃ + H ₄ SiO ₄	67
Anorthite	CaAl ₂ Si ₂ O ₇	CaAl ₂ Si ₂ O ₇ + H ₂ CO ₃ + H ₂ O → CaCO ₃ + Al ₂ Si ₂ O ₅ (OH) ₂	16
Jennite	Ca ₂ Si ₂ O ₅ (OH) ₂ + H ₂ O	Ca ₂ Si ₂ O ₅ (OH) ₂ + 1.67H ₂ CO ₃ → 1.67CaCO ₃ + H ₄ SiO ₄ + 1.77H ₂ O	47
Rankinite	Ca ₂ Si ₂ O ₇	Ca ₂ Si ₂ O ₇ + 3H ₂ CO ₃ + H ₂ O → 3CaCO ₃ + 2H ₄ SiO ₄	38
Akermanite	Ca ₂ MgSi ₂ O ₇	Ca ₂ MgSi ₂ O ₇ + 3H ₂ CO ₃ + H ₂ O → 2CaCO ₃ + MgCO ₃ + 2H ₄ SiO ₄	48
Wollastonite	CaSiO ₃	CaSiO ₃ + H ₂ CO ₃ + H ₂ O → CaCO ₃ + Na ₂ SiO ₄	38
Tobomorrite	Ca ₂ Si ₂ O ₅ (OH) ₂ + H ₂ O	Ca ₂ Si ₂ O ₅ (OH) ₂ + 0.83H ₂ CO ₃ → 0.83CaCO ₃ + H ₄ SiO ₄ + 0.13H ₂ O	30
Pynroxene (Clcosilide)	CaMgSi ₂ O ₇	CaMgSi ₂ O ₇ + 2H ₂ CO ₃ + 2H ₂ O → CaCO ₃ + MgCO ₃ + 2H ₄ SiO ₄	41
Tromolite	Ca ₂ Mg ₂ Si ₂ O ₇ (OH) ₂	Ca ₂ Mg ₂ Si ₂ O ₇ (OH) ₂ + 7H ₂ CO ₃ + 8H ₂ O → 2CaCO ₃ + 6MgCO ₃ + 8H ₄ SiO ₄	38
Eretatite	MgSiO ₃	MgSiO ₃ + H ₂ CO ₃ + H ₂ O → MgCO ₃ + H ₄ SiO ₄	44
Laumontite	CaAl ₂ Si ₂ O ₇ · 4H ₂ O	CaAl ₂ Si ₂ O ₇ · 4H ₂ O + H ₂ CO ₃ + H ₂ O → CaCO ₃ + Al ₂ Si ₂ O ₅ (OH) ₂ + 2H ₄ SiO ₄	9

Where necessary, the reaction pathway has been normalized. Figures for % CO₂ uptake (w/w) assume the mineral reaction has been fully completed.

One ton of ultramafic rocks such as olivine, could solidify up to 500 kilograms of CO₂ compared with about 170 kilograms for a ton of basalt.

Olivine

The most common ultramafic rocks are **olivine**, **dunite**, **periodite**, and **serpentine**. Dunite is rich in olivine.

Olivine is one of the most abundant minerals on Earth, making up over 50% of the upper mantle. When magma cools, olivine typically is the first mineral to crystallize. These volcanic rocks are typically located in the upper mantle, which is around 410 km (255 miles) below the surface of the Earth, making it all but inaccessible. The good news, however, is that due to tectonic forces there are areas of the upper mantle and seafloor that have been brought to the surface in a formation known as an **ophiolite**.

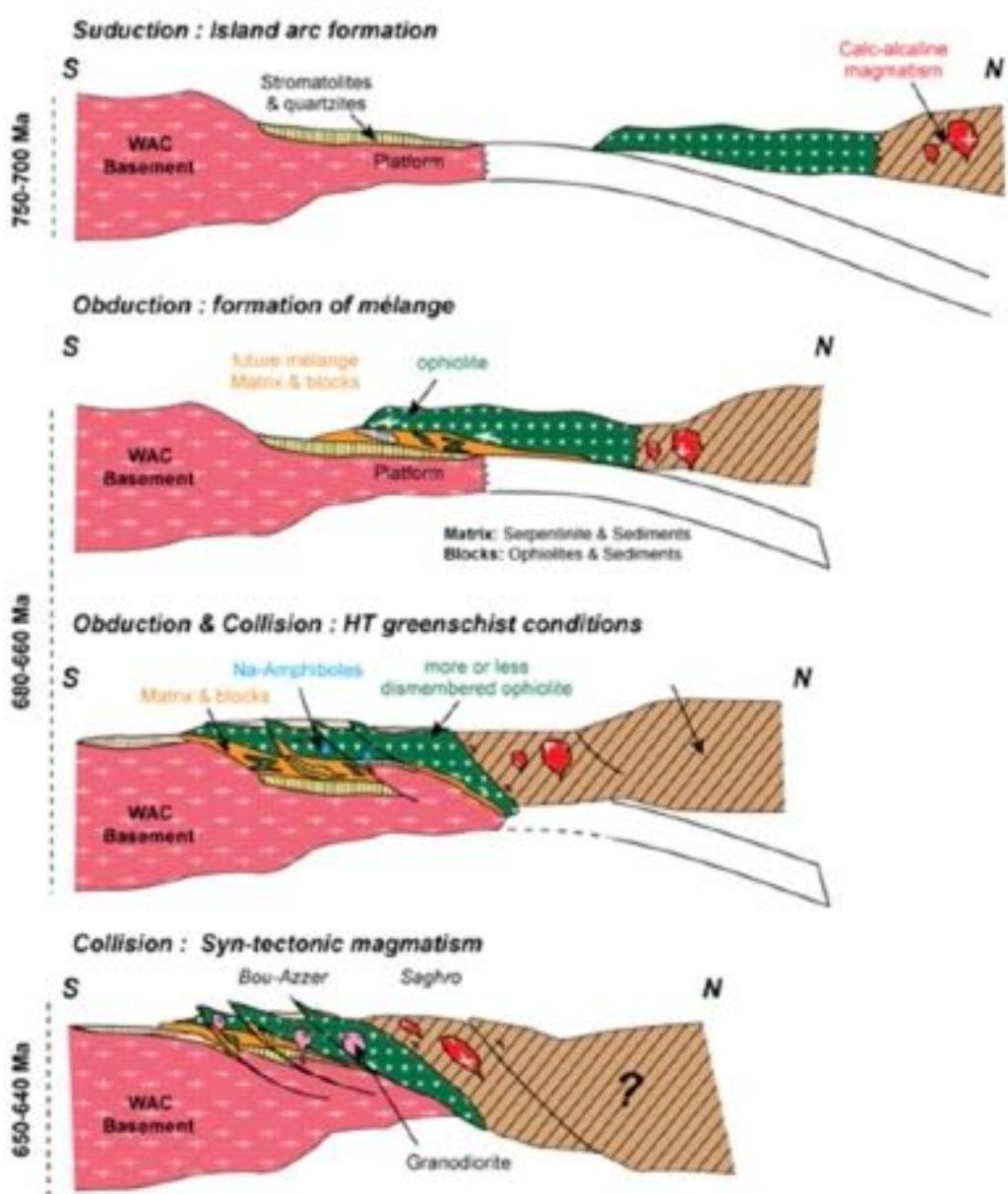
The following is a photo of my personal olivine-basalt that I purchased from a rock shop in Southern California.



The green crystalline olivine overlays a black, somewhat porous basalt.

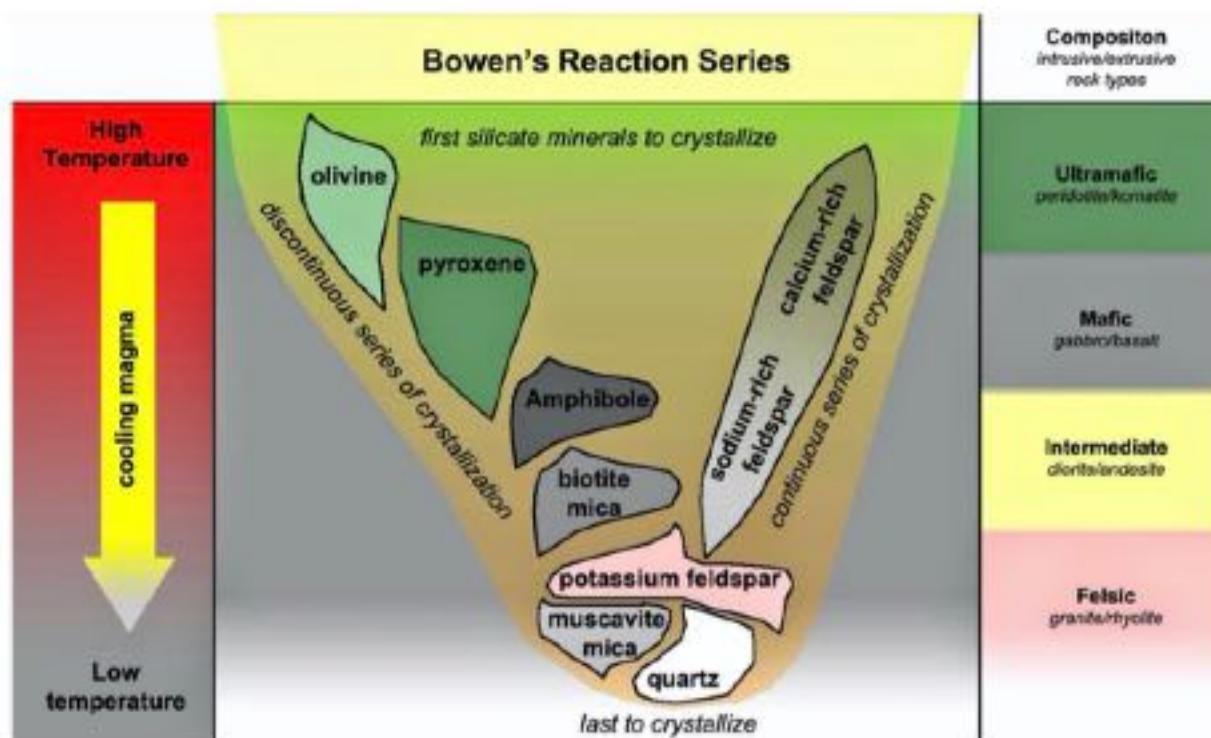
For those doing research on olivine reserves, if one searches for olivine, they will typically find only limited results. What to look for instead are the **ophiolites**. Ophiolites have an entire layer of olivine as the 90% pure form, dunite. And to further make it complicated to find olivine reserves, instead of seeing dunite listed, it is typically lumped into the category of **peridotites**. When you look at an average ophiolite, olivine and peridotite are typically found at the border between layers in the transition from the crust and the mantle, but this can vary depending on the specific formation (Project Vista).

An example of different types of **ophiolite formation** are shown in the following figure of the Bou-Azzer Inlier of the northern margin of the Western African craton during the Pan-African epic. The **ophiolite is in green**.



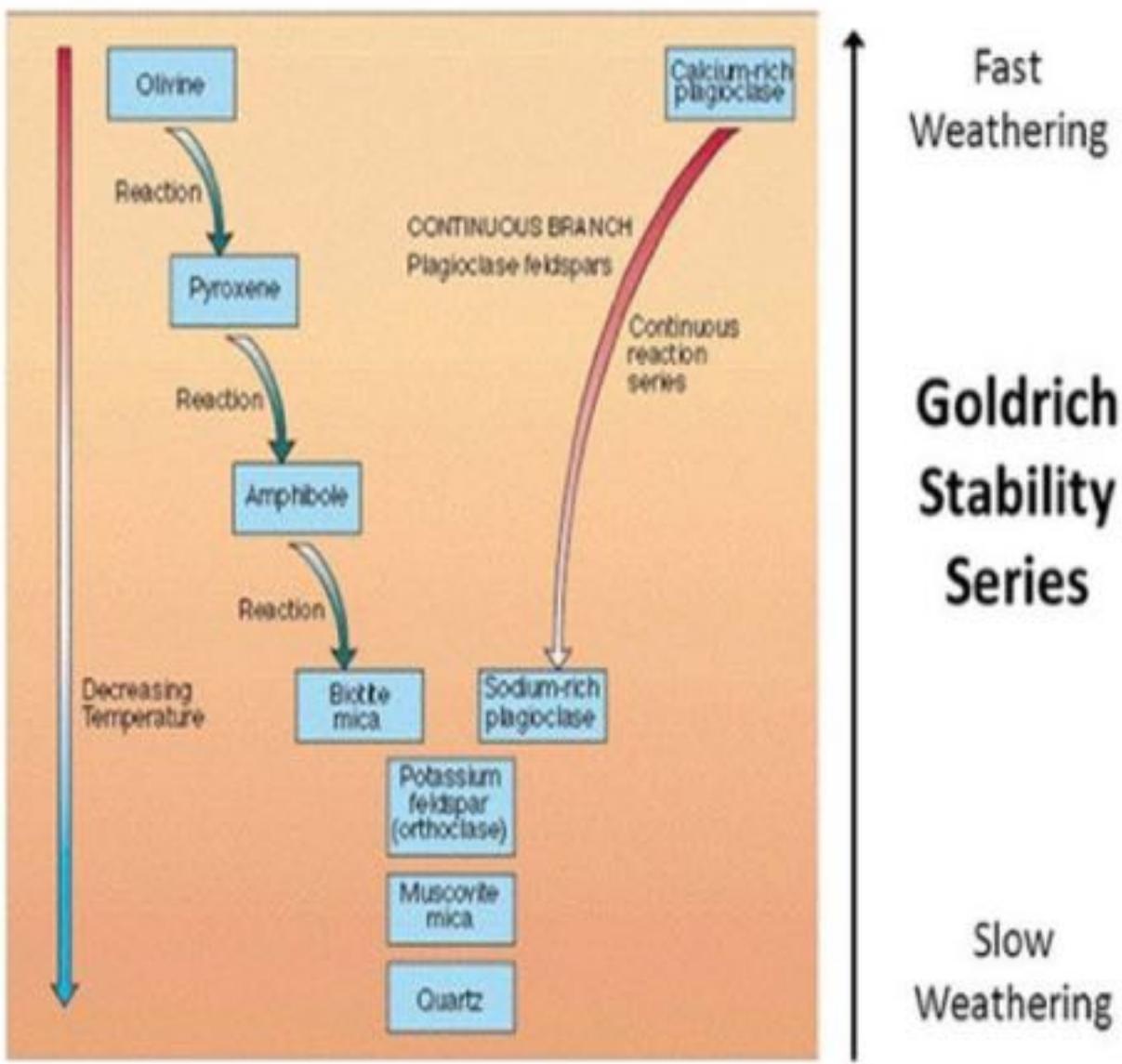
Model for the emplacement of the Bou-Azzer ophiolitic suite.

Olivine is one of the most rapidly weathering and thus CO₂ adsorbing, rocks in existence. Its chemical composition is (Mg,Fe)₂SiO₄. Sub-types are **forsterite** (Mg₂SiO₄) and **fayalite** (Fe₂SiO₄).

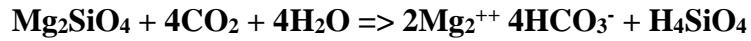


Olivine is the first to form from when magma cools, and the fastest to breakdown from weathering forces.

As shown above in green at the top of the image, olivine - dunite is the end-member of a group known as **peridotites**, which is a generic term used for coarse-grained volcanic (ultramafic) rocks that form from the cooling and crystallization of molten magma. For weathering or mineral carbonation, any of the peridotites can be used. Olivine is the best due to it being the fastest weathering silicate (see Goldrich Stability Series - below) with a ratio of **up to 1.25 tons of CO₂ removed for each 1 ton of olivine weathered**. (Project Vista)



The relevant equation for **sequestration of forsterite olivine** is:



Thus, one mole of olivine can sequester 4 moles of CO₂.

Schuiling (2013) had some interesting comments about this reaction.

"By this and similar weathering reactions throughout the history of the Earth, CO₂ was removed from the atmosphere. The resulting magnesium bicarbonate solutions are carried by rivers to the sea, where marine organisms (corals, shellfish, and plankton) convert them to carbonate rocks. This is the way by which 99.94% of all the CO₂ that has leaked out of the planet has been sustainably captured in rocks. This has saved us

from the fate of our sister planet Venus, where weathering is impossible because Venus has no liquid water. All the CO₂ that was ever emitted by Venus has stayed in the atmosphere, leading to a CO₂ pressure of 85 bars and a surface temperature of 460°C.”

Dissolved silicon is an important nutrient for diatoms, which produce a silicified cell wall, termed as frustule. Diatoms carry out a significant fraction of the net primary production taking place in the ocean (Ragueneau et al., 2000, 2010) and play a key role in the export of particulate organic matter (POM) to the deep sea. Because this export removes Si from the surface ocean, Dissolved Silicon (DSi) determines diatom production in large areas of the world ocean [Dugdale and Wilkerson, 1998].

This stimulation of diatom growth in turn means that the supply of DSi has an important influence on the marine “biological carbon pump” (Ragueneau et al., 2000, 2006; Sarmiento et al., 2007], a set of processes in which carbon incorporated into particulate organic carbon (POC) through photosynthesis may be exported from the surface ocean to the deep ocean before its oxidation back to CO₂. The carbon thus concentrated into the deep ocean is isolated from the atmosphere for the time it takes for the surface and deep ocean to mix (~1000 years, on average).

Effect of pH on Olivine Weathering

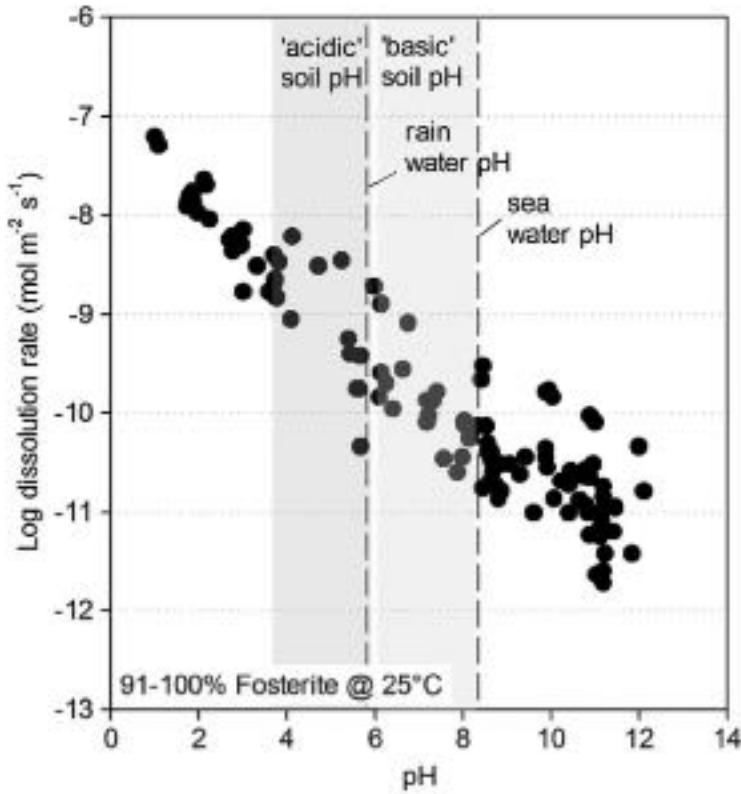
The following table shows the relative rate of weathering of olivine versus three other silicate minerals (basalt not included) at different pHs. Clearly olivine at pH 4 weathers very rapidly.

Mineral	pH 5.5	pH 4.0
Olivine	200–400	6000–8000
Pyroxene	14–25	20–200
Hornblende	26–30	100–200
Biotite	1.5–1.8	42–53

Rates of mineral dissolution (mg m²/day) obtained in the experiments of Franke & Teschner-Steinhardt (1994).

The three above non-olivine rocks can serve as approximate stand-ins for basalt. Like olivine, all three weather faster at lower pH and considerably more slowly than olivine.

The following figure shows more detail about pH and olivine weathering.

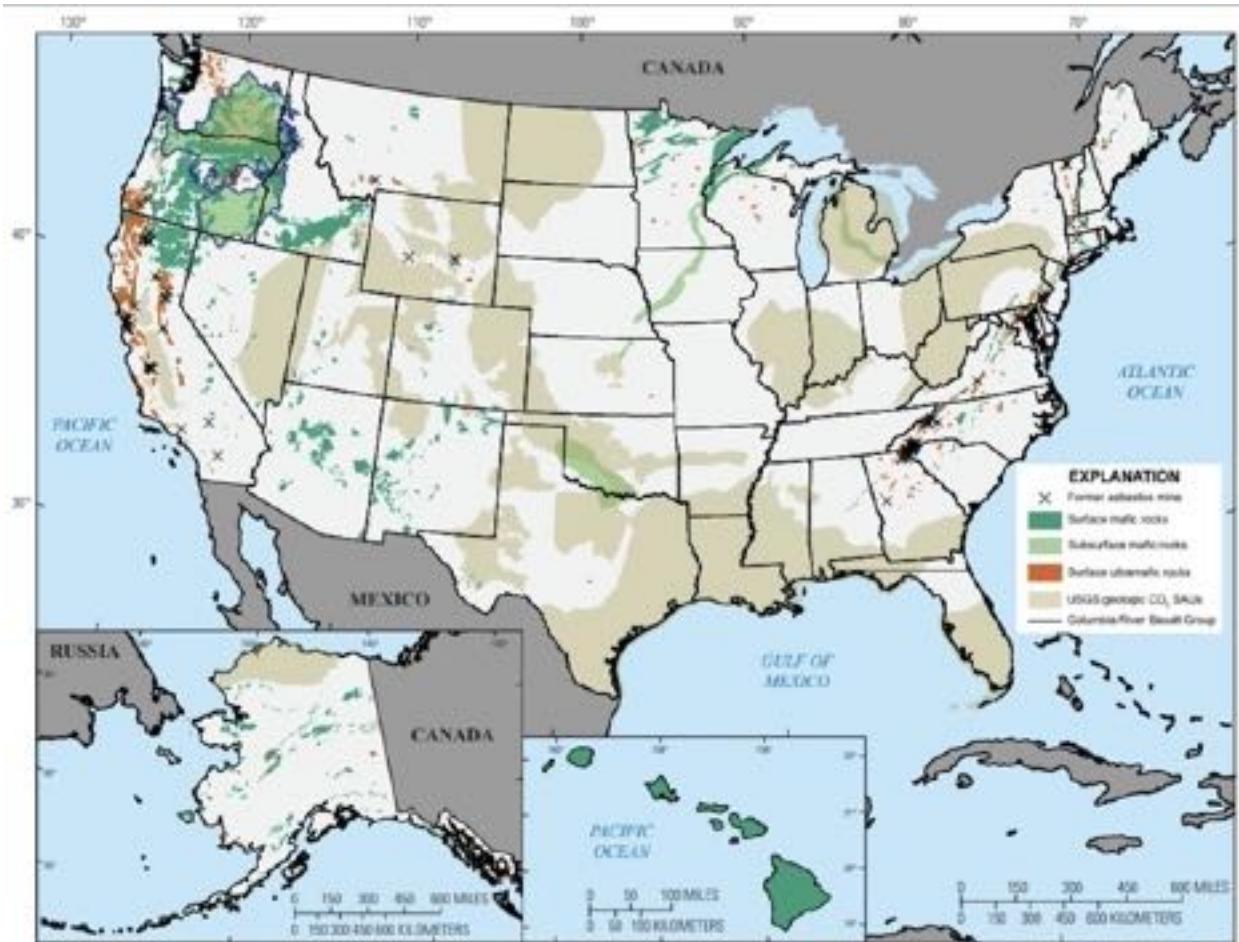


Dependence of olivine (fosterite) dissolution on pH
Figure from Hartman et al (2013)

The current average pH of ocean water is 8.1 while that of soil is 4 to 6. As can be seen, **olivine dissociates ten to one hundred times faster at the pH of soil than the pH of seawater.** Fosterite is the type of olivine that is rich in magnesium. It is the most abundant mineral in the **mantle** above a depth of about 400 km (250 mi).

Where are Mafic and Ultramafic Deposits in the U.S.?

The following USGS map shows the National map of mafic and ultramafic rocks in the United States compiled from multiple sources.



The surface mafic rocks are in dark green, the surface ultramafic rocks are in red. U.S. Geological Survey (USGS) geologic carbon dioxide (CO₂) **storage assessment units (SAUs)** (light brown) were defined in the USGS national assessment of geologic CO₂ storage resources (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013) to estimate CO₂ storage potential in saline reservoirs within sedimentary basins.

It is clear that the vast majority of the surface mafic and ultramafic rock deposits are in the Western US – Washington, Oregon and California and Hawaii. The sites in the Midwest (in light brown) are deep underground and presumably not economically viable for *ex situ* mineralization. All of Hawaii has surface deposits of mafic rocks. The following map is a clearer presentation of just the ultramafic (olivine) rocks in the U.S.

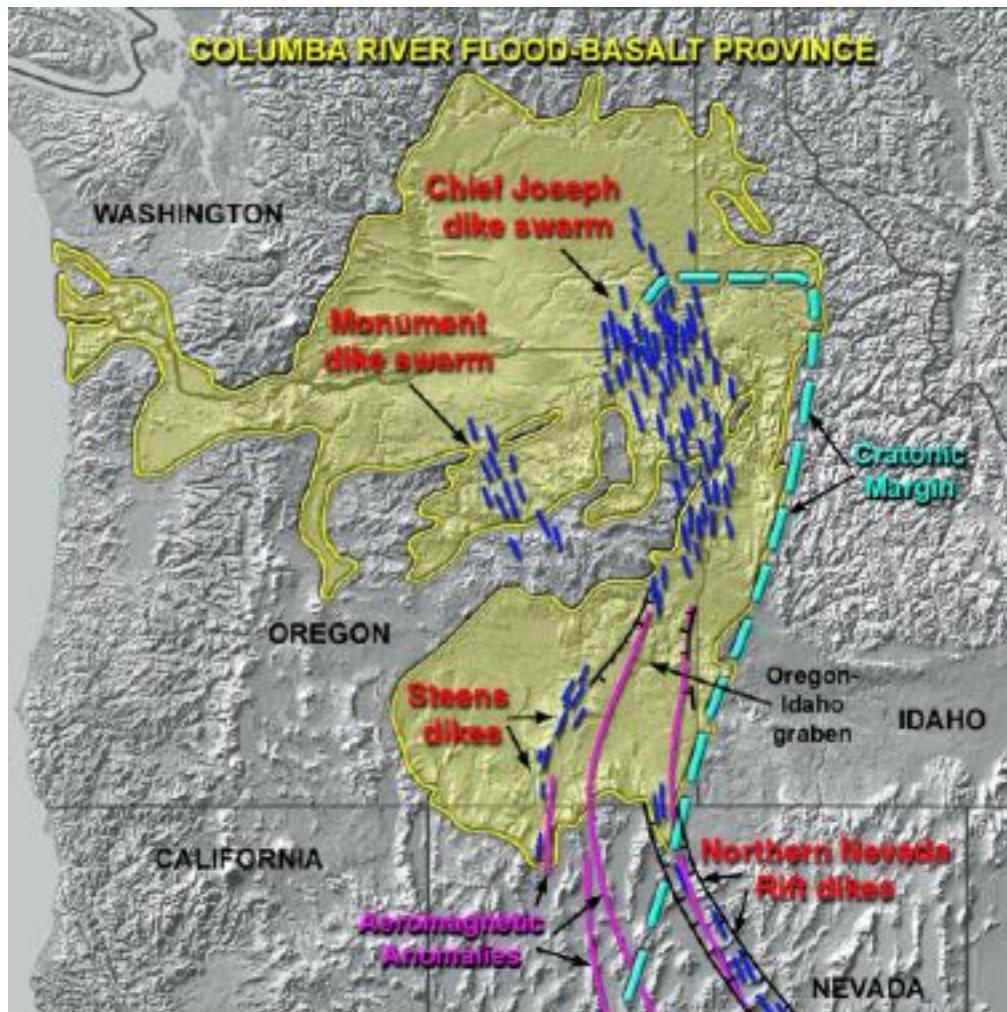


Ultramafic rock deposits in the U.S. The names of these sites are shown below.



This shows the olivine deposits on the west coast and the east coast. Goff et al (2000) and Krevor, et al (2009) describe in detail the location of deposits of olivine deposits in Vermont, Baltimore and Liberty Complexes (PA-MD-DC Region), Western North Carolina and Southwestern Puerto Rico.

The map below shows in more detail the basalt deposits in the Columbia River Basin.



Columbia River Flood Basalt

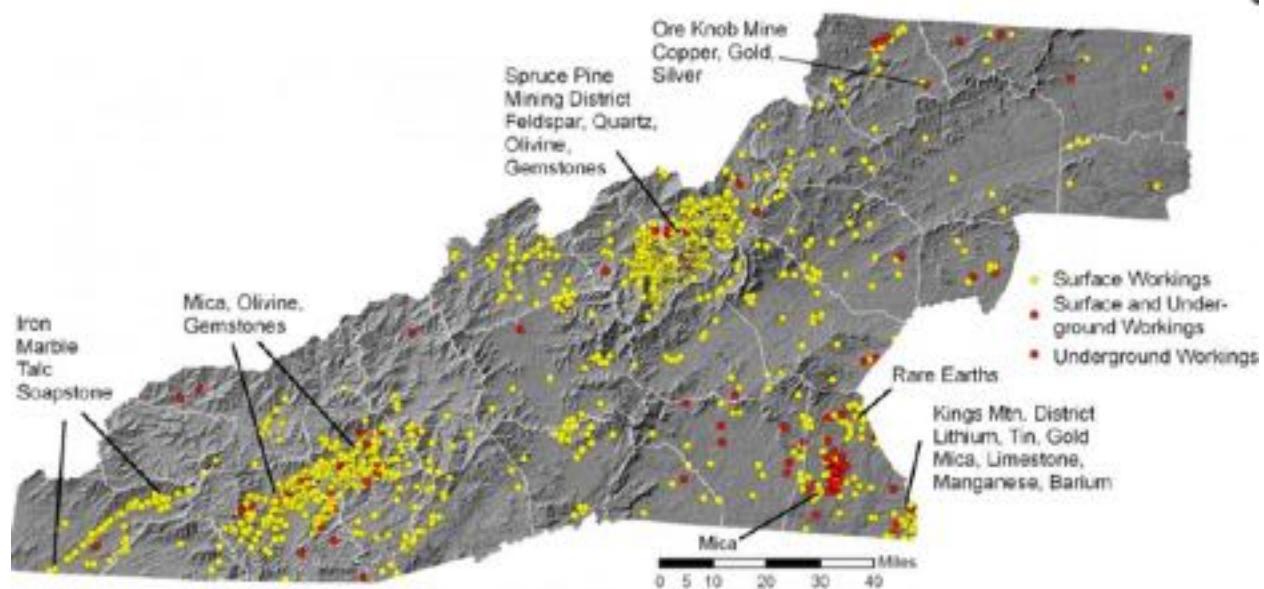
The following map shows the location of basalt deposits in the rest of the United States.



Credit: US Department of Energy/National Academies of Sciences, Engineering, and Medicine.
Map of basalt formations (red) at and near the surface of the US that would be suitable for CO₂ sequestration.

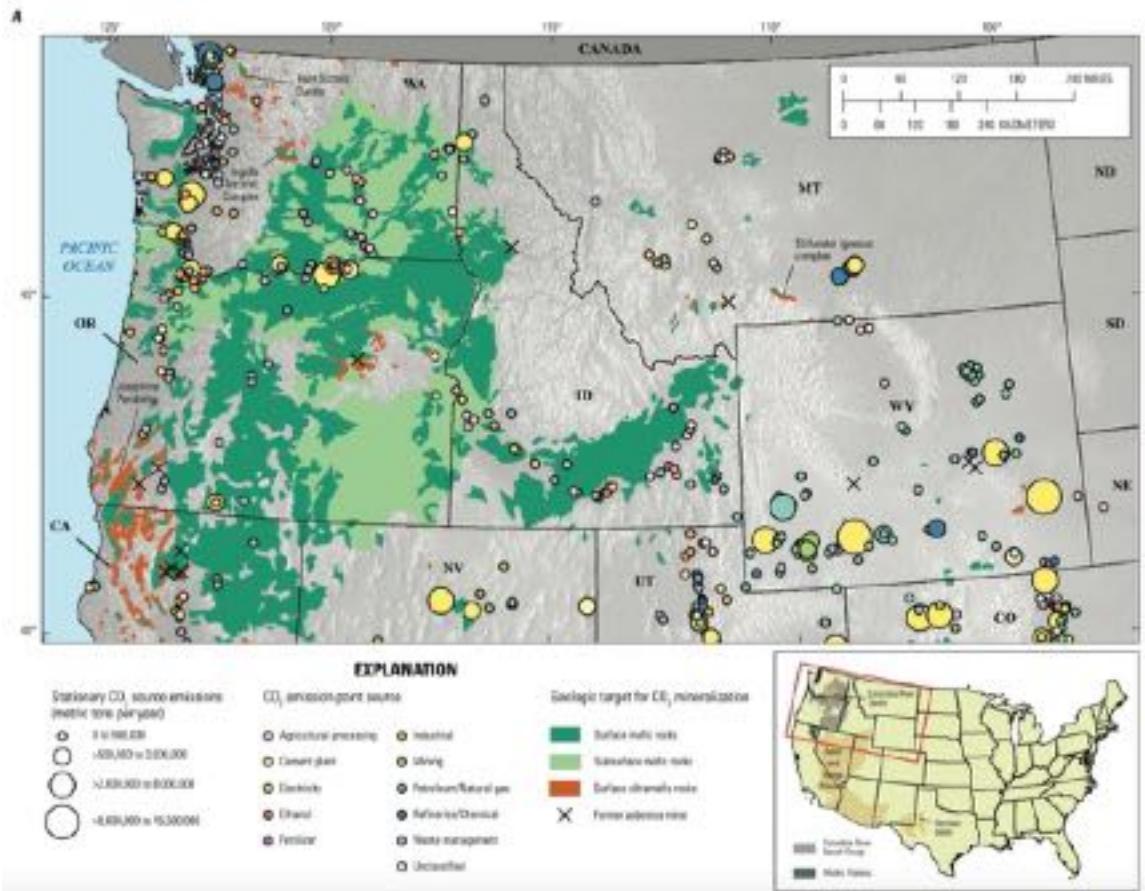
The following map shows types and location of mining in North Carolina

<http://www.wncvitalityindex.org/geology/mineral-resources>



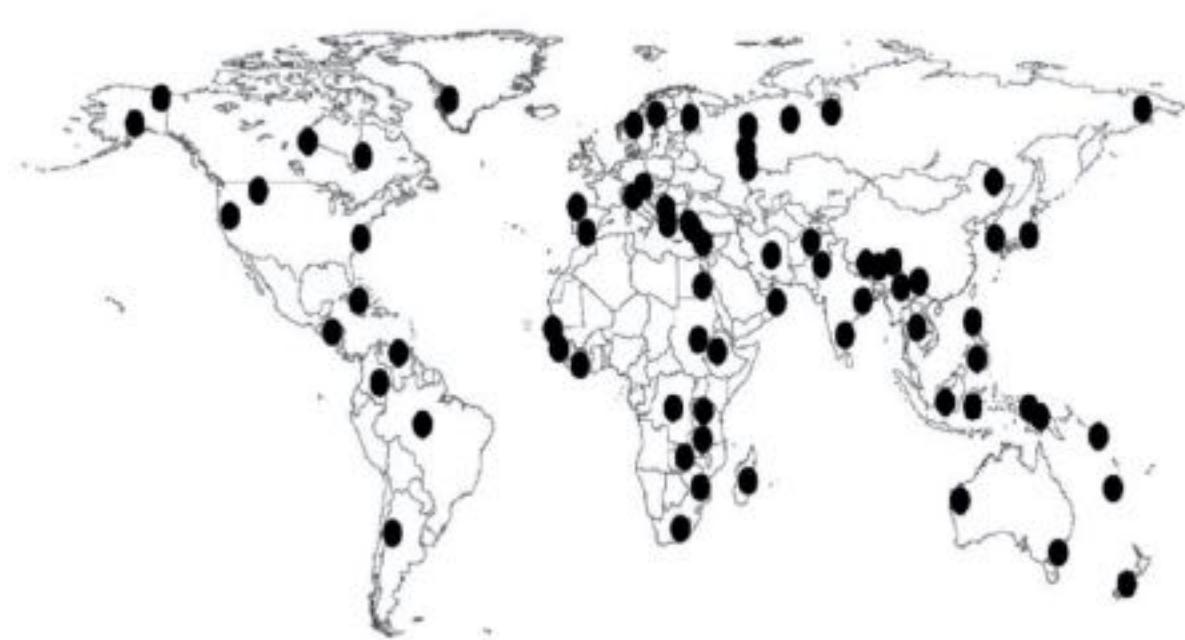
The above map shows the details of the mining sites in North Carolina.

A more detailed map of the deposits of mafic and ultramafic rocks in the Western U.S. are shown by Blondes et al (2019).



Where are the Olivine Deposits Worldwide?

The following map shows the location of olivine mines worldwide. **A detailed list of worldwide location of ophiolites is present in Appendix C Ophiolite Sites around the World** (from Wikipedia)



<https://smartstones.nl/about-olivine>

This map is highly relevant to the fact that olivine weathers more rapidly in warm, humid weather. Kramer, D.A. et al (2019) have described sources of olivine and peridotite in Europe.

Is the supply of olivine too limited for widespread EW?

A major sticking point for the use of olivine could be “How much olivine is mined worldwide each year?” Total world production of dunite, serpentinite and olivine has been estimated to be over 8 Mt a year, of which about 4 Mt a year is estimated to be ‘pure olivine’ (Rudi 2001; O’Driscoll 2004). About 3.3 Mt of olivine is consumed annually in Europe.

Other than Norway (see below) significant worldwide deposits of olivine include the Eifel Mountains of Germany; Monte Somma, Vesuvius, Italy; Mt. Briançon, Langeac, Auvergne, France; the Åheim Quarry, Møre og Romsdal, Norway; Taganana, Tenerife, Canary Islands; and Katukubura, near Kolonne, Sri Lanka.

In the U.S., the most significant and well-known deposit, which has produced excellent gem Peridot, is the San Carlos Indian Reservation, in Gila Co., Arizona. Two other important Peridot localities are Buell Park, Apache Co., Arizona; is the Kilbourne Hole, Doña Ana Co., New Mexico. The Day Book Quarry, in Burnsville, Yancey Co., North Carolina, has produced some good Olivine specimens. In Canada, large Olivine crystals come from the Parker mine, Notre-Dame-du-Laus, Québec. Of course, we are not interested in gem quality olivine, just olivine per se. The most extensive treatise on the subject is by Coleman and Irwin, (1977) - A 185-page document entitled *Ophiolites in North America*.

If we need to remove 10 billion tons of CO₂ per year, 8 Mt/year of olivine would not be enough. This could be a major reason why basalt also needs to be used. The supply of basalt is huge. However, due to low current demand for olivine relative to the proven reserves, **many dunite reserves and ophiolites are currently not being mined**. Many areas are not even fully mapped. Olivine is one of the most abundant minerals on earth. It seems clear that **a shortage of olivine should not be a limiting factor for EW**.

Where to get Commercial Olivine or Basalt

The cost of commercially mined olivine is \$50 to \$110 per short ton (1.1 metric ton), depending on grade and size (Kramer, 2020).

Olivine production, by country, (Thousand metric tons) ^(e)

	1995	1999
Norway	5,850	6,300
Japan	900	900
Spain	500	500
United States	90	90
Italy	50	50
Others	40	65
Total	7,430	7,945

The U.S. production of olivine in 1999 was 90 metric tons/yr. The production in Norway was 6,300 metric tons/yr. It was mainly used in foundries for slag conditioning and foundry sand. The two U.S. companies that produce olivine are **Unimin Corp** (North Carolina and Washington) and **Olivine Corp** (Washington). The reserves in the **Smokey Mountains, North Carolina** are about **200,000 million metric tons**, while the reserves in **Washington** are about 17 million metric tons. The total world production of olivine was approximately **8 million metric tons in 1999**. **North Carolina is the nation's major olivine producer, with mines in Jackson, Mitchell, and Yancey Counties** (Seaman, 2006) (see maps above).

Unimin Corporation is a wholly owned subsidiary of global industrial minerals company SCR-Sibelco of Belgium. **Unimin** operates 44 mining and mineral processing facilities in the United States, Mexico and Canada. In Mexico, the **Company** operates as Grupo Materias Primas de México and in Canada as **Unimin Canada Ltd/Ltee**. An additional large olivine site is **Twin Peaks, OR** (Lackner, 2002).

Norway

Norway is the main source of olivine in Europe, particularly in an area stretching from Åheim to Tafjord, and from Hornindal to Flemsøy in the Sunnmøre district. There is also olivine in Eid municipality. **About 50% of the world's olivine for industrial use is produced in Norway**. At Svarthammaren in Norddal olivine was mined from around 1920 to 1979, with a daily output up to 600 metric tons. At Robbervika in Norddal municipality an open-pit mine has been in operation since 1984.

The table above (Kramer, 2020) showed that Norway is by far the greatest commercial producer of olivine at 6,300 thousand metric tons per year versus 90 thousand metric tons for the US.



The above shows the world's largest active olivine quarry, **Gusdal Pit, in Norway**. No chemicals are needed to extract the rock, nothing is underground, the process is not mining, it is surface extraction. This raises the possibility of purchasing olivine on site, ensuring it is finely ground, and immediately distributing it in the ocean.

In a study of the financial and carbon costs of enhanced weathering using ultramafic rocks such as dunite, Moosdorf et al (2014) concluded that terrestrial enhanced weathering consumes more CO₂ than it emits for mining, crushing, grinding, transport, and application in most locations. On average, 0.5-1.0 ton of CO₂ is sequestered per ton of rock.

They also stated that very large amounts of rock would be needed to control or reduce the atmospheric CO₂ concentrations substantially with enhanced weathering. Before enhanced weathering could be applied at large scales, more research is needed to assess weathering rates, potential side effects, social acceptability, and mechanisms of governance.

Strefler et al (2018) showed that enhanced weathering is an option for carbon dioxide removal that could be competitive at 60 US \$/t CO₂ removed for dunite, but only at 200 US \$/t CO₂ removed for basalt. The potential carbon removal on cropland areas could be as large as **95 Gt CO₂/yr with dunite and 4.9 Gt CO₂/yr with basalt**.

Weathering by Type of Land

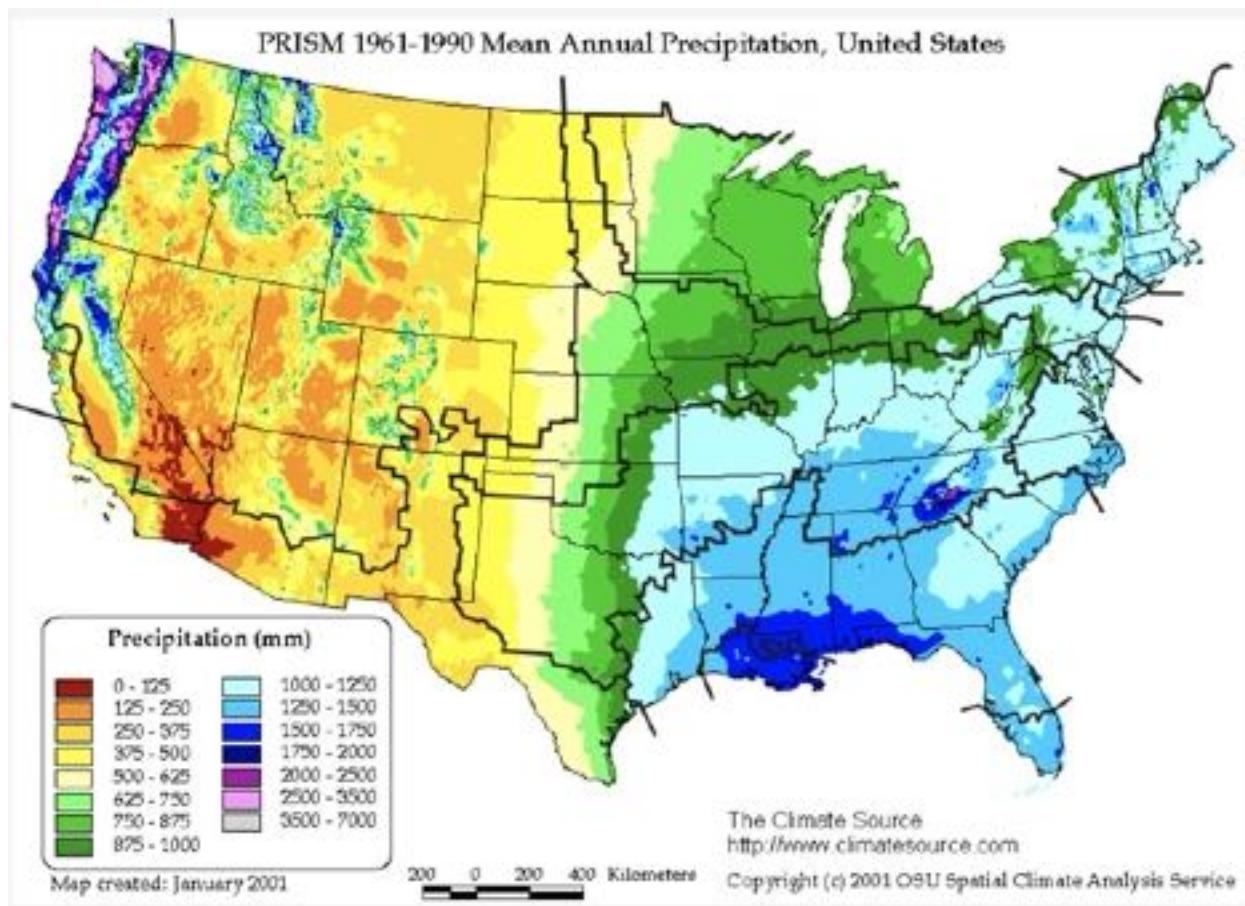
Weathering takes place faster in tropical and sub-tropical regions. But by how much? The following Table 3 is taken from Hartman and Kempe (2008) based on studies by Ludwig (1998).

Table 3 Summary of considered mineral fertilization experiments.
Average CO₂-consumption per climate

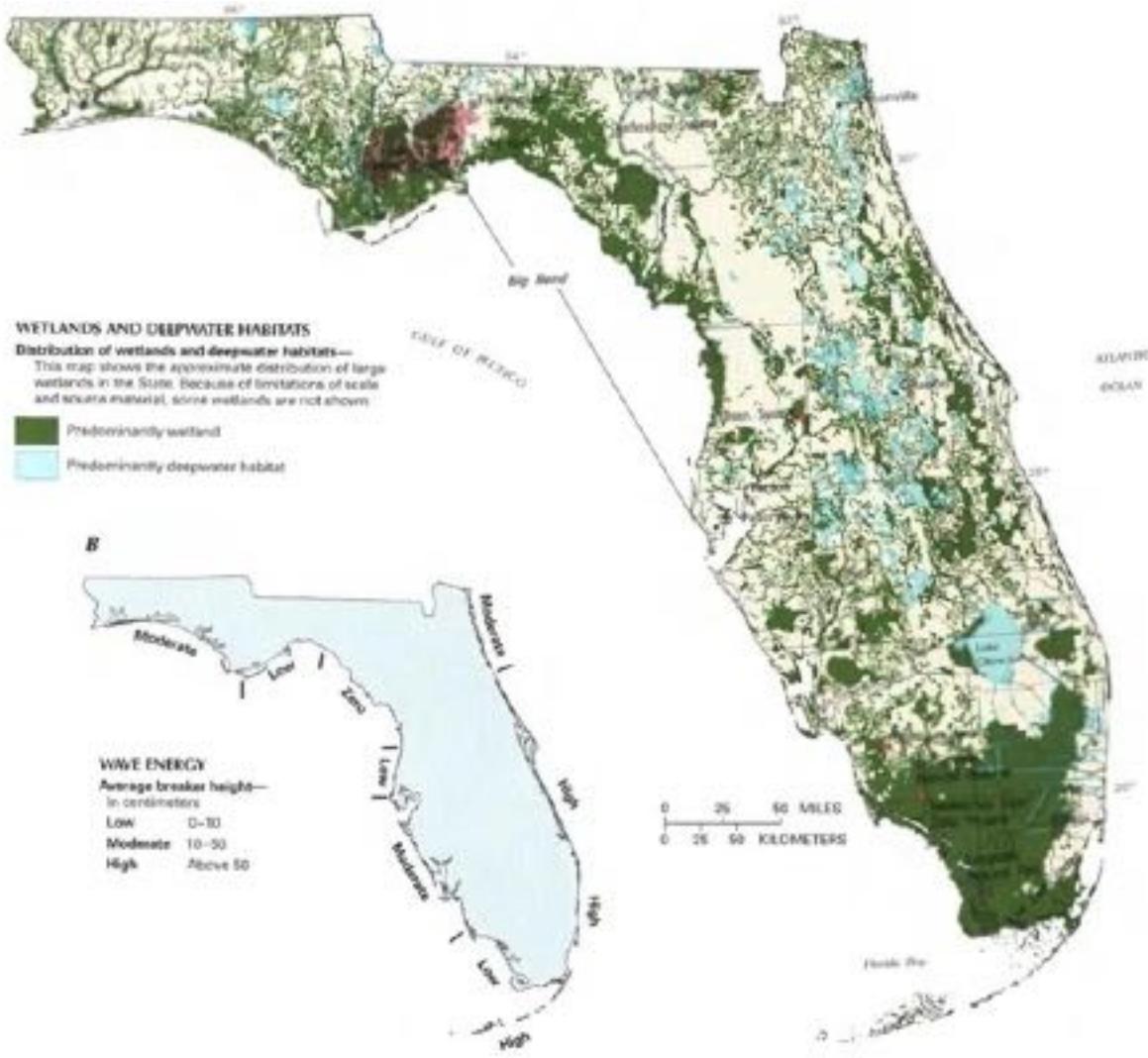
	Area 10 ³ km ²	CO ₂ consumed 10 ⁶ t C a ⁻¹	CO ₂ consumed t C km ⁻² a ⁻¹
Polar (without ice)	3,892	3.4	0.9
Tundra and Taiga	23,232	33.5	1.4
Temperate dry	9,635	4.4	0.5
Temperate wet	16,918	48.4	2.9
Tropical dry	21,790	15.1	0.7
Tropical wet	24,919	128.1	5.1
Desert	5,940	0.4	0.1

CO₂ uptake by rock weathering for different climates after Ludwig et al. (1998).

This shows that there is indeed a significant increase in sequestration of CO₂ by location and type of land. **Sequestration is 29 times greater in tropical wetlands than in temperate dry lands**, and **2.4 times greater in the tropic wetlands than temperate wetlands**. So where are the temperate wetlands in the US? The following map shows the annual precipitation in different regions of the US (The Climate Source, 2001).



Clearly the wet temperate regions in the US are in the southern states of Louisiana, Mississippi, Alabama, and Florida. The following is a more detailed map of the wetlands of Florida (Darst et al, 1991).



An additional factor that affects the rate of weathering is the presence of plants and forest vegetation (Hartmann, et al 2013).

The above data shows that there are many areas of temperate wetlands in the US. These are only 38% as efficient in weathering than tropical wetlands, but no “Hot spots” see below. This should still be adequate for many EWs projects in the US.

Heavy Metals in Mafic Rocks

A synthesis by Beerling et al (2018) of published chemical analyses indicates that olivine-rich ultramafic rocks contain relatively high concentrations of chromium (Cr) or nickel (Ni) or both. Weathering experiments reveal fast release of bioavailable Ni from olivine, and suppression of plant calcium uptake, because of competition with magnesium. Experimental work with a soil-columns dosed with olivine suggested accumulation of Ni and Cr in the soil profile (Renford, et al, 2015). By contrast, Schuiling and Krijgsman (2006) **proposed that nickel contamination would not be a problem and that most chromium would be tightly bound in very insoluble chromite grains and will not be bio-available**. Further research is needed to decide which of these conclusions is the closest to being correct.

“Mining” of Nickel from Olivine.

Olivine contains 0.2 to 0.3% nickel. **Olaf Schuiling (2018)** demonstrated that by planting plants that are **nickel hyper accumulators**, such as those in the *Alyssum* family, in the same ground that is covered with olivine, at the end of the growing season the plants can harvested by cutting them close to the ground. When these plants are burned the ash contains about 10% nickel, which is higher than the richest nickel ores. This is a very environmentally friendly way to mine nickel and can provide an income stream to help cover the costs of EW. The *Alyssum* can then re-grow for the next season with a new spread of olivine.

“Mining” Chromite from Olivine

The chromium in olivine is in the form of chromite. According to Olaf Schuiling this can be recovered from pulverized olivine using shake tables or Humphrey spirals. The recovered chromite also has some economic value. Using these two approaches it may be possible to remove most of the heavy metals from olivine before spreading it on the ground.

Non-cropland

As discussed below, there are huge amounts of non-cropland in the U.S. Crushed olivine could be spread on this land and also planted with *Alyssum* plants to extract and sell nickel. This could make using non-croplands for EW economically more feasible. One question that needs study is, “How thick can the applied olivine on non-cropland be and still sequester CO₂? If it could be up to 5 times the thickness of that applied to cropland, then it could be up to 5 times the effectiveness of EW on crops. This would considerably enhance the effectiveness of EW. If preferentially done **in southern areas of high mean temperature**, as shown above, the multiplier could be even greater.

Basalt: Advantages and Disadvantages

The rate of chemical weathering of the basaltic Deccan Traps shows CO₂ consumption rates of $0.58\text{--}2.54 \times 10^6 \text{ mol/km}^2/\text{year}$ (Dessert et al., 2001). Dissolved solid concentration in river waters, induced by basalt weathering on the Island of Réunion indicate CO₂ consumption rates of $1.3\text{--}3.4 \times 10^6 \text{ mol/km}^2/\text{year}$ (Louvat and Allègre, 1997). Such values are equivalent to the consumption of up to 130 tons of CO₂ /km²/year. With mine dumps of crushed ultramafic rocks, consumption of more than 4,000 tons CO₂/km²/year has been measured (Wilson et al., 2009).

In contrast to ultramafic olivine-rich rocks, major continental flood basalts have lower concentrations of Ni and/or Cr but **significantly higher concentrations of phosphorus, suggesting their greater utility for croplands**. Cultivation of crops on rich fertile soils that develop on flood basalts across continents is consistent with fewer environmental risks associated with this rock.

Basalt is widely recognized as producing productive soils **because it weathers rapidly releasing** elements essential for plant growth (Hinsinger, et al. 2001), including P, K, Ca, Mg and Fe. In terms of comparative weathering rates, olivine dissolution rates at oceanic pH~8 are within the range of those for basalt dissolution rates at pH 4 and above, expected in soils.

Significant potential exists for deployment at scale to remove atmospheric CO₂ with ground basalt. A **maximum carbon capture potential of ~0.3t CO₂/t is suggested for basalt**, assuming a sufficiently fine particle size for effective dissolution on decadal time scales (Renforth, 2012). The actual particle size will depend upon the mineralogy of the basalt, climate and biological activity, and requires further investigation and verification, but initial calculations suggest particles of 10-30 µm diameter.

On this basis, basalt applications of 10 to 50 t/ha/yr to 70×10^6 ha of the annual crops of corn or soy in the corn-belt of North America could sequester 0.2–1.1 PgCO₂, up to 13% of the global annual agricultural emissions, in the long run (Kantola, et al 2017).

Theoretical estimates of CO₂ capture and sequestration schemes involving global croplands and silicate rocks are very uncertain. Provisional estimates (Smith, et al, 2016), suggest that amending two thirds of the most productive cropland soils (9×10^8 ha) with basalt dust at application rates of 10-30 t/ha/yr could perhaps **extract 0.5-4 PgCO₂/yr by 2100** depending on climate, soil and crop type. These numbers still need to account for full life cycle assessment but suggest enhanced weathering could make a significant contribution to the negative emissions required by deep decarbonization strategies (Anderson & Peters, 2016; Rockstrom, et al. 2017; Field & Mach, 2017) and the ~1 Pg CO₂ eq/yr reduction from agriculture by 2030.

Use of renewable energy

A key issue affecting carbon capture efficiency is the energy cost associated with mining, grinding and spreading the ground rock, which could reduce the net carbon drawdown by 10-30%, depending mainly on grain size. Relatively high energy costs for grinding, as influenced by rock mineralogy and crushing processes, call for innovation in the industrial sector, such as grinding and milling technology **powered by renewable energy sources (solar, wind, microreactors or small nuclear reactors (see below), or Solar Chimney Power Plants (see below)**, to significantly increase the net CO₂ benefit. The benefit will increase as future energy sources are decarbonized, the grinding process becomes more energy efficient, and by utilizing already ground waste silicate materials previously or currently produced by the mining industry, i.e., tailings. By driving down costs for grinding in this way, carbon sequestration costs would be correspondingly cheaper.

Nuclear Energy There are several companies that have been working for years on developing small, modular nuclear reactors. These are:

a) **Terrestrial Energy Canada and USA**. These are molten salt reactors that are super safe. See www.TheComingsFoundation.org -> 1. Support of Nuclear Energy -> B Molten Salt Reactors. When I called each company, the Canadian company expected to obtain approval in 2025 and the U.S. company in 2030. This time frame could be helpful for our projects.

b) **NuScale Energy** is making small nuclear reactors. Should be available soon.

The beauty of these technologies is that they are modular, very safe, give base load electricity, and should be available soon.

Waste Materials - Tailings

In regard to using waste materials, according to Renforth (2019) seven billion tons of alkaline materials are produced globally each year as a product or by-product of industrial activity. The aqueous dissolution of these materials creates high pH solutions that dissolves CO₂ to store carbon in the form of solid carbonate minerals or dissolved bicarbonate ions. He showed

that these materials have **a carbon dioxide storage potential of 2.9–8.5 billion tons per year** by 2100, and may contribute a substantial proportion of the negative emissions required to limit global temperature change to <2 °C.

Cost estimates for Basalt

Current cost estimates are uncertain and vary widely, and better understanding the economics involved is a priority. The most detailed analysis for operational costs drawn-up for using a basic rock, such as basalt, gives values of US\$52-\$480 t/CO₂, with grinding and transport the dominant components (Renforth, 2012). This cost range falls below that estimated for bioenergy with carbon capture and storage (BECCS) of \$504-\$1296 t/CO₂ (\$140-\$360 t/C) (Smith, et al, 2016). Deployment costs may be partially or completely offset by gains in crop productivity, and reduced requirements for lime, fertilizer, pesticide and fungicide applications.

Given that farmers routinely apply granular fertilizers and lime, annual applications of, for example, ground basalt, an abundant, weatherable Ca- and Mg-rich rock, is feasible at large scale with existing farm equipment.

Silicon Enhancement of Soil

Enhanced weathering strategies not only capture carbon but could also help restore soils and resupply impoverished reserves of trace elements important for human nutrition and crop production (Guntzer, et al 2012). The discovery of **silicon transporters** in several plants indicates the importance of this element. There are multiple ways in which silica helps plants in various types of environmental stress. Si fertilization makes soil phosphorus more available to plants. Seven out of the top ten crops ranked according to global production data (**sugarcane, rice, wheat, barley, sugar beet, soybean, and tomatoes**) are classified as **Si accumulators** (> 1%) and intensive cultivation and repeated removal of harvested products from the field is seriously depleting plant available Si in soils. In the US, for example, crop harvesting removes 19 million tons of Si annually (Tubana, et al (2016)). Annual depletion of soil Si by continuous intensive farming, coupled with low solubility of soil Si, has led to **calls for the development of viable Si-fertilization practices** in the near future to increase plant available pools and maintain crop yields.

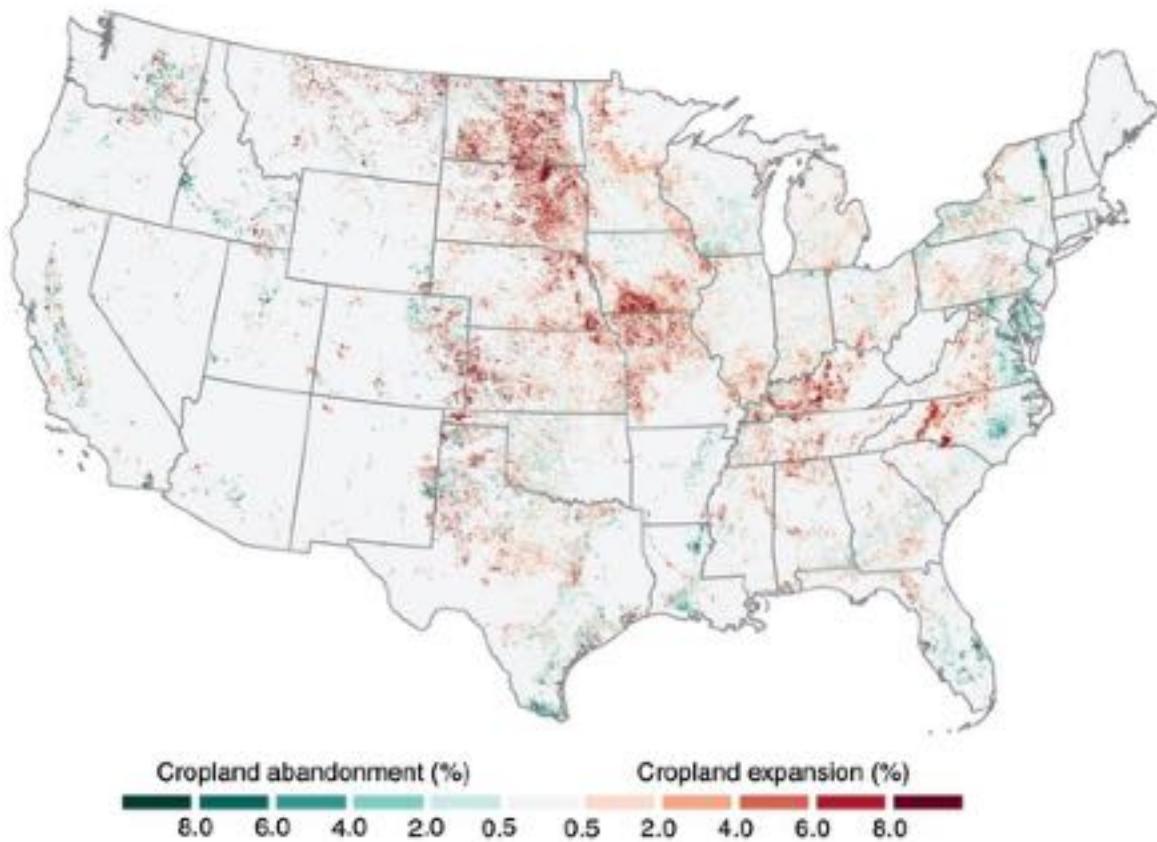
Dissolution of crushed silicates, or Si-containing mining and industrial wastes, releases Si, replenishing the plant available form. The fate and transformation of enhanced weathering derived Si in the soil-plant continuum, and its long-term biogeochemical cycling, warrant future research in the context of mitigating Si-related yield constraints on agricultural crop production.

An example of the use of crushed basalt in improving crop yields came from sugarcane trials with crushed basalt applications in excess of 20 t/ha in combination with standard NPK fertilizer treatments **increased yields by up to 30%** over five successive crops on the highly weathered soils of Mauritius compared with plots receiving fertilizer and no basalt addition.

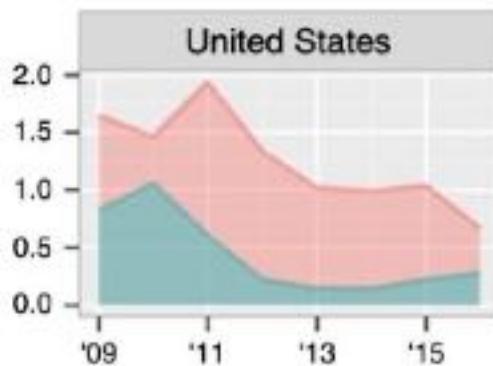
Cropland Abandonment and Expansion in the U.S.

Lark et al (2020) assessed annual land use change 2008–16 in the U.S. and its impacts on crop yields and wildlife habitat. They found that croplands have expanded at a rate of over one million acres per year, and that 69.5% of new cropland areas **produced yields below the national average**. Observed conversion infringed upon high-quality wildlife habitat especially relative to grassland milkweed critical for the Monarch butterfly. It also impacted on nesting opportunities for waterfowl in the Prairie Pothole Region of the Northern Great Plains. They thus

demonstrated a pervasive pattern of encroachment into areas that are increasingly marginal for production, but highly significant for wildlife, and suggest that such tradeoffs may be further amplified by future cropland expansion.



Net cropland conversion 2008–16. Rates of net conversion calculated as gross cropland expansion minus gross cropland abandonment and displayed as a percentage of total land area within non-overlapping 3 km × 3 km blocks. Net conversion was most concentrated in the eastern halves of North and South Dakota, southern Iowa, and western portions of Kansas, Kentucky, and North Carolina.



This figure summarizes the ratio of cropland abandonment (green) versus cropland expansion (red).

Carbon Emissions from Cropland Expansion

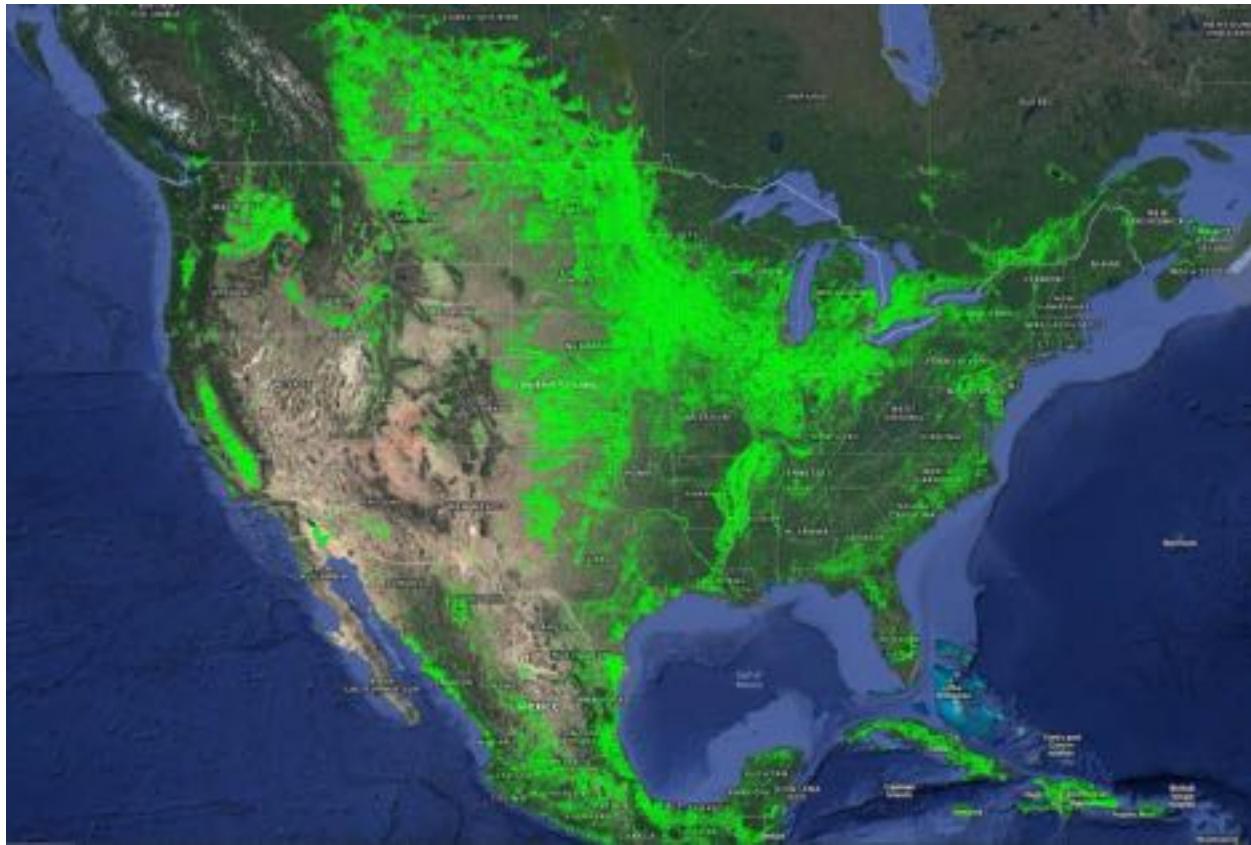
In addition to the expanded cropland being less productive, an additional disadvantage is that such expansions release significant amount of the carbon stored in grassland (Spawn et al, 2019; EFI 2020a).

So, how is this relevant to the use in EW on cropland. A major finding was that the expanded croplands performed more poorly than regular cropland. Could this be corrected by the use of ground olivine or basalt on these lands? The expanded cropland involved a total of over 10 million acres. Such treatment might also reverse some of the negative effects on wildlife. Perhaps equally or more relevant would be the **spreading of ground olivine or basalt on the abandoned cropland simply to sequester CO₂ independent of improving cropland.**

Non-cropland in the US

The above showed the abandoned cropland in the US. The real issue is how much non-forest non-cropland is there in the US? The following map shows the cropland in the US. By default, also shows the non-cropland, which is extensive.

This map shows U.S. croplands in a nominal 30-m resolution derived primarily with Landsat imagery for the year 2015. The United States has 166 million hectares of net cropland area and is ranked second in the world after India, which has 180 million hectares of croplands. This is part of the GFSAD30 Project Landstat (USGS).



Cropland and non-cropland in the US

The following figure shows the power of the Landstat technology to investigate details of cropland and non-cropland.



This map shows croplands in Texas in a nominal 30-meter resolution. This is part of the GFSAD30 Project.

The resolution of Landstat allows the investigation at the level of individual farms. This will be invaluable in planning the sites and extent of ER on cropland.

The following figures cover the whole world.



This map shows cropland distribution across the world in a nominal 30-meter resolution. This is the baseline product of the GFSAD30 Project.

The combined above figures show that if EW needs to involve both croplands and non-croplands, huge areas of land are potentially involved.

Calcium looping (CaL) (EFI, 2020c)

Oxide looping is a CDR method that leverages the high reactivity of calcium (Ca) or magnesium (Mg) oxides and hydroxides to remove CO₂ from air. The starting materials are pure calcium or magnesium carbonate minerals. Heating them to temperatures of approximately 900°C and 600°C, respectively, produces solid calcium oxide or magnesium oxide and CO₂. The CO₂ released during heating would then be captured and sequestered or used. The other byproducts, calcium or magnesium oxide, can be converted to calcium hydroxide (portlandite) or magnesium hydroxide (brucite), which react rapidly with atmospheric CO₂ to produce various solid carbonate minerals. The produced oxide/hydroxide sediment could be distributed in fields, tilled periodically to expose unreacted sediment, and recovered after a period of months to years to begin the process again.

If the total known global reserve of magnesite (MgCO₃) were to be mined and employed in this process, and if it were 100 percent efficient, it could remove approximately 4 Gt CO₂ per year from the atmosphere. Conversely, Ca looping, which is already used as a carbon capture technology for power generation, starts with pure limestone, a regionally widespread commodity

of vast abundance. Limestone is quarried in vast quantities for cement and concrete production, used as a soil amendment in agriculture, and as a building stone. Thus, CaO might be preferable to MgO in many regions, despite the higher calcining temperature.

Calcium and magnesium oxide looping has not yet been demonstrated beyond laboratory and limited-scale outdoor experiments. Models suggest that 2,000 to 7,000 km² of land would be required per Gt of CDR per year, covered with oxide or hydroxide sediment about 5 cm deep. This amount of land is on the scale of the 100 to 200 largest mines in the world, but this technology has the potential to be a more efficient and long-lived CDR pathway than mineralization at industrial sites if the required land use can be justified.

Summary of CDR Methods ((EFI, 2020c)

Summary of Characteristics of Selected Mineralization CDR Methods

CDR Method	Possible CDR Capacity (GtCO ₂ /yr.) and Land Use (km ² /Gt/yr.)	Estimated Cost (per tCO ₂)	Possible Co-Benefits	Issues, Risks, Limitations, Uncertainties	Technology Readiness
Carbonation of Mineral Wastes	2-9 Gt/yr. >2,000 km ² /Gt/yr. using existing mines	Tailings management practices: \$10s CO ₂ injection: <\$50 Accelerated leaching: >\$50	Mitigating heavy metal/dust mobility, slope stabilization via cementation; potential integration with point-source capture	Reactivity of mineral wastes; carbon accounting frameworks	Medium
Enhanced Rock weathering and Carbonation in Soils	<1-2 Gt/yr. (cropland only) >10,000 km ² /Gt/yr.	\$8-\$100, depending on feedstock	Enhancing carbonate alkalinity in the oceans; delivery of essential trace nutrients to plants and soil microbes	Soil contamination, efficiency/rate of mineralization in soil environment; opening new mines to quarry fresh rock	Medium
Calcium and/or Magnesium Oxide Looping	~4 Gt/yr. (global magnesite reserves) >400 Gt/yr. (including limestone)	\$50-\$150		Efficiency and timeframe; minimizing carbon from heating; identifying practical feedstock	Low to Medium

Nitrous oxide N₂O

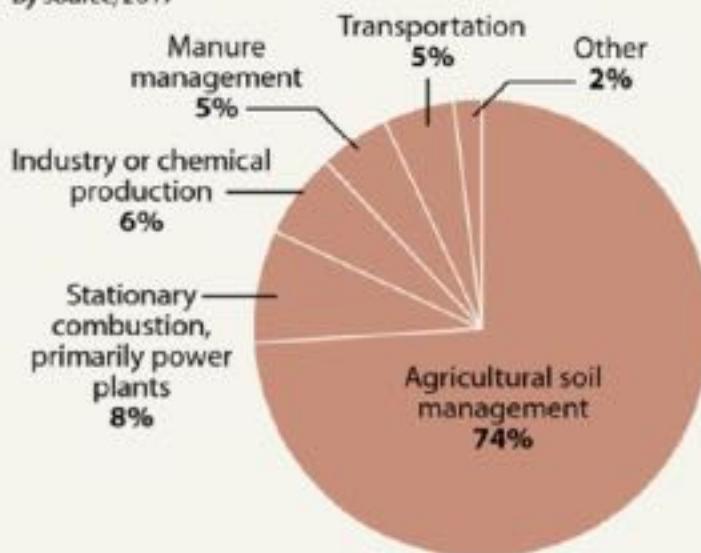
One pound of N₂O warms the atmosphere about 300 times the amount that one pound of carbon dioxide does over a 100- year timescale. Its potency and relatively long life make N₂O a dangerous contributor to climate change. It also depletes the ozone layer. As shown below, about three fourths of N₂O comes from the soil and agricultural sources.

Where Does N₂O Come From?

Agriculture, particularly fertilized soil and animal waste, accounts for about three quarters of U.S. nitrous oxide emissions.

U.S. NITROUS OXIDE EMISSIONS

By source, 2017



SOURCE: EPA

PAUL HORN / InsideClimate News

In this regard it is of interest that a further co-benefit that may arise from the agricultural application of crushed silicate rocks to soils is suppressing emissions of the powerful and long-lived greenhouse gas N₂O and averting CO₂ emissions caused by liming. Liming with CaCO₃ can release CO₂ when it is applied to acidic soils (pH <6) typical of agricultural lands. In the USA, liming contributes 2% of agricultural greenhouse gas emissions.

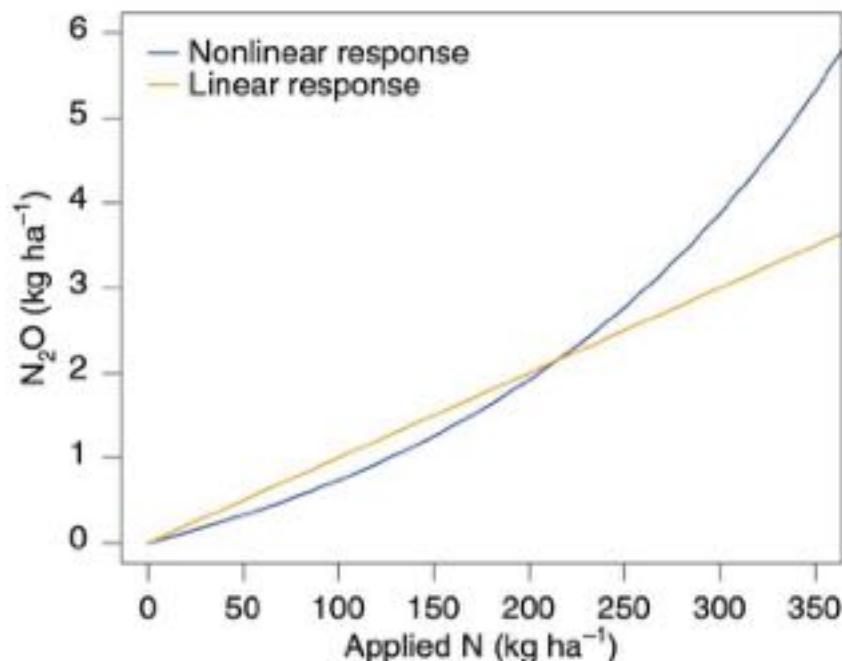
Beerling, et al (2018) concluded that substituting a weatherable silicate rock, such as basalt, or silicate waste, for limestone, and increasing application rates over those used in conventional liming operations, **may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy**.

By increasing soil pH as they weather, silicates may also **reduce emissions of N₂O**, as found with liming (Gibbons, et al., 2014). Preliminary tests with a replicated field experiment support this suggestion with the soil N₂O flux from heavily fertilized maize plots decreasing by ~50% with the application 10 kg m² of pulverized basalt with no effect on soil respiration (Kantola, 2016). Thus, basalt-treated arable fields may lower the current substantial global soil atmosphere flux from croplands of 4-5 Tg N₂O-N/yr as a by-product of weathering.

Agriculture is the main source of anthropogenic N₂O emissions, primarily through the application of synthetic nitrogen (N) fertilizers and manure on agricultural land. As the global amount of fertilizer used is expected to increase considerably over the next few decades, it is essential to establish reliable inventories of N₂O in order to define effective mitigation strategies (Makowski, D. (2019). Writing in *Nature Climate Change*, Thompson and colleagues (2019) present new global estimates of N₂O emissions and show that this greenhouse gas has increased substantially since 2009, at a faster rate than expected. Their result questions one of the main methods currently used for the inventory of N₂O emissions at the global scale.

To mitigate N₂O emissions effectively, we must first understand their origin (Makowski, D. (2019). Emissions of N₂O to the atmosphere are mostly caused by nitrification and denitrification reactions. In terrestrial ecosystems, the driving processes are soil microbial activities, which are influenced by both natural factors and human management, in particular the application of synthetic and organic fertilizers. Soil N availability plays a key role in these processes, and N₂O emissions accelerated steadily during the twentieth and twenty-first centuries with the increasing use of nitrogenous fertilizer in crop fields. **N fertilization is now recognized as a major source of anthropogenic emissions of N₂O, having contributed significantly to global warming.**

In the bottom-up IPCC approach, the hypothesis of a linear relationship between N₂O emissions and applied N fertilizers has been questioned in several field studies. Instead, there may be a nonlinear response, with an acceleration of emissions as N application increases, probably because a higher proportion of N goes unused by crops in the case of high doses of fertilizer.



Comparison of linear and nonlinear response of N₂O emission to applied N. The linear response tends to underestimate emission for high levels of applied N.

Thompson and colleagues (2019) used a top-down method based on atmospheric measurements. Here the level of increase was substantially higher than previous estimates — more than double that of the IPCC default approach — indicating a faster N₂O growth rate than expected.

The results also revealed contrasting emission trends among regions. Emissions increased sharply in China and, to a lesser extent, South Asia and Brazil. These results are consistent with

the large increases in N inputs and surplus N in crops that have occurred in these regions over the past two decades. On the other hand, N₂O emissions remained stable in the United States and Europe over the same period. Thus, a substantial decrease in N₂O emissions could occur if these regions avoided excessive N fertilization. This will require international agreements.

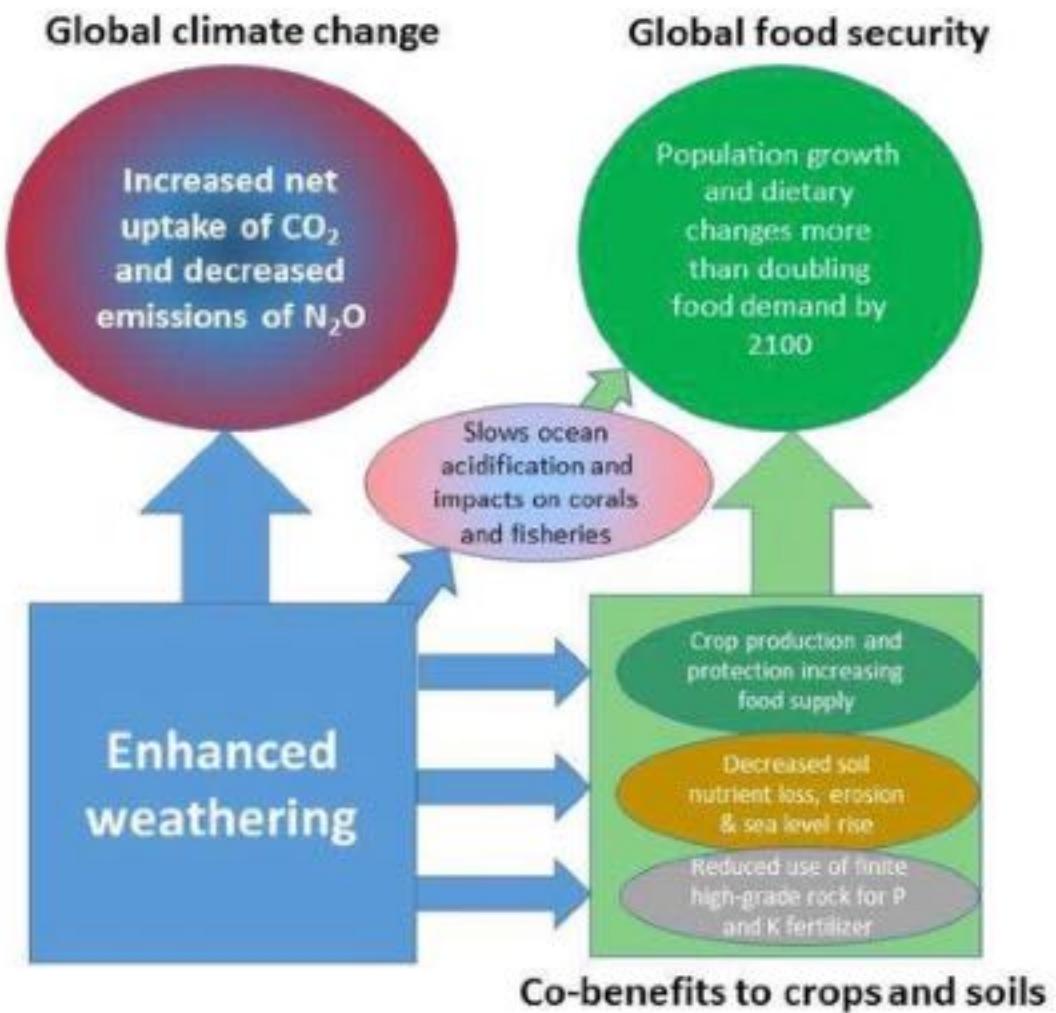
Breider, et al (2019) showed that when pH was reduced, the N₂O production rate during nitrification measured at subarctic stations increased significantly while nitrification rates remained stable or decreased. Contrary to previous findings, these results suggest that the effect of ocean acidification on N₂O production during nitrification, and nitrification rates are probably uncoupled. Collectively, these results suggest that if seawater pH continues to decline at the same rate, ocean acidification could **increase marine N₂O production during nitrification in the subarctic North Pacific by 185% to 491% by the end of the century.**

Enhanced weathering of cropland both decreases the production of N₂O by cropland and combats ocean acidification which has a secondary effect of decreasing the marine production of N₂O. Thus, **this approach could decrease N₂O both on land and in the sea.**

Advantages of Enhanced Weathering on Cropland

An additional consideration relating to the overall outlook of EW is the recent report by Bellamy and Geden (2019) who argued that contrary to widely held assumptions, **methods for CO₂ reduction do not have to be deployed at large global scales to be relevant for climate policy.** In regard to governance, they suggest that it will primarily emerge ‘bottom up’ with companies, cities and countries utilizing these techniques and not be comprehensively coordinated ‘top down’ globally. Namely, since many NETs involve individual countries and areas, any governance should be local (ground up) and not globally (top down) (Lenzi, 2018). Such local governance will be small scale. Another way of putting it is: **every little bit helps – monitor the bits locally.** In this regard, we will initially focus on EW in the U.S.

A summary of the advantages of crop weathering is shown below.



From Beerling, et al (2018)

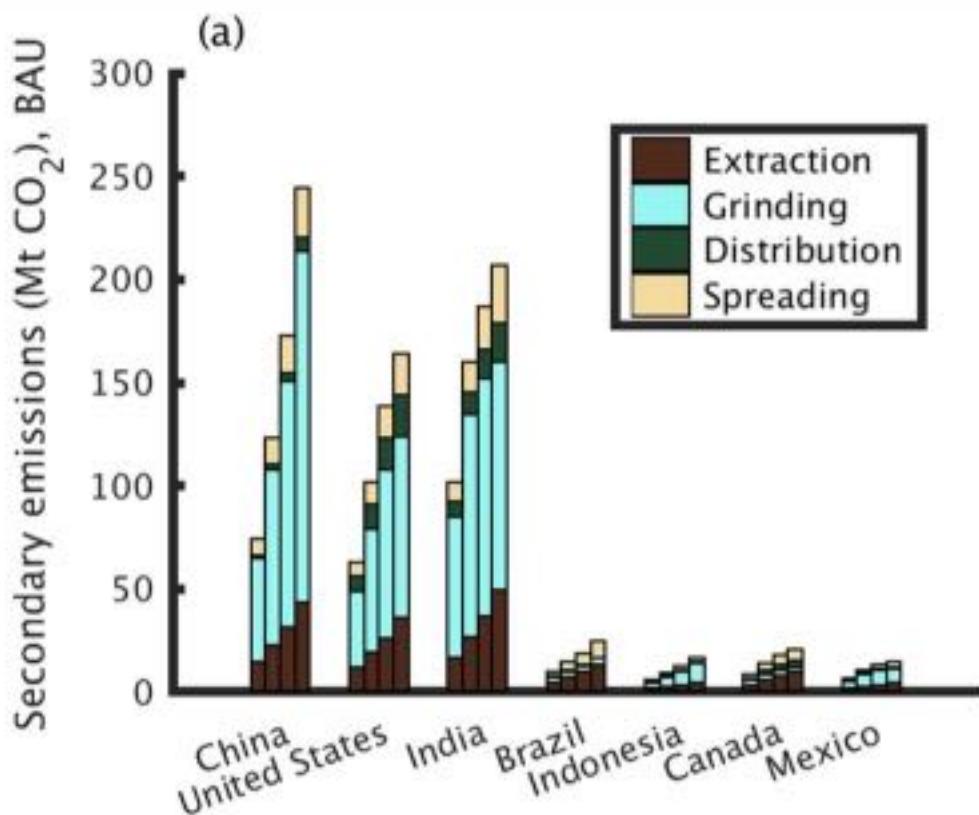
More broadly, if proven effective, and undertaken carefully to minimize undesirable impacts, enhanced weathering may have untapped potential for addressing the United Nations **Sustainable Development Goals** (SDGs) adopted by 193 countries in 2015. For example, we highlight how sequestering CO₂ constitutes action on climate change (SDG 13), restoring soils and promoting sustainable agriculture contributes to zero hunger (SDG 2), helping protect the oceans from acidification conserves global resources in life below water (SDG 14), reducing agrochemical usage and recycling wastes helps with sustainable consumption and production (SDG 12), and improving agricultural production and restoring degraded soils contributes to land sparing (SDG 15) (see above figure)

Following the Beerling et al (2018) paper in *Nature*, two articles appeared in the July 9, 2020 issue *Nature*. The primary article was again by Beerling et al, (2020) entitled “Potential for large-scale CO₂ removal via enhanced rock weathering with croplands.” It was accompanied by

a News and Views comment on the Beerling paper by Lehmann and Possinger (2020) entitled “Atmospheric CO₂ removed by rock weathering.” Combined, this was a real boost for EW.

Costs of EW

Beerling et al, examined the potential of different countries to use EW. They concluded that EW would cost, on average, **US\$160–190 per ton of CO₂ in the United States**, Canada and Europe, and \$55–120 per ton of CO₂ in China, India, Mexico, Indonesia and Brazil. Furthermore, the authors report that China, the United States and India — the three largest emitters of CO₂ from fossil-fuel use — have the highest potential for CO₂ removal using this method. One of their important conclusions was the relative cost of extraction, grinding, distribution and spreading. In the figure below, the Y axis was in terms of secondary emission (i.e., carbon cost) of these four processes. While not directly related to cost, it was a reasonable estimate of cost.



This showed that the cost of grinding contributed significantly to the total cost of this NET. The intriguing aspect of this analysis is that the use of dedicated clean energy sources could significantly reduce the cost of this NET. It is of interest that Terrestrial Energy anticipates that their small, modular Integrated Molten Salt Reactor will be approved in Canada by 2025 and in the US by 2030. These are super-safe reactors.

Hartmann et al, (2013) examined the issue of the relative cost of different methods of grinding in terms of energy use and produced the following Table 4.

TABLE 4. Typical Energy Requirements for Various Crushing Technologies

Crushing and Grinding Technology	Food Particle Size (μm)	Product Particle Size (μm)	Capacity (t h^{-1})	Energy Use (kWh t^{-1})
Roller mills	10^4 - 10^5	18-65	12-225	6.6-11.0
	20-30	7-12	15-65	7.6-36.0
Centrifugal mills	11	1-2		150.0
Ball/stirred media mills	150	<37	0.1-35 ^a	13.0-233.0 ^a
Impact crushing	10^4 - 10^5	10^2 - 10^3	130-1780 ^b	0.6-1.5 ^b
Cone crushing	10^5	10^2 - 10^3	80-1050 ^b	0.3-1.5 ^b
Jaw crushing	10^3 - 10^6	10^3	60-1600 ^b	1.0-1.4 ^b

^aIndicative values derived from Kefid technical data sheets.^bIndicative values derived from Meso technical data sheets.

Sources: Wang and Forsberg [2003], Lowndes and Jeffrey [2009], Fuertes and Abouzeid [2002], O'Connor et al. [2005].

The often-recommended size of ground particles suitable for EW is 1 μm . As shown above centrifugal and ball mills are the only methods listed to achieve this size, and they are the costliest, in terms of energy use.

The cost of transport is also an important issue. The following table 5, also from Hartmann (2013), that provides an estimate of relative transportation costs.

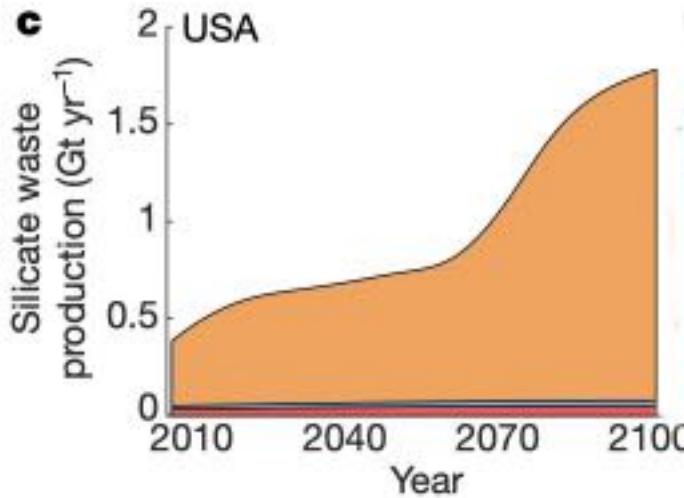
TABLE 5. Emissions From a Range of Freight Transport

Freight/Haulage Transport Method	gCO ₂ Emissions $\text{km}^{-1} \text{t}^{-1}$
Airfreight	602
Road heavy goods vehicle	62
Diesel rail	15
Electric rail	14
Inland waterways	31
Large tanker	7

Sources: McKinnon and Piecyk [2009], McKinnon and Piecyk [2010], Institution of Mechanical Engineers [2009].

Obviously, transporting by air would be prohibitively expensive while transport by large tanker is the least expensive. This bodes well for the possibility of transporting olivine from Norway to the US or other countries. One could imagine placing olivine as mined on a large tanker and performing the grinding on board, then dispersing some of that olivine into the ocean as the tanker proceeds across the Atlantic to a suitable port where the remaining olivine can be used on land and repeating this many times a year. If the tanker was thoroughly covered with solar panels, the cost of grinding could be significantly reduced.

An additional reduction of costs could come from reducing the extraction part by the use of products of various industrial processes. For example, the use of artificial silicon and calcium-rich cements used in construction and the by-product of slag from steel manufacturing could provide an important source of these materials. It was predicted that these sources of silicates would increase over the century (see figure below).



Forecast of increases in national bulk silicate production over the next century. Simulated future increases in bulk artificial silicate by products: slag, cement, kiln dust and cement demolition waste (orange), slag and kiln (blue) and slag (red). production during the twenty-first century are given for the USA.

Soil pH

Increasing soil pH alone by adding mafic rocks, would substantially boost crop yields in many regions of the world, because it is possible that **low pH constrains crop production on more than 200 million hectares of arable and orchard soils** (von Uexküll & Mutert, 1995). This area is equivalent to about 20% of the total extent of these soils (967 million hectares). Consequently, **on a global scale, acidity is the most important soil constraint for agriculture** (Wood, et al, 2000).

Co-deployment of enhanced rock weathering with other soil-based sequestration approaches might both reduce limitations and maximize synergies (Amann & Hartmann, 2019). It was proposed that carbon markets might be required to help finance this, and other, approaches (Lehmann and Possinger, 2020).

The note by Lehmann and Possinger included a photograph showing what the process of spreading finely ground basalt would look like.



Application of silicate material to cropland (Lehmann and Possinger, 2020).

Reducing Emission of CO₂ from Soil

With all the reports on the role of proper soil practices to sequester CO₂, it may come as a surprise that the estimated annual flux of CO₂ from soils to the atmosphere is estimated be 65 to 79 Pg C/yr. Approximately 10% of the atmosphere's CO₂ passes through terrestrial soils each year. At a global scale, rates of soil CO₂ efflux correlates significantly with temperature and precipitation.

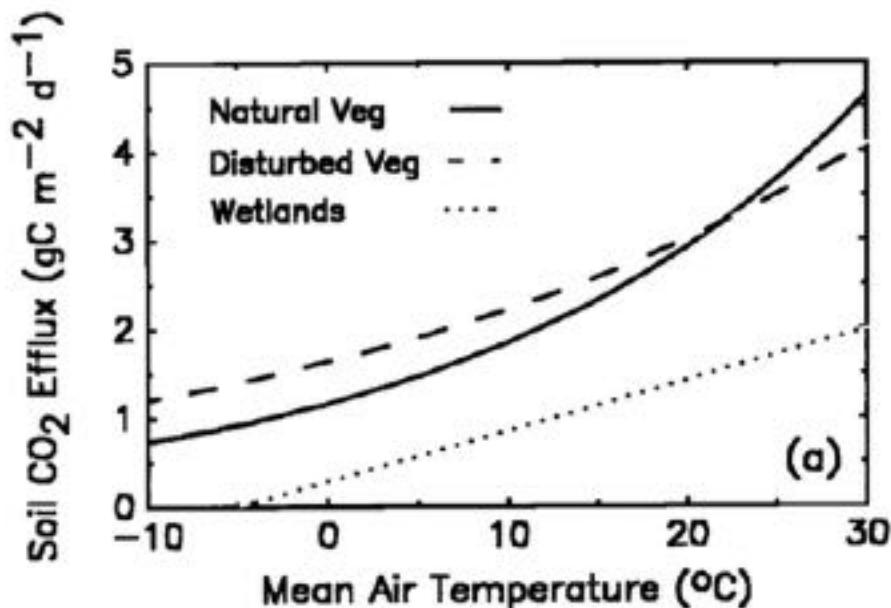
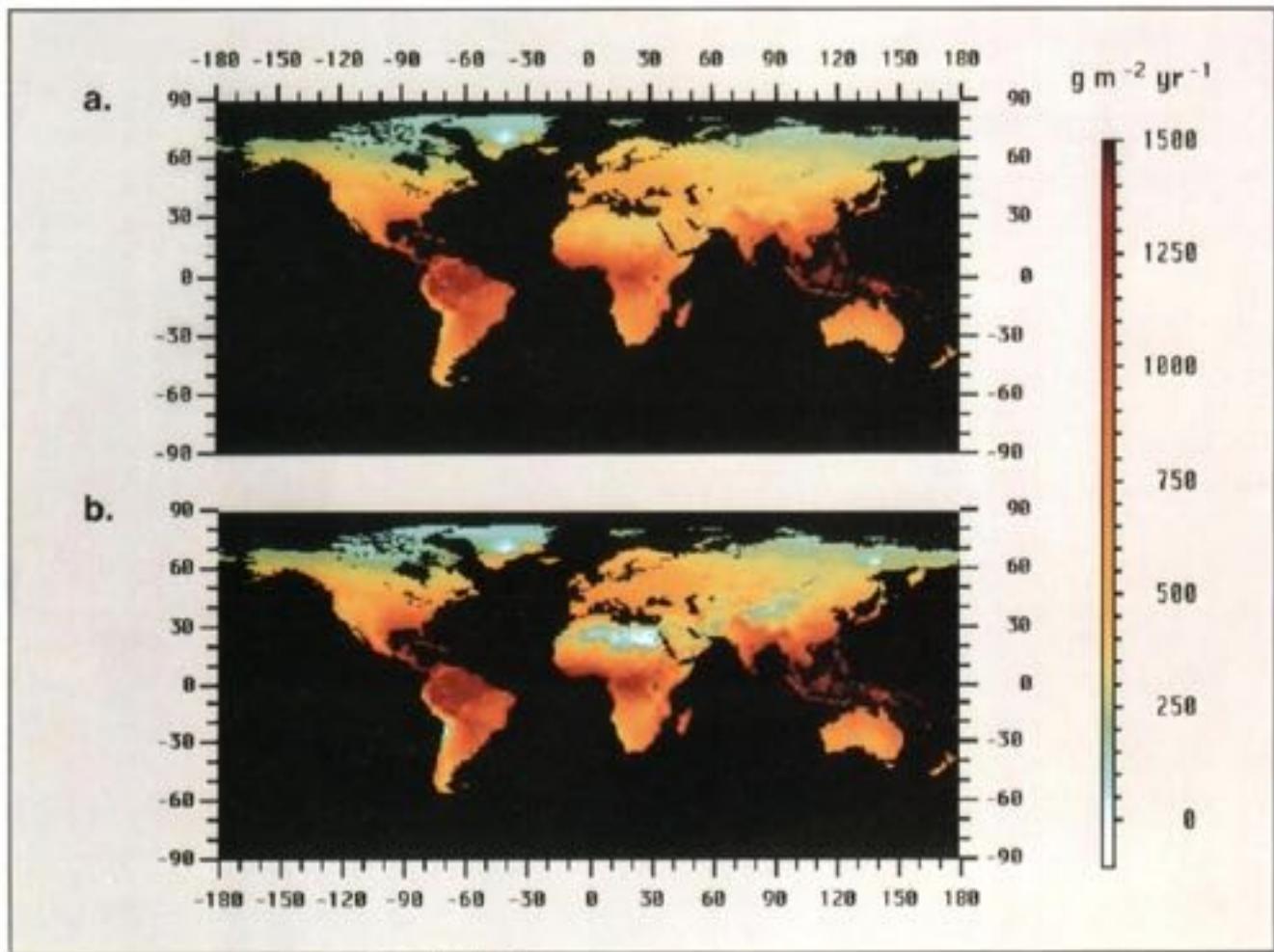


Figure from Raich & Potter, 1995

As shown in this figure, there is a 5-fold increase in soil efflux of CO₂ from 0 to 30 °C. Thus, clearly soil CO₂ fluxes have a pronounced seasonal pattern in most locations, maximum emissions coincide with periods of active plant growth. Our models suggest that soils produce CO₂ throughout the year and thereby contribute to the observed wintertime increases in atmospheric CO₂. (Raich and Potter, 1995).

It is clear from the above, that there will be marked differences in the rate of CO₂ by geographic region. This is illustrated in the following figure.



Global annual soil CO₂ emissions as predicted by the (a) log-transformed model A and (b) the untransformed model B, including corrections for wetlands (models C and D, respectively). Raich and Potter, (1995).

It is of interest that this map correlates closely with the map below of Hartmann et al (2009a) showing a published **weathering hot spot map for the world**. This suggested that the use of EW in these areas would be particularly productive. It would match need with utility.

Soil organic matter contains a large reservoir of carbon. Recently estimated at --1600 Pg more than twice the atmospheric CO₂-C pool. Changes in the size of the soil C pool therefore can

significantly affect atmospheric CO₂ concentration. In fact, concern has been raised about the potential for global warming to increase rates of CO₂ production by soils, thereby exacerbating the CO₂ loading of the atmosphere and providing **a positive feedback to climate warming** (see references in Raich and Potter (1995).

Ray et al (2020) state the soil is a source and also a sink of CO₂ exchange. A study in Texas showed that agricultural management practices influence soil water dynamics, as well as carbon cycling by changing soil CO₂ emission and uptake rates. The rate of soil CO₂ emission varied for different crops and different organic fertilizers (Ray et. al. 2020). The higher the amount of organic fertilization (chicken manure, dairy manure, and Milorganite) the higher the CO₂ emissions.

The above represents the emission side of the soil story. Also of importance is the side of the equation wherein proper soil management sequesters CO₂ (Paustian et al, 2007). Given the magnitude of the emission of CO₂ from soils, the use of EW on soils should significantly mitigate that.

Can a Carbon Capture Apparatus by Married to an Olivine Mine?

Klaus Lackner demonstrated a **moisture swing sorbent cycle for capturing carbon dioxide (CO₂) from air**. The sorbent, an anionic exchange resin, has been shown to absorb CO₂ when it is dry, and to release it again when exposed to moisture. By Lackner's calculation, each air capture device would be about 1,000 times more effective than a single tree.

Currently Lackner prefers to form the white resin into a honeycomb pattern—similar to thousands of straws stacked atop each other with the wind blowing through the holes. Their approach of what to do with the CO₂ is CCU - Carbon Capture and Use. While a number of such uses have been proposed it is doubtful that there a sufficient number of uses to sequester billions of tons of CO₂. They also proposed mineralization as a safe and permanent disposal of carbon dioxide and suggested using olivine or serpentine.

Obviously, if a concentrated stream of CO₂ was used, mineralization of olivine should be much more efficient than exposure to the atmosphere. This raises the possibility of placing a number Lackner type apparatuses at an olivine mining site. This would avoid the cost of transporting olivine to croplands. Research is necessary to determine how and if it is possible to marry carbon capture devices (Lackner, Climeworks, other) to olivine mining sites. The Lackner moisture sensitive resin would seem to require far less energy to release the CO₂ that other methods, and thus cheaper. This needs further research.

Exposing the olivine to the concentrated CO₂ during the grinding process is one potentially simple approach to the marriage of olivine with carbon capture devices.

Use of Tailings for EW

Ex situ mineralization involves exposing reactive rock and minerals, alkaline industrial wastes, or mineral wastes from mining operations (**tailings**) to CO₂ above the Earth's surface. This process can be facilitated by crushing and grinding reactive feedstocks to fine grain sizes and either spreading it across a surface or transporting it to pressure vessels where it can react with CO₂. Several byproducts of industrial processes that provide opportunities for carbon mineralization include **cement kiln dust, waste concrete, fly ash, mine tailings, alkaline waste from paper mills, red mud, iron and steel slag**.

Romanov et al (2015) reviewed all of the relevant research about different types of tailings and reported a marked increase within the last few years in research into utilizing industrial waste streams as a source of Ca and Mg cations available for carbonation. Interest for using industrial residue materials and byproducts as reactant mineral carbonation sources has arisen because they are **readily available, cheap, and often generated near large CO₂ emission sources**. Fly ash and bottom ash from furnace operations typically contain a significant amount of lime (CaO) and magnesium oxide (MgO), which are more readily carbonated than the silicates. Their small particle sizes also facilitate rapid reaction rate. Cement kiln dust and waste concrete, mining waste, slags from iron and steel-making operations, and alkaline paper mill waste are also promising feedstock material for carbonation. The capacity to sequester CO₂ with these alkaline residues depends directly on the proportion of divalent cations bound in oxides (CaO and MgO) and/or hydroxides (Ca(OH)₂ and Mg(OH)₂) present in the waste matrix.

Among the solid residues generated by **municipal solid waste incineration (MSWI)** **bottom ash** accounts for 20–30% by mass of the original waste and tends to have lower CaO and higher SiO₂ content compared to fly ash. Accelerated carbonation has been proposed as an application for this ash prior to its final disposal. There are multiple advantages to carbonating MSWI ash. **First**, the ash contains a high CaO content. **Secondly**, MWSI ash already consists of fine-size particles and thus is ready for carbonation with no pre-treatment. **Thirdly**, the incineration process generates a significant amount of CO₂, so alternately sequestering a portion of the CO₂ along with the waste products would be advantageous. **Fourthly**, carbonating the ash tends to decrease the leaching of potentially hazardous heavy metals contained within the ash. Using this resource could compensate for the CO₂ emitted when it is produced.

Fly ash is the finely divided residue that results from the combustion of pulverized coal and is transported from the combustion chamber by exhaust gases into the air. Over 61 million metric tons (68 million tons) of fly ash were produced in 2001.

Renforth (2019) reported that **7 billion tons of alkaline materials are produced globally each year as a product or by-product of industrial activity**. The aqueous dissolution of these materials creates high pH solutions that dissolves CO₂ to store carbon in the form of solid carbonate minerals or dissolved bicarbonate ions. Renforth showed that these materials **have a carbon dioxide storage potential of 2.9–8.5 billion tons per year by 2100**, and may contribute a substantial proportion of the negative emissions required to limit global temperature change to <2 °C.

A listing of these sources is as follows.

Table 1 Carbon production intensities and sequestration potential of highly alkaline materials, by-products and wastes

Material	2010 CO ₂ intensity ^a	2050 CO ₂ intensity ^b	Carbonation potential ^c	Measured carbonation ^d	Enhanced weathering potential ^e	Carbon offset recycling/reuse ^f
Blast furnace slag			413 ± 13	90–230	620 ± 19	-100. Up to 700 in high substitution specialised cements.
Basic oxygen furnace slag	12,000	2700–4300 (286–1080) ^g	402 ± 17	50–540	602 ± 25	<5 as aggregate
Electric arc furnace slag			368 ± 10		552 ± 15	—
Ordinary portland cement	800	200–400 (100–200) ^h	510	300	773	—
Cement kiln dust	6900 ⁱ	1700–3500	330 ± 12	82–260	530 ± 21	-0 Recycled into kiln
Construction and demolition waste	—	—	77–110	—	110–190	<5 As aggregate
Lime	1000	200 ^j	777 ± 13	—	1165 ± 19	—
Ultrabasic mine tailings	8–250	—	40–250	<50	60–377	—
Hard coal ash			36 ± 6	20–30	73 ± 10	
Lignite ash	20,000	(2000–2600) ^j	146 ± 26	230–264	246 ± 52	
Marine algae biomass ash			31	—	348	
Wood/woody biomass ash			—89–815		—118 to 1766	-100. Up to 700 in high substitution specialised cements
Herbaceous and agricultural biomass ash	490	<–16,200	—239–520	80–380	—323 to 1505	
Animal biomass ash ^k			56–376	—	145–724	
Biomass average			186 ± 125	—	461 ± 260	
Red mud	5400	(1080)	47 ± 8	7–53	128 ± 18 < 440 with acid neutralising capacity of liquor	—

Input data are presented in Supplementary Table 2 and Supplementary Note 1; all units in kg CO₂ t⁻¹.
^aCalculated by dividing the emissions of the production process by the mass of alkaline material.
^bPredicted future emissions normalised to mass of alkaline material.
^cMaximum CO₂ capture potential by forming carbonate minerals.
^dCO₂ capture measured in experimental work.
^eMaximum enhanced weathering CO₂ capture potential.
^fCO₂ mitigation potential from other uses of material.
^gSee Supplementary Notes 2 and 3.
^hBased on an 80% emission reduction target¹⁶ (e.g., UK and EU).
ⁱAccounting for aggregate primary energy carbon intensities in RCP2.6 by 2050. Brackets denote 2100 projected.

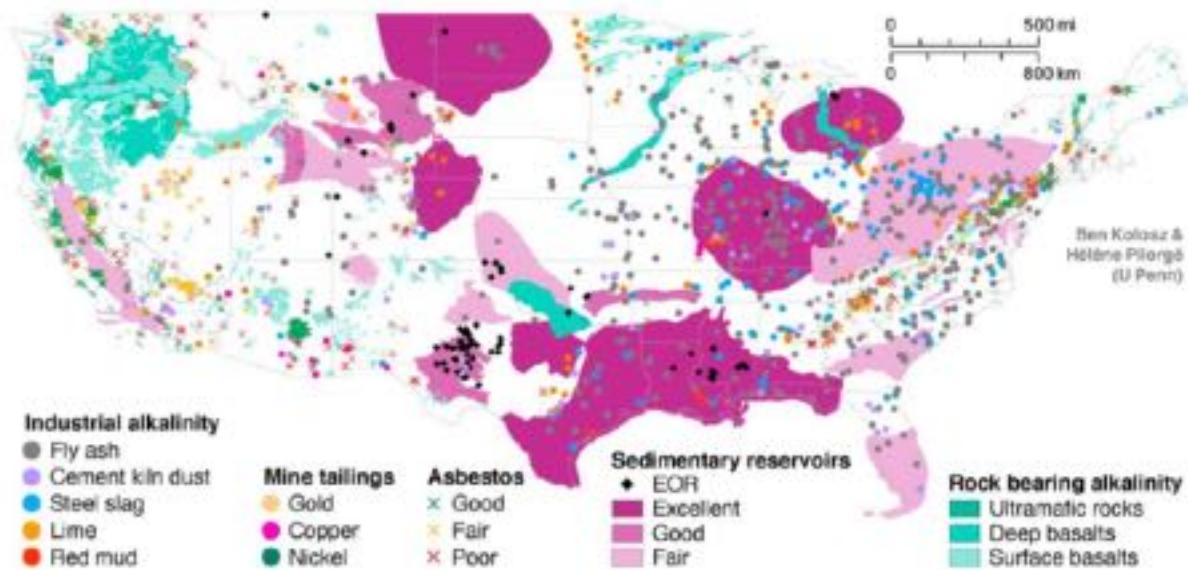
Blondes et al. (2019) in a U.S. Geological Survey Scientific Investigations Report 2018-5079 entitled *Carbon Dioxide Mineralization Feasibility in the United States*, Blondes et al provided detailed maps on the location of sites for mafic and ultramafic mineral in the U.S. In addition, as shown below, they provided a detailed report on the use of **tailings in the U.S.**

Mafic and ultramafic mine tailings are generated during the extraction and production of asbestos, chromite, diamond, nickel, platinum-group metals, and talc. These tailings react passively with atmospheric CO₂ to produce carbonate minerals under natural conditions (Levitin and others, 2009; Wilson, Dipple, and others, 2009; Wilson, Raudsepp, and others, 2009; Pronost and others, 2012). Piping CO₂ into the tailings and designing tailings storage methods to favor increased reactions would significantly increase the carbonation reaction rate (Gerdemann and others, 2007; Harrison and others, 2013; Power and others, 2013; Power and others, 2014). Power and others (2014) and references therein reviewed strategies to increase tailings-hosted reaction rates, including bioleaching.

In the United States, large amounts of mine wastes composed of ultramafic rocks and serpentinite rock have been left behind at abandoned asbestos mines, which could offer potential sites and sources of material for pilot projects of ex situ CO₂ mineralization. Prominent examples occur in Vermont and California (Krevor and others, 2009), such as the abandoned Belvidere asbestos mine near Eden Mills in northern Vermont and the former asbestos mines of the Coalinga mining district in San Benito and Fresno Counties of west-central California.

The relevant references can be found in that report.

EFI (2020c) Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management. This report included a map of the location of sites relevant to EW in the US.



There are clearly a large number of tailings sites.

What About Methane?

We stated in the introduction that one of the advantages of Enhanced Weathering was its potential to remove N₂O and methane as well as CO₂. The effect on N₂O was covered above. So where does the removal of methane come in?

Even if humans stop combusting fossil fuels and discharging CO₂ into the atmosphere, the average global temperature of the earth will continue to increase for the rest of the century for several reasons.

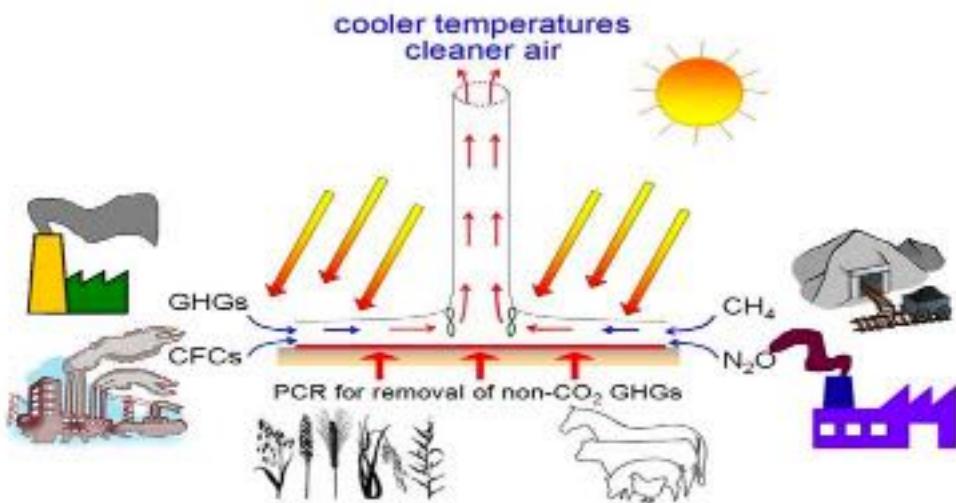
First, the long lifetime of CO₂ (estimated in the 100,000-year range) means that the excess atmospheric stocks (515 Gt Carbon) would continue to drive radiative forcing and global warming for many decades.

Second, even if atmospheric concentrations were to decrease, CO₂ would outgas from the oceans and offset this decrease, because of the dynamic equilibrium between the CO₂ in the atmosphere and the carbonates HCO₃⁻/CO₃²⁻ dissolved in the oceans.

Third, there is the contribution of **other GHGs, besides CO₂, which together account for about 34% of radiative forcing**. Even if all excess anthropogenic atmospheric CO₂ were removed, radiative forcing would only be reduced by half. Methane emissions from ruminants contribute roughly 120 MtCO₂ equivalents per year in the United States. The following is a proposal on how to remove part of the other half, especially methane.

The Removal of Methane from the Atmosphere with Solar Chimneys

A hybrid of a **Solar Chimney Power Plant (SCPP)** and a **Photo-Catalytic Reactor (PCR)** has been proposed as a method of removing non-CO₂ greenhouse gases. The concept is shown here (deRichter et al. 2017; Schlaich, 1995; Schlaich, et. al. 2005).



The SCPP is an established concept that generates electricity in a solar updraft tower incorporating axial-flow turbines. Hot air is supplied to the tower by a large solar hot air collector. A conventional SCPP-PCR is composed of 4 principal components:

1. A very large collector for the greenhouse effect.
2. A tall chimney for the stack effect.
3. A thermal energy storage layer (water) to store the solar radiation for night-time operation.
4. Several turbines to generate renewable electricity which is carbon free.

PCR can be incorporated in the SCPP by coating its collector with a photo catalyst, such as TiO₂, which is able to transform methane and other non-CO₂ GHGs into less harmful products. Transformation of 1 kg of methane into 2.75 kg of CO₂ reduces its climate change effect by 90% and is equivalent to removal of 25.25 kg of CO₂ from the atmosphere.

The SCPP component could produce sustainable decarbonized renewable energy for grinding the rocks. If the costs of SCPPs can be kept low, the world-wide installation of 50,000 SCPPs, each of capacity 200 MW, would generate a cumulative 34 PWh of renewable electricity by 2050. In addition to providing green energy, these SCPP-PCP devices would **reduce or stop the atmospheric growth rate of the non-CO₂ GHGs and progressively reduce their atmospheric concentrations.**

Direct Capture of N₂O

Just as methods are available for the direct capture of CO₂ from the atmosphere, the same is true for N₂O. Jang et al, (2021) present an energy-efficient **clathrate-based greenhouse gas-separation (CBGS)** technology that can operate at room temperature for selectively recovering N₂O from gas mixtures. We propose to test this approach to the removal of N₂O as an ancillary part of SCPP-PCR i.e., SCPP-PCR-CBGS.

One of the research projects the Comings Foundation would support, **is determining if SCPP-PCR-CBGS works as proposed above.** One potential approach would be to enlist the help of **Fluor**, a company that “provides professional and technical solutions to deliver safe,

well-executed, capital-efficient engineering, procurement, and construction (EPC) projects to clients around the world.”

Studies of Enhanced Weathering with Soil

There have been more experimental investigations of the reactivity of olivine than any other multi-oxide silicate mineral. For example, Oelkers et al (2018) review cites over 70 references. In contrast with most other minerals, olivine reactivities measured in different studies and using distinct experimental methods tend to be consistent with one another. Some of these studies will be reviewed here.

O’Conner et al (2004). This DOE study is one of the most comprehensive studies of the **relative carbonation potential, R_{CO_2}** , of different mafic minerals. The following table shows these results. R_{CO_2} was calculated from the total molar concentration of Ca, Fe²⁺, and Mg in the feed, and is defined here as the **mass ratio of rock or mineral necessary to convert a unit mass of CO₂ to the solid carbonate**. By this definition, a low R_{CO_2} is preferable.

Table I. Mineral chemistry, carbonation potential, and reactivity.¹

Rock/mineral group	Mineral	Formula	Concentration, wt pct				$R_{CO_2}^2$	$\epsilon_{30}, \%$	$R_s^3, \%$			
			Feed		Prod.							
			Ca	Fe ²⁺	Mg	CO ₂						
Feldspar	Anorthite (An)	CaAl ₂ Si ₂ O ₈	10.3	3.1	4.8	1.9	4.4	23	9			
Serpentine	Antigorite (Ant)	Mg ₃ Si ₂ O ₅ (OH) ₄	<0.1	2.4	24.6	24.2	2.1	47	92			
Pyroxene	Augite (Aug)	CaMgSi ₂ O ₆ + (Fe, Al)	15.6	9.6	6.9	11.1	2.7	37	33			
Basalt	An, Aug, Mt, Ol		6.7	6.7	4.3	2.9	4.9	37	15			
Olivine (Ol)	Fayalite (Fa)	Fe ₂ SiO ₄	0.6	44.3	0.3	19.2	2.8	36	66			
Olivine (Ol)	Forsterite (Fo)	Mg ₂ SiO ₄	0.1	6.1	27.9	29.7	1.8	56	81			
Serpentine	Lizardite (Liz)	Mg ₃ Si ₂ O ₅ (OH) ₄	0.3	1.5	20.7	16.0	2.5	39	40			
Oxide	Magnetite (Mt)	Fe ₃ O ₄	0.6	21.9	0.3	1.5	5.5	18	08			
Ultramafic	Talc	Mg ₃ Si ₄ O ₁₀ (OH) ₂	2.2	9.2	15.7	5.2	2.8	36	15			
Ultramafic	Wollastonite (Wo)	CaSiO ₃	31.6	0.5	0.3	22.9	2.8	36	82			

¹ Carbonation test conditions: 80% -37 µm feed; 1 hour; 185°C; P_{CO₂}=150 atm; 15% solids; 0.64 M NaHCO₃, 1 M NaCl.

This showed that the minerals with the **lowest R_{CO_2}** were olivine as forsterite (1.8), olivine as fayalite (2.8), serpentine as antigorite (2.1) and serpentine as lizardite (2.5) talc (2.8) and Wollastonite (2.8). Of interest basalt had the second highest R_{CO_2} (4.9). These studies were carried out in aqueous media at elevated temperature (185 °C), elevated CO₂ pressure (150 atm) and elevated salts (0.64 M NaHCO₃ and 1 M NaCl). How well these very abnormal conditions relate to carbonation of mafic minerals at ambient temperature and pressure on croplands are not known but the relative carbonation rates are probably relevant. Pre-treatment consisting of fine grinding was important for olivine and serpentine.

The ultramafic minerals investigated for mineral carbonation generally occur within large ophiolite complexes that are described as remnants of oceanic crust that have been compressed and folded along convergent continental margins. In North America, these ultramafic belts occur along both coasts, rather than the interior, which places some limitations on the application of EW to Midwest crops.

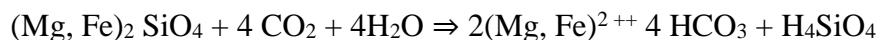
Map of Ultra Mafic sites in US.

An evaluation of the scale of major CO₂ point sources and their proximity to the potential mineral sources resulted in the identification of 7 primary ultramafic mineral carbonation regions within the conterminous U.S. is shown on the following map.



Ultramafic Mineralization Carbonation sites.

Schouling and Krijgsman (2006) The title of this article is: *Enhanced Weathering: An Effective and Cheap Tool to Sequester CO₂*. The problem is how many others agree with this optimistic appraisal? He points out that weathering, until recently, has received little attention, although it is the most important way in which nature keeps the CO₂-levels in the atmosphere down. Mg Olivine (Mg₂SiO₄) is an abundantly available magnesium silicate which weathers according to the reaction



This formula indicates that 4 mol of CO₂ are sequestered by 1 mol of olivine, equivalent to 1.25 t of CO₂ (or 0.34 t of C) per ton of olivine.

Olivine is a cheap and widely available material. By the authors calculations, in order to neutralize the CO₂ currently in the atmosphere, we need to spread a layer of olivine over the whole surface of the earth at about 0.12 cm thickness. If we limit the olivine spreading to the **land mass, the thickness of the layer would be 0.4 cm**. This is a huge amount, equivalent to 1% of the total volume of rock moved by human civilization in its entire history, but even much smaller amounts of olivine could sequester substantial amounts of CO₂, i.e., every little bit helps.

As to the **nickel in olivine** the authors state that If we spread one ton of dunite, it contains 1.4 kg of nickel. A hectare of soil with an average soil depth of 0.5 m weighs approximately 10,000 tons. This means that we add only 0.14 ppm of nickel to such soils every 30 years. As nickel is the most abundant potential contaminant in olivine-rich rocks, it appears that heavy metal pollution is not an issue with dunite applications and that there are **no adverse environmental consequences if we substitute liming by the application of olivine.**

The second commonest trace metal in ultramafic rocks like dunite is chromium, but most of it is tightly bound in very insoluble chromite grains and will not be bio-available.

In conclusion, they state that point sources of CO₂ such as coal generation of electricity, can be treated by reaction with reactive magnesium or calcium-silicates in autoclaves. The products, magnesium-carbonate or calcium-carbonate and precipitated silica should find application, in construction materials, and would make this process economically more attractive. In addition, since some of the reactions with olivine produce heat, this could be used constructively (Schuiling, 2006).

Since many parts of the world are still susceptible to acid rain, it is also possible to use the concept of enhanced weathering by applying powdered olivine or crushed basalt to farmland and woodland that are threatened by acid rain; this is probably the cheapest way to sequester large volumes of CO₂, while it provides at the same time an effective way of counteracting the effect of acid rain on forests and improving the quality of the forest soil.

In summary, the authors get their claim of a cheap tool by producing commercial products and mechanisms of protecting farmlands from acid rain. It still does not negate the huge amounts of olivine required.

ten Berge et al (2012) The author's objectives were to assess weathering of olivine in soil, and its effects on plant growth and nutrient uptake. In a pot experiment with perennial ryegrass (*Lolium perenne* L.), weathering for 32 weeks, was inferred from bioavailability of magnesium (Mg) in soil and plant. Olivine doses were equivalent to 1630 (OLIV1), 8150, 40,700 and 204,000 (OLIV4) kg/ha. Olivine increased plant growth (+15.6%) and plant K concentration (+16.5%). At all doses, olivine increased bioavailability of Mg and Ni in soil, as well as uptake of Mg, Si and Ni in plants. Olivine suppressed Ca uptake. Weathering estimated from a Mg balance was equivalent to 240 kg/ha (14.8% of dose, OLIV1) to 2240 kg/ha (1.1%, OLIV4). This corresponds to gross CO₂ sequestration of 290 to 2690 kg/ha similarity with kieserite treatments ranged from 13% to 58% for OLIV1. Weathering appears fast enough to support the 'enhanced weathering' concept. Olivine amounts must remain within limits to avoid imbalances in plant nutrition, notably at low Ca availability, and to avoid Ni accumulation in soil and crop.

Note how much more understandable the Berge et al statement that the rate of weathering corresponds to gross CO₂ sequestration of 290 to 2690 kg/ha versus the Renforth et al (2015) statement (see below) that the rate of weathering was between 10^{-16.4} and 10^{-15.5} moles(Mg)/cm²/s. Although the latter is based on the math of the Olsen model that does not make it clear to the average reader. Why use seconds instead of days or months? Why weird exponentials like 10^{-16.4} instead of a more understandable 2 x 10⁻¹⁶?

Renforth, (2012) The silicate resources in the UK are large and could theoretically capture 430 billion tons (Gt) of CO₂. The majority of this resource is contained in basic rocks (with a carbon capture potential of ~0.3 tCO₂/t rock). There are a limited number of ultrabasic formations (0.8 tCO₂/t rock) with a total carbon capture potential of 25.4 GtCO₂. It is shown that

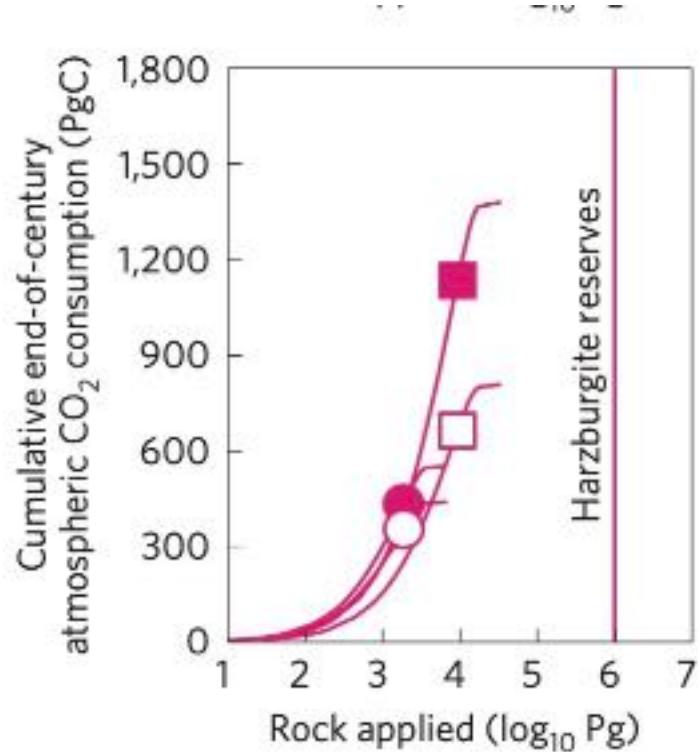
the energy costs of enhanced weathering may be 656–3501 kWh/tCO₂ for basic rocks and 224–748 kWh/tCO₂ for ultrabasic rocks. Grinding and transport are the most energy intensive processes accounting for 77–94% of the energy requirements collectively. The operational costs of enhanced weathering could be £44–361/tCO₂ (\$70–578/tCO₂) and £15–77/tCO₂ (\$24–123/tCO₂) for basic and ultrabasic rocks respectively. Providing sufficient weathering rates full exploitation of this resource is not possible given the environmental and amenity value of some of the rock formations. Furthermore, the weathering rate and environmental impact of silicate mineral application to the land surface is not fully understood, and further investigation in this area is required to reduce the uncertainty in the estimated costs presented here.

Moosdorf, N. et al (2014) Terrestrial enhanced weathering consumes more CO₂ than it emits for mining, comminution, transport, and application in most locations. The CO₂-efficiency is dominated by the choice of source rocks and material comminution. CO₂ emissions from transport have a small effect on the overall budget (on average 0.5-3% of potentially sequestered CO₂ and the emissions of material mining and application are negligible. After all emissions, 0.5-1.0 t CO₂ can still be sequestered on average per ton of rock. However, very large amounts of rock would be needed to control or reduce the atmospheric CO₂ concentrations substantially with enhanced weathering. Before enhanced weathering could be applied at large scales, more research is needed to assess weathering rates, potential side effects, social acceptability, and mechanisms of governance.

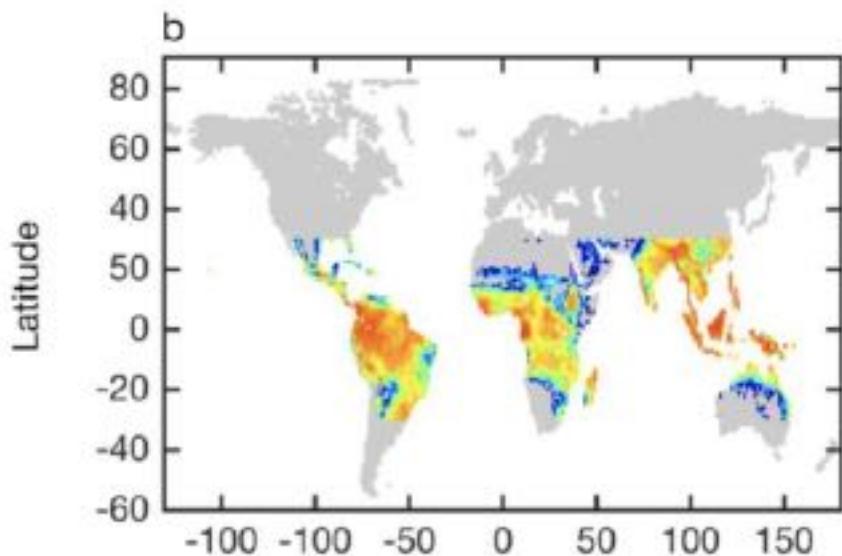
Soldal (2015) The emphasis in this study is the role of olivine weathering in combating the low pH-based release of N₂O. In this regard olivine, nepheline syenite and norite gave the highest pH increase of the silicates.

Taylor et al (2016) In one of the few articles that **take advantage of the striking increase in weathering of olivine type rocks in moist, tropical regions and weathering hotspots**. They found that enhanced weathering scenarios over less than a third of tropical land could significantly draw down atmospheric CO₂ and ameliorate ocean acidification by 2100. However, they emphasize the problems with cost, acceptance and potential unanticipated side effects.

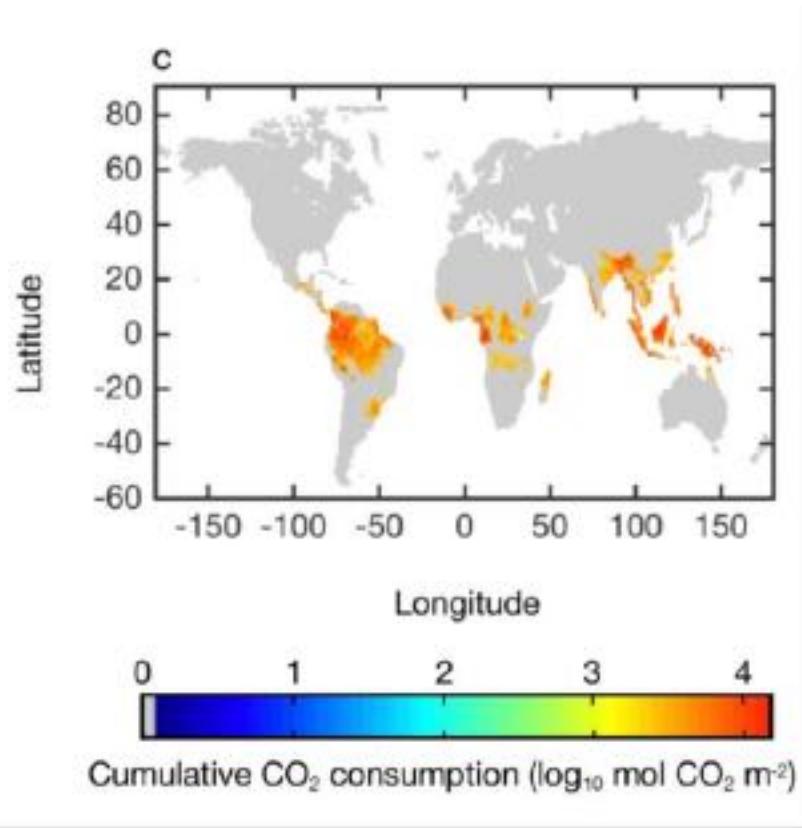
They examined the use of three minerals: Dunite (olivine – (Mg-Fe)₂SiO₄, Harzburgite (olivine + low Ca⁺⁺ pyroxene) and Basalt. The results for Harzburgite were as follows:



This showed the simulation of the application of Harzburgite. Squares represent application in square plots and circles the application in circular plots. The red squares and circles represent limitation of Harzburgite to **Tropical Weathering Hot Spots**. The white squares and circles represent application of Harzburgite to all tropical areas. At a level of application of 4 Pg of Harzburgite there was a sequestering of 1,150 Pg of carbon. The vertical line labeled Harzburgite indicates there were adequate reserves of the mineral.

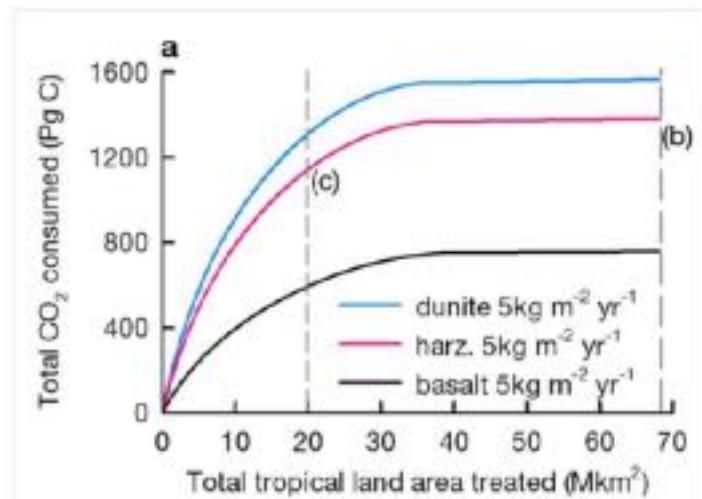


This is a map of the total tropical area 30° N to 30° S. It include both the tropical weathering hot spots and non-hot spots.



This is a map of the **Tropical Weathering Hot Spots** illustrates the meaning of this term, namely areas where the cumulative CO_2 consumption is between 3 and 4 $\log_{10} \text{mol CO}_2/\text{meter}$.

The next figure summarizes all of the above. This diagram shows the data for the hot spots only.

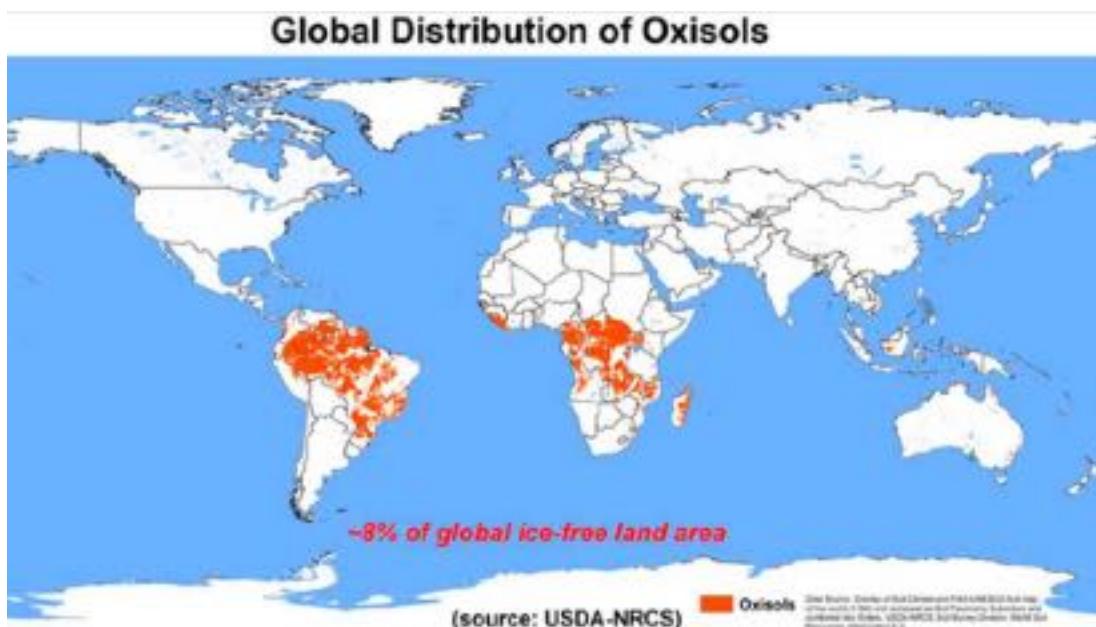


In this diagram of simulations, the vertical line **b** represents how much of each mineral is deposited over the entire tropics consisting of both hot spots and non-hot spots. The vertical line

c how much of each mineral was deposited **only on hot spots** representing 20 Mkm². Their conclusion was that **over 80% of the total CO₂ consumption could be obtained by restricting the application to 5 kg/m² of harzburgite per year to the hot spots.** This suggests that the 29-fold greater Enhanced Weathering in tropical wet climate than in temperate dry regions (see p45) needs to be multiplied by 5, or **145 times to compare temperate dry regions to tropical hot spots.**

Oxisols and Ultisols

Oxisols (from French *oxide*, "oxide") are very highly weathered soils that are found primarily in the tropical regions of the world.

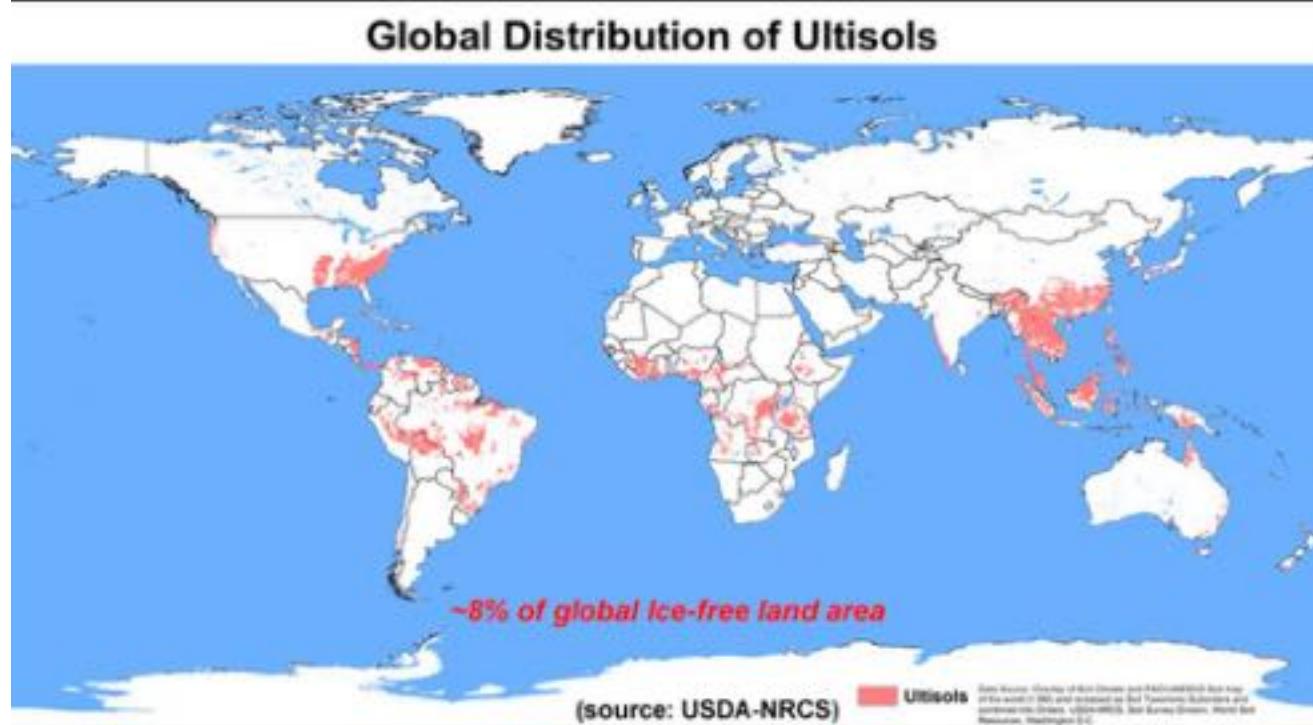


These soils contain few weatherable minerals and are often rich in Fe and Al oxide minerals. Most of these soils are characterized by **extremely low native fertility**, resulting from very low nutrient reserves, high phosphorus retention by oxide minerals and low cation exchange capacity (CEC). Most nutrients in Oxisol ecosystems are contained in the standing vegetation and decomposing plant material. Despite low fertility, **oxisols can be quite productive with inputs of lime and fertilizers**. Oxisols occupy approximately 7.5 percent of the global ice-free land area. In the U.S., they only occupy approximately .02 percent of the land area and are restricted to Hawaii.

Ultisols (from Latin *ultimus*, "last") are strongly leached, **acid forest soils with relatively low native fertility**. They are found primarily in humid temperate and tropical areas of the world, typically on older, stable landscapes. Intense weathering of primary minerals has occurred, and much Ca, Mg and K has been leached from these soils. Ultisols have a subsurface horizon in which clays have accumulated, often with strong yellowish or reddish colors resulting from the presence of Fe oxides. The "red clay" soils of the southeastern United States are examples of Ultisols.

Because of the favorable climate regimes in which they are typically found, Ultisols often support productive forests. The high acidity and relatively low quantities of plant-available Ca, Mg and K associated with most Ultisols make them **poorly suited for continuous agriculture**.

without the use of fertilizer and lime. With these inputs, however, Ultisols can be very productive. They occupy approximately 8.1 percent of the global ice-free land area and support 18 percent of the world's population. They are the dominant soils of much of the southeastern U.S. and occupy approximately 9.2 percent of the total U.S. land area.





The above was based on information from University of Idaho, College of Agricultural and Life Sciences, Twelve Soil Orders.

These areas are also referred to as **laterite soils**, which are formed **under conditions of high temperature and heavy rainfall with alternate wet and dry periods**. This leads to leaching of soil, leaving only oxides of iron and aluminum. It lacks fertility due to a lower base-exchanging capacity and a lower content of nitrogen, phosphorus, and potassium (Leonardos et al, 1987).

The distribution of oxisols and ultisols is highly relevant to the subject of Enhanced Weathering of croplands for several reasons.

1. It shows those areas of the world and U.S. that would benefit the most from EH of croplands.

2. Enhanced weathering with mafic and ultramafic are very effective in treating acid ultisols.

3. Many of these areas are also close to sources of mafic and ultramafic rocks, significantly reducing transportation costs.

4. World-wide it shows a remarkable similarity between the distribution of weathering hot spots (see above) and areas of oxisols and ultisols. Thus, the areas that need mafic and ultramafic rocks as fertilizer and the areas of weathering hot spots are very similar. This is because the very factors that make hot spots, e.g., warm temperatures and high rainfall, also cause oxisols and ultisols. Initially focusing on these areas for the application of mafic and ultramafic rock would make the process far more efficient.

How are Weathering Hot Spots Identified?

Tropical areas are weathering hotspots because high forest primary production and warm, wet climates promote mineral weathering. While Taylor et al (2016) identified weathering hot spots as areas where the cumulative CO₂ consumption is between 3 and 4 \log_{10} mol CO₂/meter, how is this CO₂ consumption determined? Three 2009 papers by Hartmann (Hartman et al, 2009 a, b; Hartmann, 2009) provide the answer. These areas are determined by two different approaches: i) a reverse approach based on hydro-chemical fluxes from large rivers and ii) a forward approach applying spatially explicit a function for CO₂ consumption. Here a CO₂ consumption model, trained at high resolution data, was applied to a global vector based lithological map with 15 or more lithological classes. The calibration data were obtained from areas representing a wide range of weathering rates. The authors used this latter technique which has far greater resolution. The results highlight the role of **hotspots** (> 10 times global average weathering rates) and **hyperactive areas (5 to 10 times global average rates)** (Maybeck et al 2006). Only 9 % of the global water runoff area is responsible for about 50 % of CO₂ consumption by chemical weathering. If hotspots and hyperactive areas are considered: 3.4% of water outflow surface area corresponds to 28% of global CO₂ consumption.

Regions dominated by volcanos are hyperactive or even “hot spots” in relation to dissolved silicon (DSi) mobilization (Hartman et al, 2009). Many of the "hottest" spots are found in Southeast Asia. Some of these hotspots coincide with, or are near to, tropical peat swamp forests in coastal Sumatra, Malaysia and Borneo, which are also global biodiversity hotspots currently under pressure from logging, fire and land use change. As shown in the above figure, there are also hot spots in Central and South America, which would be far more amenable for a Comings Foundation research program.

Renforth et al (2015) Despite considerable work in recent decades, significant gaps in understanding natural weathering remain. Dissolution rates determined from catchment scale investigations are generally several orders of magnitude slower than those predicted from kinetic information derived from laboratory studies. On the basis of these laboratory studies, temperature, mineral saturation, pH and surface area are important variables. In soil rainfall rate is also important.

The authors presented results from laboratory flow-through dissolution experiments which seek to bridge this observational discrepancy by **using columns of soil returned to the laboratory from a field site**. Continual addition of water to the top of the soil columns, and analysis of elemental composition of waters exiting at the base was conducted for a period of five months, and the solid and leachable composition of the soils was also assessed before and after the experiments. Chemical results indicate clear release of Mg⁺² from the dissolution of olivine and, by comparison with a control case, allow the rate of olivine dissolution to be estimated between $10^{-16.4}$ and $10^{-15.5}$ moles(Mg)/cm²/s. This is based on the Olsen (2017) and TNO (2008) model of the rate of dissolution. The olivine dissolution rates are intermediate between those of pure laboratory and field studies and provide a useful constraint on weathering processes in natural environments, such as during soil profile deepening or the addition of mineral dust or volcanic ash to soils surfaces.

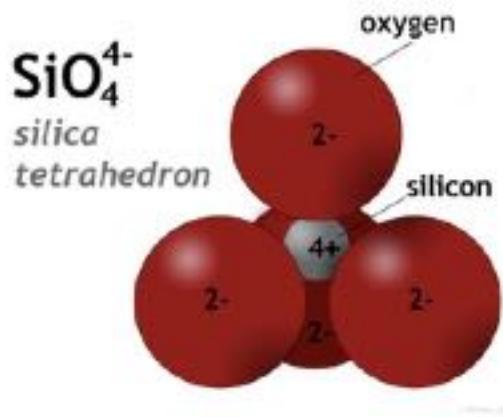
A number of workers have suggested that the release of potentially toxic elements during the dissolution of olivine may pose an environmental risk which would subsequently lower the potential of terrestrial enhanced weathering (Hartmann et al., 2013; Renforth, 2012). From the results of this study, **there was elevated Cr in 5 of the solution samples from the olivine**

column, the remaining samples showed no difference compared to the control. Ni was measured but was below the detection limit in all of the effluent solutions.

This suggests that >99% of these trace elements are retained within the soil, which is unsurprising given the high concentration of these elements in very mature soils such as laterites (Lewis et al., 2006), implying that the **short-term environmental impact of trace metals from the added olivine may be limited**. However, the long-term accumulation of these elements may pose an environmental risk, which could eventually limit the application.

The largest uncertainty is the **energy requirements of material pulverization**. (Renforth, 2012). Simple calculations indicate that it would be necessary to grind olivine to a particle size of 1 um or less to enable dissolution in 1–5 years, requiring grinding energy of around 1.5 GJ (electrical) per ton of rock (comparable with the more extensively studied alternatives for CO₂ uptake such as direct air capture). Setting up renewable energy sources could divert these costs.

Oelkers et al. (2018) Olivine dissolution reactivity is relatively simple. Its structure is comprised of isolated Si-O⁴⁻ 4-tetrahedra linked by divalent cations.



Aqueous species that adsorb to these bonds apparently accelerate their destruction. For example, the absorption of H⁺, H₂O and, at some conditions, selected aqueous organic species will increase olivine dissolution rates. Nevertheless, other factors can slow olivine dissolution rates. Notably, olivine dissolution rates are slowed by lowering the surface area exposed to the reactive aqueous fluid, by for example the presence and/or growth on these surfaces of either microbes or secondary phases.

A survey of the literature suggests that the major factors influencing forsterite olivine dissolution rates are **pH, water activity, temperature, and surface area**. Evidence suggests that the effects of aqueous inorganic and organic species are relatively limited and may be attributed at least in part to their influence on aqueous solution pH. Moreover, the observed decrease in rates due to the presence of secondary mineral coatings and/or the presence of microbes can be attributed to their ability to decrease olivine surface area directly exposed to the reactive aqueous fluid. Each of these factors limits and or influences the application of forsterite dissolution to 1)

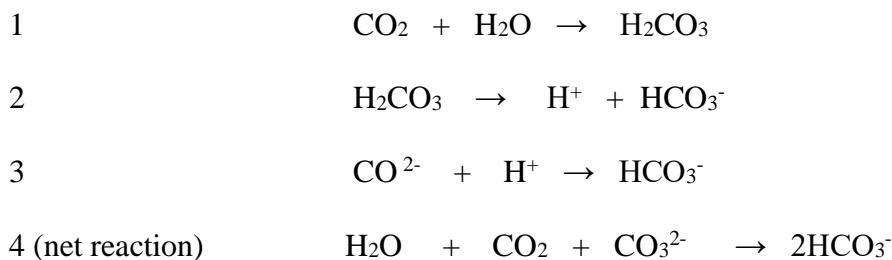
enhanced weathering efforts, 2) mineral carbonation, and 3) the low temperature generation of hydrogen or hydrocarbons via the oxidation of its divalent iron.

Olivine dissolution can proceed by the breaking of just the ionic Mg-O bonds, liberating the SiO_4^{4-} anions directly into solution. Due to both the absence of covalent Si-O-Si bonds and the relative weakness of the ionic divalent metal-oxygen bonds in its structure, olivine is among the fastest dissolving silicate minerals.

Philip, et al (2021) This study presents lithium and magnesium isotope ratios of soils and their drainage waters from a well-characterized weathering experiment with two soil cores, one with olivine added to the surface layer, and the other a control core. The experimental design mimics olivine addition to soils for CO_2 sequestration. At the start of the experiment, waters draining both cores have similar Mg isotope composition to the soil exchangeable pool. The composition in the two cores evolve in different directions as olivine dissolution progresses. For Li, waters exiting the base of the cores initially have the same isotope composition, but then diverge as olivine dissolution progresses. For both Mg and Li, the transport down-core is significantly retarded and fractionated by exchange with the exchangeable pool. This observation has implications for the monitoring of enhanced weathering using trace elements or isotopes, because dissolution rates and fluxes will be underestimated during the time when the exchangeable pool evolves towards a new equilibrium.

The Basics of CO_2 and Ocean Chemistry (Harvey, 2008)

The emission of CO_2 into the atmosphere from human activities leads to an increase in the partial pressure of atmospheric CO_2 , and in response to this, there is a net flow of gaseous CO_2 into the surface layer of the ocean. Once dissolved in surface water, CO_2 combines with water to form a weak acid (carbonic acid, H_2CO_3), which then dissociates to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. The reactions are



Reaction (2) would tend to increase the acidity of seawater as CO_2 is added, except that CO_3^{2-} consumes the H^+ that is released by reaction (2), so that there is no change of pH as long as the occurrence of reaction (2) is balanced by reaction (3). The carbonate ion thus acts as a buffer, inhibiting changes in pH to the extent that it is available. However, **the supply of CO_3^{2-} in the surface layer of the ocean is limited, so as more CO_2 is absorbed by the ocean, the H^+ concentration (and hence acidity) of ocean water increases.**

At the same time as ocean acidity increases, the concentration of CO_3^{2-} decreases. CO_3^{2-} is a constituent in CaCO_3 (calcium carbonate), which occurs in two mineral forms: used as the structural material of corals and pteropods (high-latitude zooplankton), and **calcite**, used as the structural material of the foraminifera (animals ranging in size from less than 1 mm to several

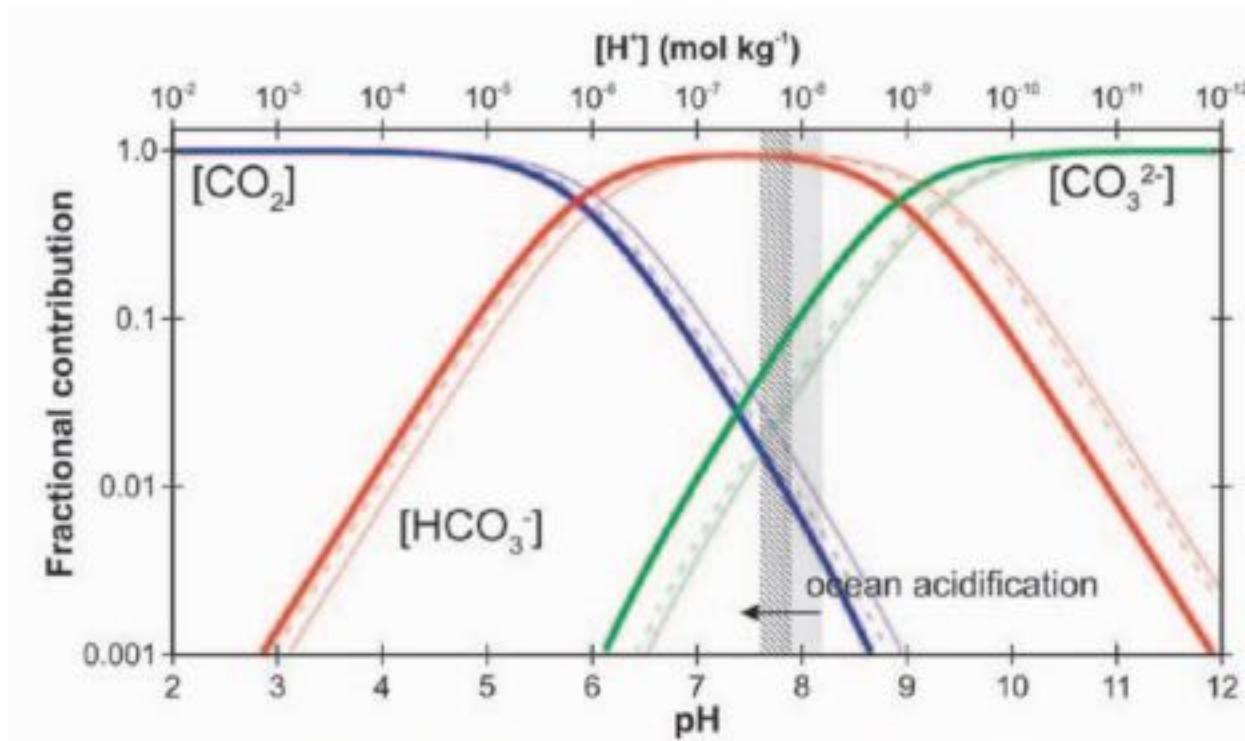
centimeters) and coccolithophores (a group of phytoplankton). Also, many echinoderms and mollusks and some crustaceans contain calcareous shells or exoskeletons.

Although calcareous plankton account for only a few percent of marine primary productivity, calcareous organisms occur throughout the marine food chain, while coral reefs are thought to shelter over two million species of marine life. The surface waters of the oceans are presently supersaturated with respect to both forms of calcium carbonate, a condition that is essential for the growth and health of calcareous organisms. However, the absorption of CO₂ by the oceans reduces the degree of supersaturation by reducing the carbonate (CO₃²⁻) concentration. These decreases in the supersaturation with respect to calcite and aragonite are likely to have profoundly negative impacts on marine ecology.

The carbonate concentration required for supersaturation increases with increasing pressure and hence with increasing depth in the ocean. As a result, deep ocean waters are unsaturated with respect to CaCO₃, and carbonate sediments produced by the downward rain of dead calcareous plankton accumulate only on the shallower ocean floor (above depths ranging from about 0.3 km to 4 km). Over a period of several thousand years, the decrease in CO₃²⁻ concentration as the ocean absorbs anthropogenic CO₂ will induce the dissolution of the deepest carbonate sediments, **as water that had been supersaturated becomes unsaturated.** This will restore the CO₃²⁻ that had been depleted from ocean water, neutralize the increase in acidity of ocean water, and allow the ocean to absorb further CO₂ from the atmosphere over a period of several thousand years. The whole process can be sped up if finely ground limestone, which is overwhelmingly CaCO³, were to be sprinkled into the surface layer of the ocean and allowed to sink into unsaturated deep water, where it would dissolve. Seawater with restored CO₃²⁻ could be available to absorb more atmospheric CO₂ within as little as a few years after the addition of CaCO₃.

Bjerrum Plot for Carbonate Systems

To obtain an estimate of the relative amounts of the carbonate cycle that are in sea water at a given pH we turn to a Bjerrum plot named after Niels Bjerrum. It is a graph of the relative concentrations of the different species of a of the carbonate cycle in a solution, as a function of pH, when the solution is at equilibrium. Due to the many orders of magnitude spanned by the concentrations, they are commonly plotted on a logarithmic scale.



To determine the ratio of CO_2 , HCO_3^- and CO_3^{2-} to each other, run a straight line up from any pH. For example, at ocean pH of about 8, approximately .93 or 93% are in the form of HCO_3^- , 0.08 or 8% is in the form of CO_3^{2-} and 0.01 or 1% is in the form of CO_2 . The solid bars are at temp = 25°C and salinity = 35%. The other lines are for different conditions. The hashed region represents the ocean pH in 2010. The grey region is the ocean pH years prior to 2010.

From the above it can be seen that the ability of seawater to buffer changes in its pH as CO_2 is added depends on the amount (or concentration) of CO_3^{2-} present. Note that as $\text{CO}_{2\text{(aq)}}$ increases CO_3^{2-} decreases. The buffering capacity of seawater will decrease as more CO_2 is added and CO_3^{2-} is progressively consumed. Because of this, **the proportion of CO_2 added to seawater that remains as $\text{CO}_{2\text{(aq)}}$ increases as more CO_2 is added**, an effect first recognized by Roger Revelle and Hans Suess (Revelle & Suess 1957) and quantified as the '**Revelle Factor**'.

The proportion of DIC present as CO_2 is also affected by temperature. The consequence of this is that, as the ocean warms, less DIC will be partitioned into the form of CO_2 (and more as CO_3^{2-}), hence enhancing the buffering and providing a 'negative feedback' on rising atmospheric CO_2 . A well-known positive feedback in the carbon cycle arises due to the decrease in solubility of CO_2 gas in seawater at higher temperatures. In fact, this greatly outweighs the negative feedback described above, meaning that **as the ocean surface warms, even more of the emitted fossil fuel CO_2 will remain in the atmosphere**.

By way of conclusion, Revelle remarked that "Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future." This sentence has **since been quoted more than any other statement in the history of global warming**, (Roger Revelle's Discovery, 2021).

In summary, before scientists would take green-house effect warming seriously, they had to get past a counter-argument of long standing. It seemed certain that the immense mass of the

oceans would quickly absorb whatever excess carbon dioxide might come from human activities. Roger Revelle discovered that the peculiar chemistry of seawater prevents that from happening. His 1957 paper with Hans Suess is now widely regarded as the opening shot in the global warming debates (Roger Revelle's Discovery, 2021).

Putting Mafic Rocks in the Ocean

The limits imposed by needing to avoid large shifts in pH in freshwater (river) systems might be avoided by dissolving olivine in the surface ocean (Köhler et al., 2013; Hartman et al., 2013) where the concentration of dissolved silicon (DSi) is well below the saturation level and much larger volumes of water are involved.

Direct dissolution of olivine in the open ocean might significantly increase the realistic scope of Enhanced Weathering with olivine (or other minerals). The CO₂ sequestration per amount of olivine being dissolved is slightly smaller if olivine is dissolved in the ocean compared to on land, but this effect is relatively small, and the benefit would be a faster rise in surface ocean pH, a very welcome outcome for counteracting ocean acidification. However, surface ocean pH is approximately 7.8–8.3, and dissolution would proceed at a much slower rate than in tropical soils (see figure page 11), thus requiring smaller mineral grain sizes for comparable dissolution rates relative to the application of the minerals onto soils. Moreover, potential complications such as the settling of grains into the deep ocean prior to their complete dissolution would have to be carefully assessed (Hartman et al., 2013).

Based on the discussion of total alkalinity at the beginning of this presentation, the input of Mg²⁺ and Ca²⁺ leads to an immediate increase of TA. The “one-time-input” weathering of 10 Gt olivine (e.g., pure forsterite (Mg₂SiO₄) would result in an input of 1.4×10^{14} mol Mg²⁺. If this input were evenly distributed over the whole ocean surface (taken here as the upper 50 m of the water column), the impact on TA and pH would be relatively small ($\Delta\text{TA} = 8 \text{ mmol kg}^{-1}$, $\Delta\text{pH} = 0.001$. (Hartmann, et al 2013). However, changes in TA and pH would increase over time if the same amount of olivine was weathered every year over a longer period. If the “one-time-input” is restricted to a much smaller volume the local changes in TA and pH would be much higher ($\Delta\text{TA} = 790 \text{ mmol kg}^{-1}$, $\Delta\text{pH} = 0.11$ for 1% of the upper ocean volume). The extent of the change in TA and pH in the surface ocean over time will depend in part on circulation and mixing and thus has to be calculated using an ocean circulation model.

The above opens the possibility of **raising the ocean pH of a relatively small area around the Great Barrier Reef of Australia** and rescuing those corals. As shown above, there are a number of mining sites in Australia or nearby New Guinea and New Caledonia, that could keep the transportation costs low.

The above maps on the location of mafic rocks in the US show that some of the largest concentrations are close to the Pacific coast. By contrast, there are fewer sites in the Midwest where most of the farming is. This raises the question of whether it would be more efficient to dump finely ground mafic rocks directly into the ocean. Studies of the weathering of mafic rocks in seawater are reviewed below.

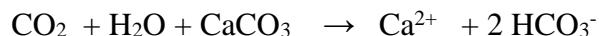
Ocean Alkalinity Enhancement (OAE) and Electrochemistry

The concept of OAE has been presented above. The following reviews several of the relevant critical papers and reviews the electrochemistry involved. The two major approaches to ocean alkalinity enhancement (OAE) are 1. The addition of carbonate minerals, 2. The addition of silicate minerals.

1. The Addition of Carbonate Minerals.

And here there are also three approaches.
a. **Carbonate rocks can be crushed, reacted with CO₂**, such as at captured at power plants, to produce carbonic acid solution bicarbonate ions that would be released to the ocean (Rau and Caldeira, 1999, 2001; Rau et al, 2001; Caldeira and Rau, 2000; Rau, 2008). This is termed the **carbonate-dissolution process**.

CO₂ rich exhaust gases from fossil fuel power plants when dissolved in seawater in a reactor vessel at the power plant would produce a carbonic acid solution H₂CO₃. This readily solubilized crushed carbonate rocks, such a CaCO₃, producing Ca²⁺ and 2HCO₃⁻.



The latter is released back into the seawater where it is diluted. The added Ca++ results in an increase in alkalinity while the HCO₃⁻ which cannot directly interact with the atmosphere, thus sequestering carbon (Caldaria and Rau, 2000). Mann (2020) pointed out that the process of CO₂ capture at power plants is only 90% effective in capturing CO₂, thus large amounts are still released into the atmosphere. Caldaria and Rau (2000) recognized that and stated that to attain 100% capture, additional methods would need to be added.

They reported that substantial infrastructure would be required to mine, transport, crush and dissolve these minerals plus substantial pumping for a large operation. The power plants would have to be located near the coast. They estimated a cost of \$68 per ton of C sequestered versus \$300 per ton for deep sea injection.

b. Alternatively, **Crushed carbonate minerals could be directly released into the ocean** (Kheshgi, 1995; Harvey, 2008). Carbonate minerals such as limestone could be heated to produce lime (Ca(OH)₂) which could be added to the ocean to increase alkalinity (Kheshgi, 1995). The problem with this is that it releases CO₂ to the atmosphere, thus cutting its effectiveness in half.

c. To avoid this release of CO₂ into the atmosphere, **the splitting of calcium carbonate can be done electrochemically** (House et al, 2007; Rau, 2008).

2. The Addition of Silicate Minerals.

Here there are two approaches.
a. **Directly releasing pulverized silicate rocks into the ocean** (Kheshgi, 1995) to increase alkalinity and drawdown of atmospheric CO₂.

Using carbonate or silicate mine tailings, which are already crushed to a small particle size is a viable alternative. Here energy requirements would be lower because of the small particle size, but little is known about trace contaminants in mine tailings that might be released (Renforth, 2017).

b. This process can also be **enhanced electrochemically** (House et al, 2007).

Electrochemistry

As indicated above, electrochemical processes have been proposed for the enhancement of the use of both carbonate and silicate minerals in OAE. The use of electrochemistry has the following **advantages**. Because of these we cover electrochemistry in some detail.

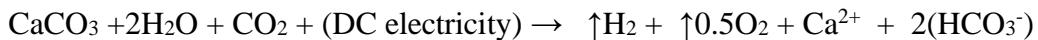
- a) It has the potential of being the cheapest method of OAE.
- b) If placed on ships it can do OAE in many places thus speeding up its ocean wide dispersion.
- c) If placed on ships it can be used locally such as at the Great Barrier Reef to counter the destruction of the coral reefs.
- d) If placed on ships the following sources of non-fossil fuel could make the process independent of fossil fuels: solar, wind, and closed ammonia driven OTEC (Ocean Thermal Energy Conversion).
- e) If placed on ships it could concentrate on areas of the greatest ocean to air emissions (out gassing) and areas of greatest utility for using OTEC.
- e) If the electrolysis-GDA (gas diffusion anode) process is used it is up to 5 times more energy efficient than the Chloralkali process.
- f) If EW with the production of H₂ by Electrolysis is used it is up to 50 times more efficient than BECCS.
- f) The mafic rock used would not have to be ground to a 1 um size, further saving energy.

So, how do these electrochemical processes work?

a. For Carbonate Rocks.

In the **Rau (2008)** article, *Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity*.

In this process the chemical reaction involved is:



Powdered CaCO₃ (limestone, chalk, dolomite) is added to the reaction mix. CaCO₃ comprises more than 4% of the earth's crust and is found throughout the world. It's inexpensive and occurs in common natural forms such as listed above. It cannot be directly added to the ocean and be expected to take up CO₂ since that is the final form by which nature stored CO₂ in the ocean. However, when electricity is used in the presence of seawater, CO₂ is consumed (above). The reaction produces hydrogen and oxygen gas, Ca²⁺ and soluble bicarbonate (HCO₃⁻) both of which increase the alkalinity of the ocean which leads to increased CO₂ uptake by the ocean and combats ocean acidification. In experiments by Rau (2008), after the electricity of this mix was turned on the pH of the solution **increased from 8.0 to 9.0. in 1.5 hrs.**

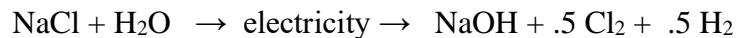
The electrolysis could be done directly in the ocean seawater where the electrodes and carbonate would penetrate the water surface from either stationary (e.g., docks, jetties, platforms) or mobile, piloted, or vessels (barges, ships, buoys, etc.). If non-fossil-fuel electrical power is generated on site using wind and solar, the electrochemical splitting of the carbonate could proceed on site without using fossil fuels and generating alkalinity directly into the ocean. Calcium carbonate would need to be supplied at a rate of 1 mole of CaCO₃ per mole of CO₂ consumed, or 2.3 tones per net ton CO₂ consumed. (The molecular weight of CaCO₃ is 100.0 and of CO₂ is 44.0. 100.0/44.0 = 2.27).

The exact quantity would be dependent upon the purity and reactivity of the carbonate used. In turn the H₂ produced could be **used in fuel cells** to supplement the other non-fossil fuel sources of electrical power. (It would be of interest to determine how much of the electricity used for electrochemistry can be recovered with the fuel cells).

b. For Silicate Rocks

In the **House et al (2007)** article, *Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change*, the authors describe the process of removal of HCl from the ocean which liberates sodium hydroxide and thereby increases the alkalinity of seawater. This process enhances oceanic uptake of CO₂. Alternatively, NaOH and HCl can be produced via electrolysis of an artificial brine made from mined rock salt or from desalination plants. After neutralizing the HCl via **the dissolution of silicate rocks**, the dissolution products and the NaOH are added to the ocean to increase its alkalinity. The thermodynamics of the process that employs seawater are essentially the same as the process that employs an artificial NaCl solution. The steps of the process are as follows.

Step 1 involves the removal of chloride ions from a salt solution. This **Chloralkali process** is a standard electrochemical process for producing chlorine gas and hydrogen gas from NaCl



With modification this can be employed to produce Cl₂ and H₂ from seawater.



In this step H₂ and Cl₂ can be used in a special **fuel cell** to produce electricity and HCl.

Step 3. The HCl can be added to mafic rocks to produce MgCl₂ and SiO₂ which can be added to sea water to **increase alkalinity**.



Step 4 The NOH can be used to capture and store CO₂ on land as well as alkalinizing the ocean.



Each mole of HCl removed from the ocean and neutralized increases ocean alkalinity by 1 mol, and on a time scale of about 100 years. Each additional mole of alkalinity causes ~1 mol of atmospheric CO₂ to dissolve into the ocean. The mixing processes will distribute the additional alkalinity into deeper water over hundreds to thousands of years, enhancing the current ocean uptake, which is approximately 7.5 gigatons of CO₂, (2 Gt C per year) (McNeil et al 2003). The higher alkalinity will also increase the supersaturation of calcite or aragonite, leading to its enhanced precipitation.

These time scales for the ocean wide distribution of the alkalinity can be decreased by carrying out the electrolysis on ships that traverse wide swaths of the ocean. The authors listed a number of other potential difficulties involved in bringing this process to scale.

Rau, et al (2013) experimentally demonstrated that direct coupling of **silicate** mineral dissolution with saline water electrolysis and H₂ production effected **significant air CO₂ absorption, chemical conversion, and storage in solution**. They observed as much as a 10⁵ - fold increase in OH⁻ concentration with a **pH increase of up to 5.3 units**, relative to experimental controls following the electrolysis of 0.25 M Na₂SO₄ solutions when the anode was encased in powdered silicate mineral, either wollastonite or an ultramafic mineral. After electrolysis, full equilibration of the alkalinized solution with air led to a significant pH reduction and as much as a 45-fold increase in dissolved inorganic carbon concentration. This demonstrated significant **spontaneous air CO₂ capture, chemical conversion, and storage as a bicarbonate, predominantly as NaHCO₃**. The excess OH⁻ initially formed in these experiments apparently resulted via neutralization of the anolyte acid, H₂SO₄, by reaction with the base mineral silicate at the anode, producing mineral sulfate and silica. This allowed the NaOH, normally generated at the cathode, to go un-neutralized and to accumulate in the bulk electrolyte, ultimately reacting with atmospheric CO₂ to form dissolved bicarbonate.

Using renewable electricity, optimized systems at large scale might allow relatively high-capacity, energy-efficient (<300 kJ/mol of CO₂ captured), and inexpensive (<\$100 per ton of CO₂ mitigated) removal of excess air CO₂ with production of carbon-negative H₂. Furthermore, when added to the ocean, the produced hydroxide and/or bicarbonate could be useful in **reducing sea-to-air CO₂ emissions** and in neutralizing or offsetting the effects of ongoing ocean acidification.

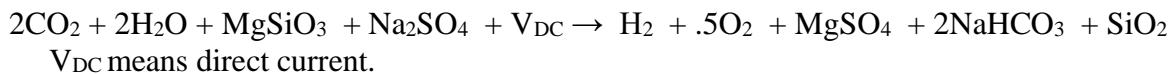
Although silicate weathering is extremely slow under ambient conditions, silicate mineral dissolution and subsequent reaction with CO₂ can be significantly increased in strong acids and/or bases. Because very large pH gradients are produced in **saline water electrolysis cells** [anolyte pH < 2, catholyte pH > 12], it was reasoned that placing a silicate mineral mass in direct contact with such solutions would facilitate their dissolution to metal and silicate ions. Once formed, the positively charged metal ions could migrate to the negatively charged catholyte to form metal hydroxide, whereas the negatively charged silicate ions would react with the H⁺ rich anolyte to form silicic acid, silica, and/or other silicon compounds. Contacting of the produced hydroxide solution with CO₂ would lead to **CO₂ capture and storage as bicarbonate or carbonate**.

It was demonstrated that significantly elevated pH and hydroxide concentrations (relative to controls) can be attained in bulk electrolyte during the **electrolysis of seawater** (naturally containing 0.48 M NaCl) when the anode is encased in a porous carbonate mineral (CaCO₃) mass.

Such approaches have the **potential to be more energy-efficient and less environmentally risky than more widely discussed chemical air CO₂ capture and concentration methods**. This is because they avoid:

- (i) energy-inefficient base/sorbent regeneration and production of highly concentrated molecular CO₂ and
- (ii) the need to guarantee long-term sequestration of CO₂.

The mafic rock used was a serpentinized hornblende metaperidotite from the Canadian Shield containing 38.8% SiO₂, 22.6% MgO, 12.5% FeO, 9.23% Al₂O₃, and smaller quantities of other constituents. The primary net reaction inferred was as follows:



The ability to **significantly enhance atmospheric CO₂ absorption into a salt solution with the strategic addition of silicate minerals and the application of DC electricity has been demonstrated**. One implication of the preceding observations is that globally abundant and relatively inexpensive silicate minerals, as well as natural or artificial brines, could be reacted using renewable energy to effect spontaneous capture of air CO₂ and its **long-term storage as bicarbonate or carbonate**. The cogeneration of valuable carbon-negative H₂ and O₂ or Cl₂ could help offset costs or could allow some energy recovery, for example, via fuel cell conversion to electricity with the production of fresh water or acid (HCl). This could be neutralized by adding it to mafic rocks, as proposed by House et al (2017).

Regarding the energy and carbon penalty for mineral extraction, grinding, and transportation, several studies indicate that depending on the circumstances, these costs will be small relative to that for the electrolysis. This is predicated on the assumption that **grinding silicate minerals to extremely small particles** (e.g., 1 μm Kohler et al, 2013) **will not be required for the process**. Significant amounts of preexisting waste silicate mineral particles and fragments (tailings) are also available at little or no cost at certain locations.

Methods of cost-effectively producing and using hydroxides in once-through schemes also allow the use of the massive air contacting offered by natural water bodies (e.g., the ocean), as opposed to reliance on expensive, engineered air contactors to effect air CO₂ absorption and chemical conversion to environmentally beneficial marine (bi)carbonates in solution at global scales.

Perhaps more significantly, the strategic addition of chemical base to the surface ocean in locations when/where the dissolved CO₂ concentration exceeds that in the overlying atmosphere e.g., out gassing regions (Takahashi T, et al. (2009)). This process could consume some of the excess dissolved CO₂, and thus **avoid its degassing to the atmosphere**. This would then reduce some of the ocean's CO₂ emissions back into the atmosphere per year (Prentice, et al. (2001)), and hence proportionately reduce the CO₂ burden in the atmosphere without the need of performing the more difficult task of directly removing CO₂ from air. Furthermore, excess ocean CO₂ removal is required for any effective air CO₂ capture scheme because removal of air CO₂ alone will simply reduce air CO₂ concentration relative to that in the ocean. This leads to an increase in the ocean-to-air CO₂ flux, largely replacing the air CO₂ removed (Cao and Caldeira, 2010). Schemes that consume (Lampitt et. al, 2008) or remove and sequester excess ocean CO₂ (Eisaman et al. 2012) therefore effectively address both excess ocean and air CO₂, **sidestepping the need for direct air CO₂ capture**.

Systems using seawater as an electrolyte would be optimally sited at coastal locations, where solar, wind, or ocean-derived electricity would also be locally available and where silicate mineral resources and H₂ markets are in close proximity. The electrolysis could, in fact, be done directly in brine or seawater reservoirs or in the ocean, where the electrodes and silicate would penetrate the water surface from either stationary or mobile platforms (e.g., **modified or specially designed ships**). This would preclude the need and expense of pumping seawater into

electrochemical facilities on land but would also require sea-going infrastructure, maintenance, and resupply. The electrochemical dissolution of the mineral silicate could then proceed *in situ*, generating hydroxide alkalinity and CO₂ absorption potential directly into the water body. However, as previously mentioned, the consequences or avoidance (or use) of various side reactions and byproducts produced during the electrolysis of seawater (e.g., Cl₂, chlorinated organics) would need to be carefully considered (House et al, 2007). Rau, et al (2013) discussed a number of other issues relating to scaling up this approach.

Both proposals suggest that boats could be built or retrofitted to have electricity from on board solar and wind. Most of the time they are on the ocean there is no need for the speed that is provided by diesel engines. Thus, the diesel motors could be supplemented with **electric motors to minimize the use of fossil fuels**. When docked they could be loaded with CaCO₃, other carbonate rocks or ultramafic rocks. If feasible, plans could be standardized for such vessels and each country with access to the ocean and ultramafic or carbonate rocks, could be encouraged to buy one or more. A world-wide fleet of several hundred such vessels would be needed. If each ship was capable of onloading, for example, 100,000 tons of rock, and dispersing it in a week to 10 days, then returning for more, each vessel could accommodate 3,650,000 tons of rock per year. A fleet of 100 such boats could accommodate .36 gigatons per year or approximately .15 gigatons of CO₂ per year. While not the total answer to CO₂ capture it is part of the solution and directly addresses ocean acidification. Another part of the solution can come from enhanced weathering on crop or non-crop land and *in situ* EW.

In relationship to carbon free electricity, there is precedent for using OTEC on ships (Avery and Wu, 1994). The following diagram illustrates the **concept of OTEC**.

Ocean Thermal Energy Plant

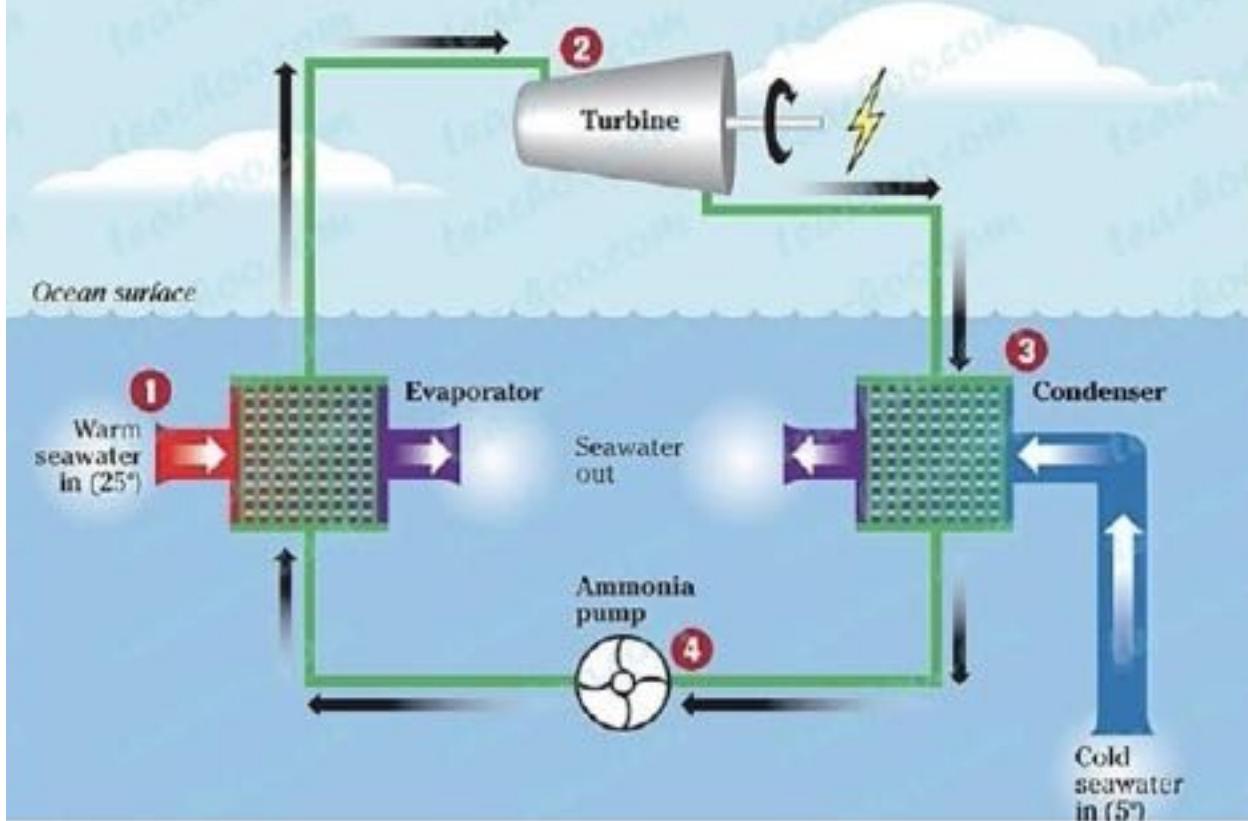
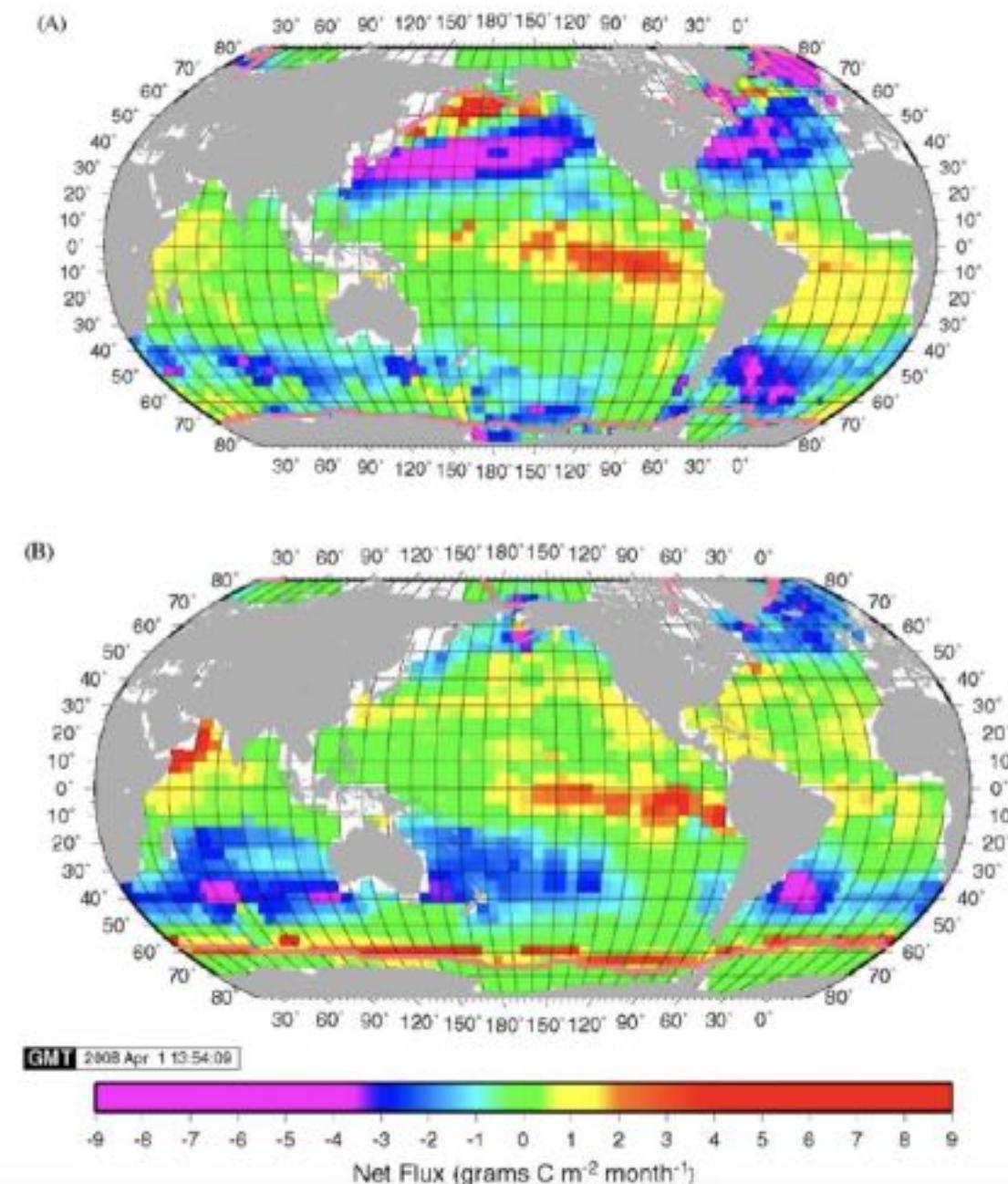


Diagram showing elements of OTEC.

A summary of the US and world production of limestone, CaCO_3 , is available from the USGS (2012). CaCO_3 also occurs as chalk and is mined in northern Europe from the southern UK to eastwards deep into Russia. Dolomite $\text{CaMg}(\text{CO}_3)_2$ is found in Midwestern quarries of the USA; Ontario, Canada; Switzerland; Spain and in Mexico, along with many other places in the world. There are many other types of carbonate minerals.

Ocean Upwelling (Outgassing) of CO_2

It is correctly believed that the ocean adsorbs vast amounts of CO_2 . It is much less appreciated that some areas of the ocean also release huge amounts of CO_2 back into the atmosphere. If this outgassing can be significantly reduced it would have a very positive effect on controlling global warming. Worldwide areas of upwelling are shown in the red and to a lesser degree the yellow areas in the following figure from Takahashi, et al (2009).



Legend for above figure. Climatological mean sea-air CO₂ flux (g-C/m²/month) in **February (A)** and **August (B)** in the reference year 2000. Positive values (yellow-orange-red) indicate **sea-to-air fluxes**, and negative values (blue-magenta) indicate **air-to-sea fluxes**. (Takahashi et al. 2002, 2009).

The areas of the greatest year-round out gassing of CO₂ back into the atmosphere are in the **Equatorial Pacific** west of Ecuador. In the winter (February) the major area is the **Arctic Ocean**. In the summer (August) the major areas are the **Southern Ocean** around Antarctica and **Arabian Sea** next to Yemen.

Upwelling in the Equatorial Belt

Temperate and polar oceans of both hemispheres are the major sinks for atmospheric CO₂, whereas **the equatorial oceans are the major areas for outgassing of CO₂** (Takahashi, T. et al, 1997; Boutin et al, 1999).

The **equatorial areas of outgassing** are between 14N to 14S and **emit +0.7 Pg-C/y back to the atmosphere each year** (Feely et al (2006). Here 0.7 Pg or pentagrams (10^{-15}) equals 0.7 gigatons (10^{-9}) of Carbon or **2.56 Gt (gigatons) of CO₂**. If our goal initially is to remove 10 Gt of CO₂ from the atmosphere each year this would represent 25% of that goal, and this is just the equatorial area. The big question is: **can local efforts from ship based OAE reduce this outgassing?**

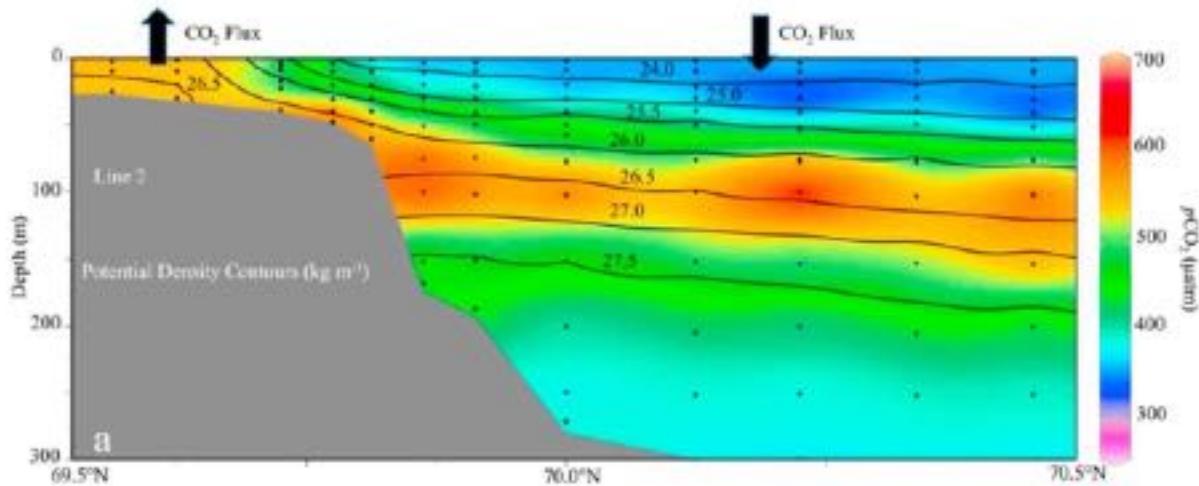
During non – El Niño periods the central and **western equatorial Pacific is a major source of CO₂ to the atmosphere**; it is near neutral during strong El Niño periods, and a weak source during weak El Niño periods (Feely et al (2006). El Niño events occur roughly once every 2 – 7 years and typically last about 12 – 18 months. The opposite phase of the cycle, called La Niña, is characterized by strong trade winds, cold tropical surface temperatures, and enhanced upwelling along the equator. The mean circulation of the equatorial Pacific Ocean is characterized by upwelling that brings cold nutrient- and carbon-rich water to the surface along the equator east of about 160°E during non–El Niño periods. The primary source of the upwelled water along the equator is the narrow Equatorial Undercurrent (EUC), which flows eastward across the basin (Feely et al (2006).

In the western equatorial Pacific, the variability in pCO₂ is also governed by the displacement of the boundary between warm pool waters, where air–sea CO₂ fluxes are weak, and equatorial upwelled waters which release high CO₂ fluxes to the atmosphere (Boutin et al, 1999).

Upwelling in Arctic (Mathis et al, 2012)

The continental shelves of the western Arctic Ocean play an important and likely increasing role in the global carbon dioxide cycle through complex and poorly understood interactions with sea ice, ocean and atmospheric circulation, and terrestrial processes (Bates et al., 2011). Recent studies in this region have shown significant warming of the atmosphere coupled with rapidly declining sea ice extent and thickness and increased storm activity.

In October 2011, persistent wind-driven upwelling occurred in open water along the continental shelf of the Beaufort Sea in the western Arctic Ocean. During this time, cold salty halocline water—supersaturated with respect to atmospheric CO₂ ($p\text{CO}_2 > 550 \text{ matm}$) and undersaturated in aragonite ($\Omega_{\text{aragonite}} < 1.0$) was transported onto the Beaufort shelf. A single 10-day event led to the outgassing of 0.18–0.54 Tg-C and caused aragonite under saturations throughout the water column over the shelf. If we assume a conservative estimate of four such upwelling events each year, then **the annual flux to the atmosphere would be 0.72–2.16 Tg-C**, (T = trillion or 10^{12} , or 10^6 or a million tons of Carbon, or up to **7.9 million tons of CO₂**) which is approximately the total annual sink of CO₂ in the Beaufort Sea from primary production.



Cross-sectional plot of $p\text{CO}_2$ (matm) with density (kg/m^3) contours along CTD (conductivity temperature depth) line. The black arrows indicate the direction of the CO_2 flux (Mathis et al, 2012).

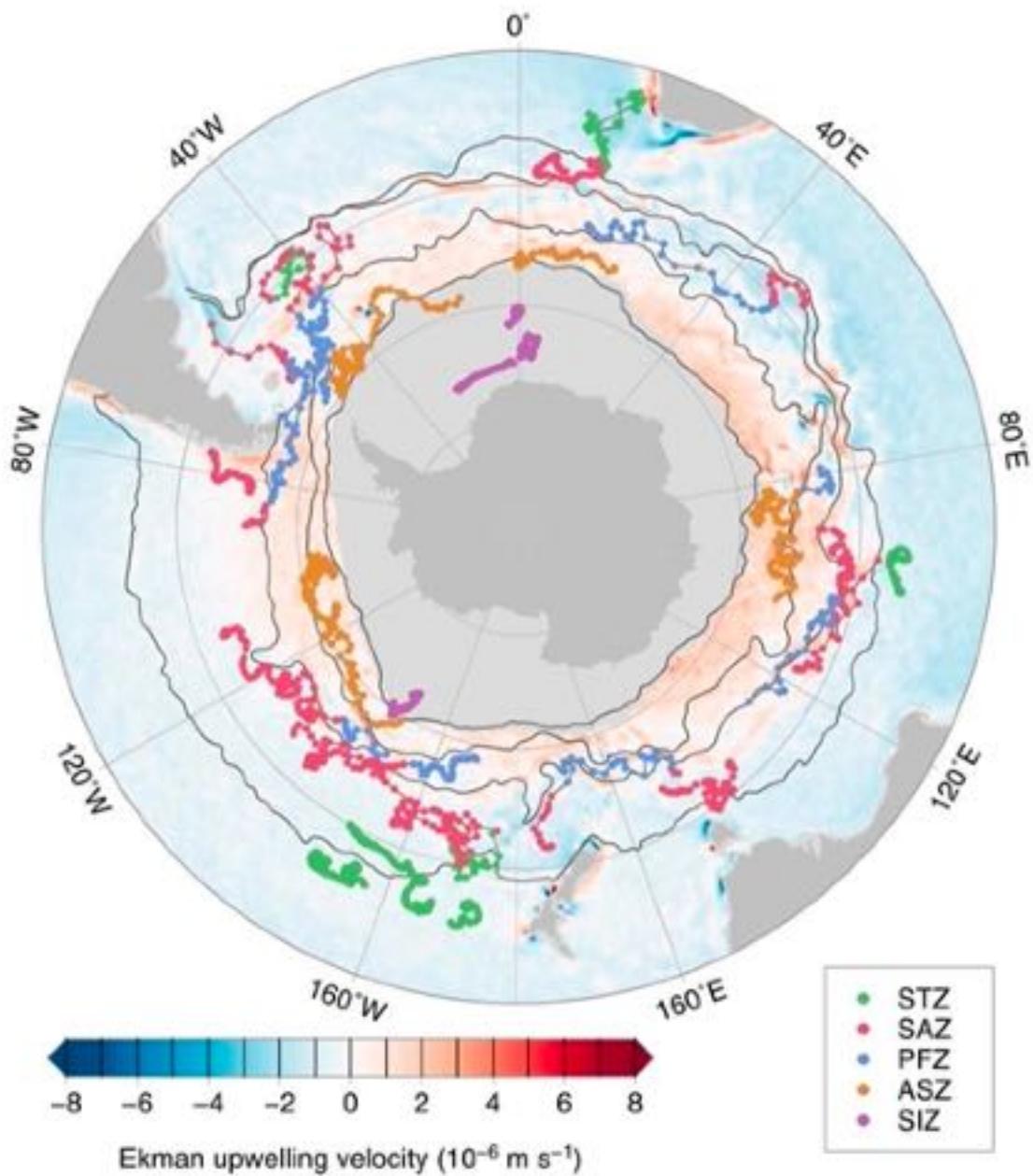
As sea ice retreat continues with global warming, and storms increase in frequency and intensity, further outgassing events and the expansion of waters that are undersaturated in carbonate minerals over the shelf are probable.

Since these upwelling events are natural occurrences, it is likely that this part of the western Arctic shelf has always been a larger source of CO_2 to the atmosphere than has previously been assumed. However, recent reduction in sea ice extent and duration, coupled with increased storm activity, has likely exacerbated the impacts of upwelling on water column saturation states and CO_2 flux across the air-sea interface.

Upwelling in the Antarctic - Southern Ocean

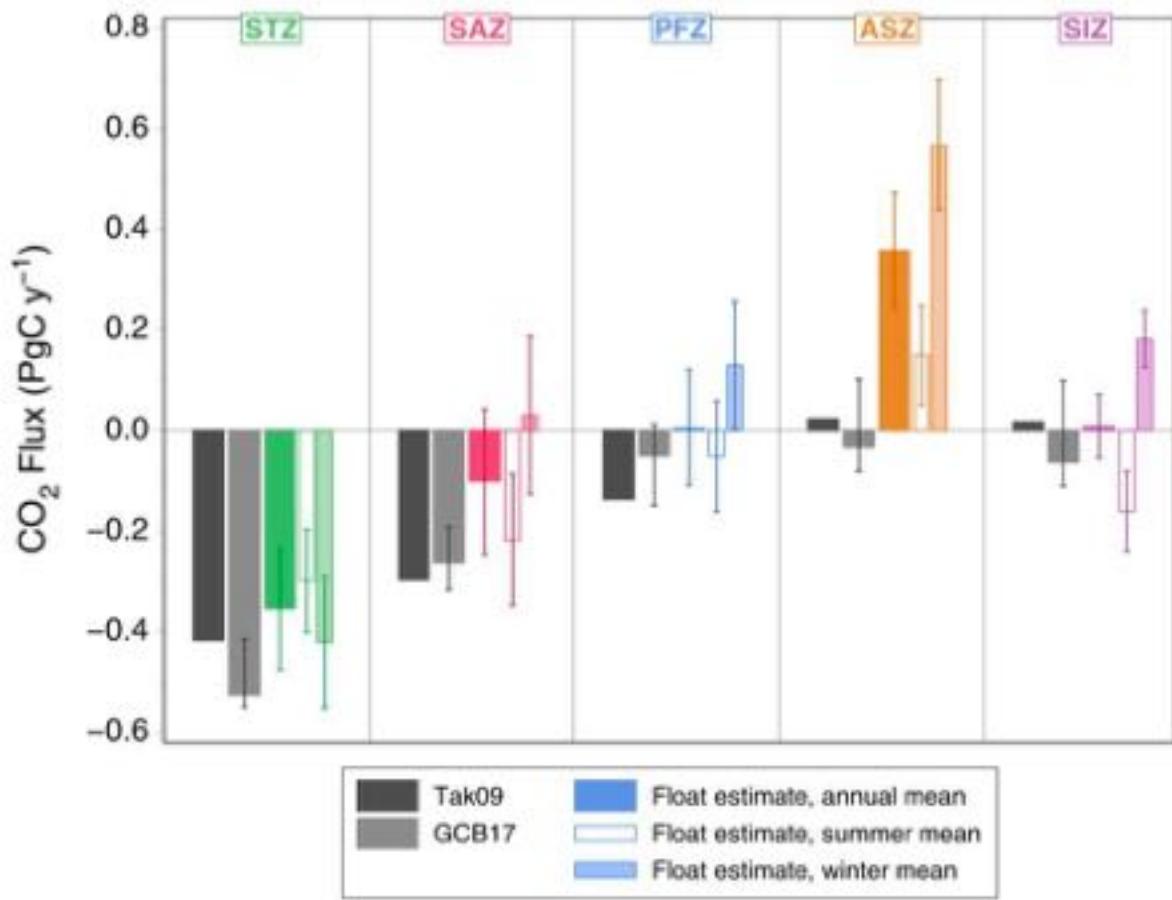
The ocean is able to act like a sponge for anthropogenic CO_2 because of the high concentration of carbonate ions, which react with excess CO_2 to form bicarbonate. That process keeps the oceanic CO_2 concentration low, and thus allows for more uptake. But as the ocean takes up more carbon, the carbonate ions are reduced, which reduces the ocean's ability to absorb CO_2 . As ocean surface temperature increases in the future, the solubility of CO_2 will decrease, which will, in turn, increase the oceanic partial pressure of CO_2 and decrease the rate of ocean carbon uptake. In short, those two processes lead to a positive feedback on global warming: As the ocean warms, it removes less CO_2 from the atmosphere, which leads to increased warming (Morrison, et al, 2015).

So, how much outgassing of CO_2 occurs in the Southern Ocean and where? Precise answers to these questions were provided by Grey et al (2018). In their paper entitled *Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean*. They set out 35 autonomous $p\text{CO}_2$ testing floats at the following locations in the Southern Ocean. This allowed measurements to be made throughout the year, and especially the difficult winter months.



Profile locations from 35 autonomous biogeochemical floats deployed in the Southern Ocean from 1 May 2014 through 30 April 2017, colored according to zone. Dark gray contour lines show the boundaries of the five regions used in the analysis. Background colors show the annual mean wind-induced upwelling velocity, calculated from the Scatterometer Climatology of Ocean Winds (Risien & Chelton, 2008), with light gray indicating the region covered by both seasonal and permanent sea ice in that climatology. STZ = Subtropical Zone; SAZ = Subantarctic Zone; PFZ = Polar Frontal Zone; ASZ = Antarctic-Southern Zone; SIZ = Seasonal Ice Zone.

First, the background colors show that the maximum upwelling velocity is close to the land mass of the continental Antarctica (pink). The following figure shows the positive CO₂ flux (outgassing) and negative flux (CO₂ adsorption) for the five different zones.



Annual net oceanic CO₂ flux (Pg C/year) estimated from float data (solid colors) and from two ship-based estimates, Tak09 (dark gray) and GCB17 (light gray), calculated by sampling the gridded estimates at the same locations as the floats. The mean float-based estimates calculated for May–October (winter) and for November–April (summer) are shown by the narrow bars. Positive indicates net outgassing. Negative indicates uptake. See above for abbreviations.

This shows that the greatest outgassing of CO₂ occurs closest to the coast of Antarctica, (ASZ zone). Thus, approximately 0.5 PgC or 0.5 gigatons of C, or **1.8 gigatons of CO₂** are outgassed around Antarctica each year.

Arabian Sea (Verneil et al, 2021)

The Arabian Sea (AS) is a region of the ocean that has been found to naturally release CO₂ to the atmosphere (Sarma et al., 1998), mitigating the ocean's role in moderating atmospheric CO₂ accumulation. While the AS regional basin is considered too small to greatly impact global budgets of air-sea CO₂ exchange it attracts attention because some of the highest

rates of air-sea CO₂ flux and values of partial pressure of CO₂, or pCO₂, have been observed there, in addition to unique features such as the world's thickest oxygen minimum zone (OMZ) and corresponding Carbon Maximum Zone (CMZ) (Paulmier et al., 2011). A potential advantage of performing OAE in the Arabian Sea is that **Oman, a major source of ultramafic rocks is very close by.** However, it is also rather politically unstable.

Verneil et al, (2021) found that the AS emits ~160TgC/yr, which equals 160 megatons C/y, which equals 587 megatons CO₂/yr or **0.59 gigatons CO₂/yr.**

If we assume that the Arctic and Antarctic outgassing areas are too difficult to reach, that leaves 0.59 gigatons CO₂/yr for the Arabian Sea and 2.56 Gt (gigatons) of CO₂/yr for the Equatorial Zone or **a total of 3.15 Gigatons CO₂/yr that could be amenable to partial reduction by localized OAE.** If OAE was successful in reducing this by half, this would be 1.6 gigatons of CO₂/yr or 16% of the goal of 10 gigatons of CO₂/yr. If it reduced outgassing by 80% that would equal 2.5 gigatons CO₂/yr or **25% of the goal of 10 gigatons CO₂/yr.**

c. Electrolysis-GDA (gas diffusion anode)

Davies et al. (2018) discuss using the brine produced from desalination plants as a source of MgOH₂ for alkalinization of the ocean. Seawater brine contains significant amounts of metal ions which have potential to combine with and sequester CO₂ as carbonate or bicarbonate. This approach is to convert the magnesium chloride in seawater brine to magnesium oxide or hydroxide, which has similar absorptive capacity for CO₂ as calcium oxide as proposed for ocean liming.

Recently, advanced electrochemical methods have been developed to improve seawater brine electrolysis. For example, Xie et al.(2013) introduced a new way of decomposing magnesium chloride by an electrolysis process incorporating a gas diffusion anode (GDA), yielding magnesium hydroxide and hydrochloric acid. This **electrolysis-GDA** method is particularly appealing in terms of **its potentially low energy consumption and simpler configuration of the electrolysis cells.** These would be the key factors in keeping both capital and operational costs low for large scale processing. The following diagram illustrates the apparatus.

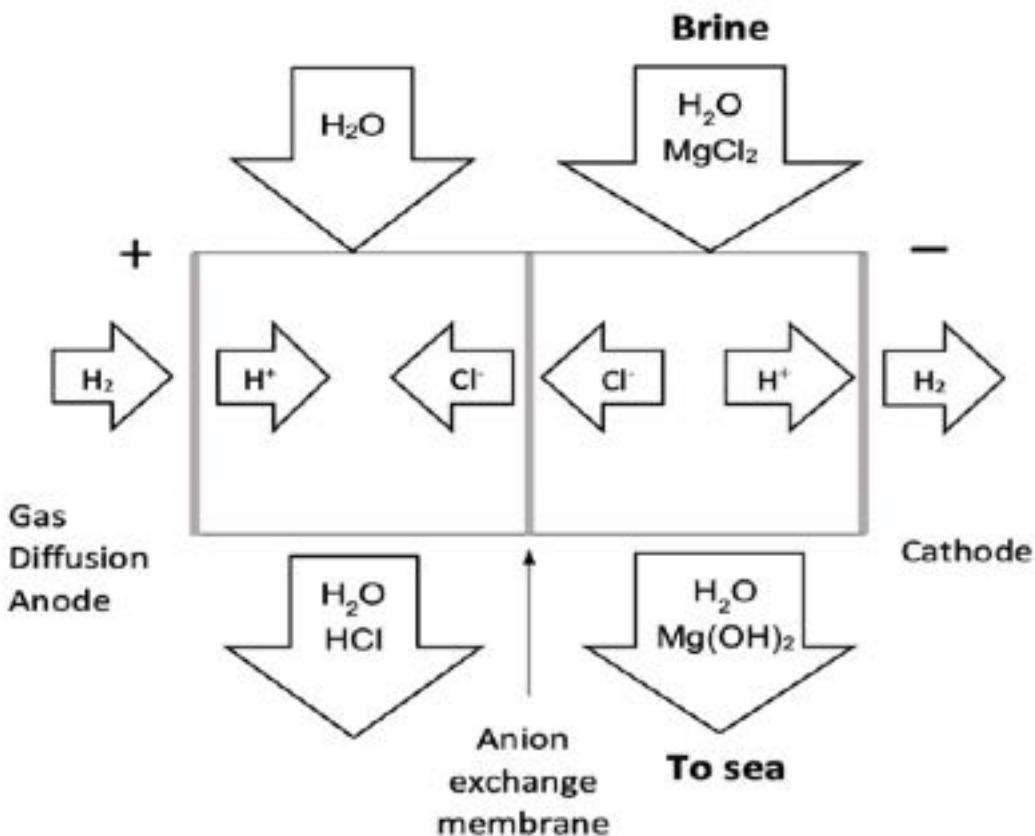
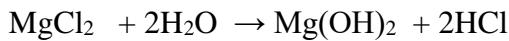


Illustration of the electrolyzer with gas diffusion anode (GDA) for splitting brine containing magnesium chloride into HCl and Mg(OH)_2 . Modified from Xie et al (2013). Davies' objective was to estimate the energy and water requirements of such NET-desalination, and to compare these penalties to the other NETs based on values provided in the literature.

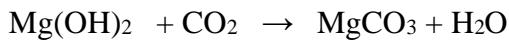
With use of the GDA, the two half-cell reactions are:



The overall electrolysis reaction is accordingly:



Magnesium hydroxide reacts stoichiometrically with CO_2 in seawater to form magnesium carbonate:



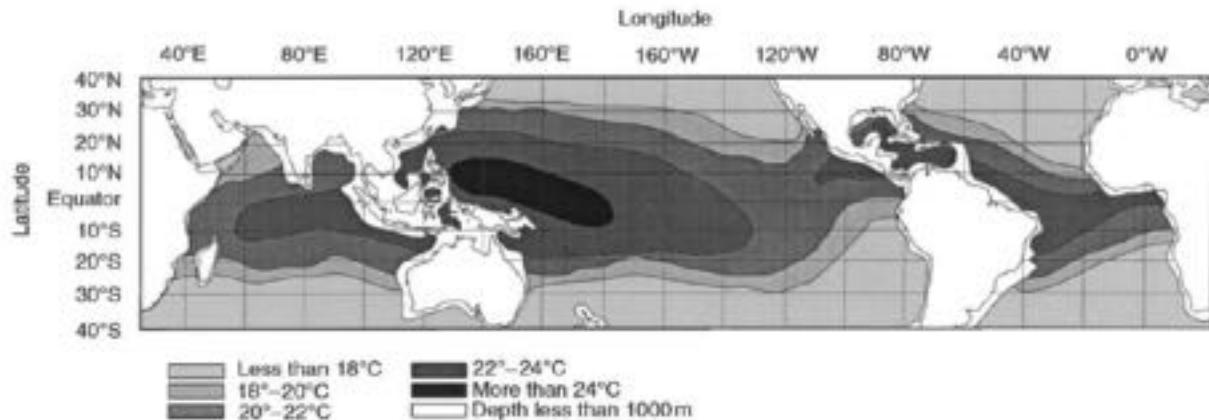
Further reaction to form magnesium bicarbonate absorbs in total of up to 2 moles of CO₂ per mole of magnesium:



Due to the reversible nature of this second reaction, the ratio achieved in practice is less than 2, with an estimated in the range 1.4 to 1.7 according to conditions of CO₂ concentration, temperature and salinity.

Compared to the Chloralkali process (House et al, 2007), which may be considered the most similar option to the current one, Davies et al calculated a **significant lowering of energy penalty, by a factor of about 1.5–5, using electrolysis-GDA**.

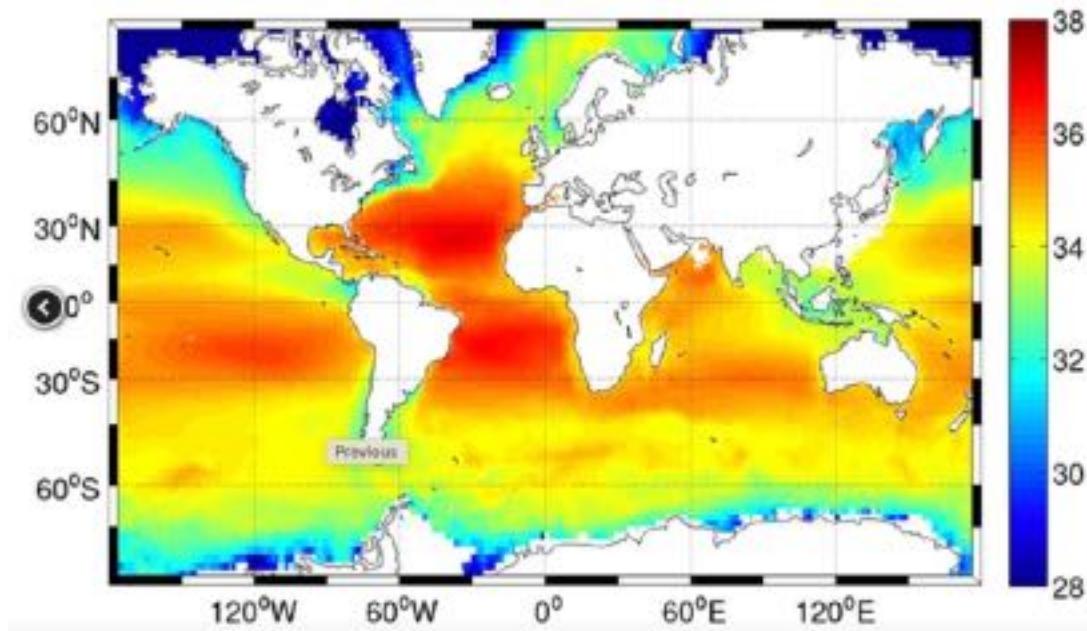
OTEC (see above) could also be explored as a potential source of electrical energy (Rau and Baird, 2018). The following map shows the areas of the ocean where the thermal difference between deep versus surface water is sufficient to use OTEC.



A thermal difference of 20°C or more is required to produce electricity. Of note, there are regions along the equator between longitude 160°W to 120°W that are in the above maximum CO₂ out gassing areas.

A possible objection to the above proposal is that, by absorbing CO₂ from the ocean, we introduce a long delay of many decades before this CO₂ is absorbed from the atmosphere because of the relatively slow mixing between these two compartments (Harvey et al, 2008). NET-desalination could deliver a relatively rapid neutralization effect, and this should be explored with regard to relatively confined seas, such as the Mediterranean, Red Sea, or Gulf, where many desalination plants are already installed – giving prospects to provide local remediation of acidification over relatively short time scales on account of the smaller volume of seawater to be processed compared to the open oceans.

The electrolysis-GDA process could be applied not just to desalination brine but also to **raw seawater**. If raw seawater was used, it would be more effective to concentrate on parts of the ocean with the highest salinity. The following map shows ocean salinity world-wide. In parts per thousand.



The mid Atlantic off both north and south America have the highest **salinity**. The salinity of the brine from desalination plants averages about 80 ppm, more than double the input salinity which is usually about 35-37 ppm. Thus, the salinity of brine, while higher than that of the ocean water input, is not that much higher. If this is the cheapest electrolysis method, it needs to be investigated. Again, note the high salinity west of Ecuador coinciding with the above areas of maximum CO₂ outgassing and optimal areas for OTEC.

d. EW with Production of Hydrogen Gas (H₂) by Electrolysis vs BECCS

Rau et al (2018) estimated that methods of combining saline water electrolysis with mineral weathering powered by any source of non-fossil fuel-derived electricity could, on average, increase energy generation and **CO₂ removal by >50 times relative to BECCS, at equivalent or lower cost**. This electrogeochemistry avoids the need to produce and store concentrated CO₂, instead converting and sequestering CO₂ as already abundant, long-lived forms of ocean alkalinity. Such energy systems could also greatly reduce land and freshwater impacts relative to BECCS and could also be integrated into conventional energy production to reduce its carbon footprint.

BECCS is believed to have the potential to remove up to 12 GtCO₂/yr while possibly generating as much as 300 EJ/yr of primary energy (Smith et al, 2016). One EJ = (10¹⁸) joules. This not only reduces CO₂ emissions by substituting for emissions-intensive fossil energy but also provides a way of removing and sequestering CO₂ from air by preventing biomass carbon from returning to the atmosphere via natural respiration and decomposition. However, to remove and store gigatons of CO₂ per year in this manner would require significantly expanded land management which could impact existing land uses for food, fiber and fuel production, as well as potentially denigrate other ecosystem services. Land impacts could be reduced or alleviated, and global negative-emissions energy production potential increased by the use of marine biomass in a BECCS process yet potential negative impacts to the marine environment would need to be considered. The CCS component of the process can also be problematic because of its cost and

because of the environmental, seismic and storage security concerns of injecting large quantities of such CO₂ underground.

Rau et al (2018) evaluated the application of recently described electrogeochemical methods of converting any non-fossil fuel-derived electricity source to a negative-emissions fuel or energy carrier, H₂. This is outlined in the following figure.

Figure below. Various schemes for electrolytically generating H₂ while consuming CO₂ and transforming it to dissolved mineral bicarbonate. When powered by electricity derived from low- or non-CO₂ -emitting energy sources, these schemes are strongly CO₂ -emissions negative.

Fig a. Scheme according to House et al, (2007).

Fig b. Scheme according to refs Rau, (2008),Rau et al, (2013) .

Fig c. Scheme according to Willauer, et al (2017).

SW = seawater; Vd.c. , direct current electricity.

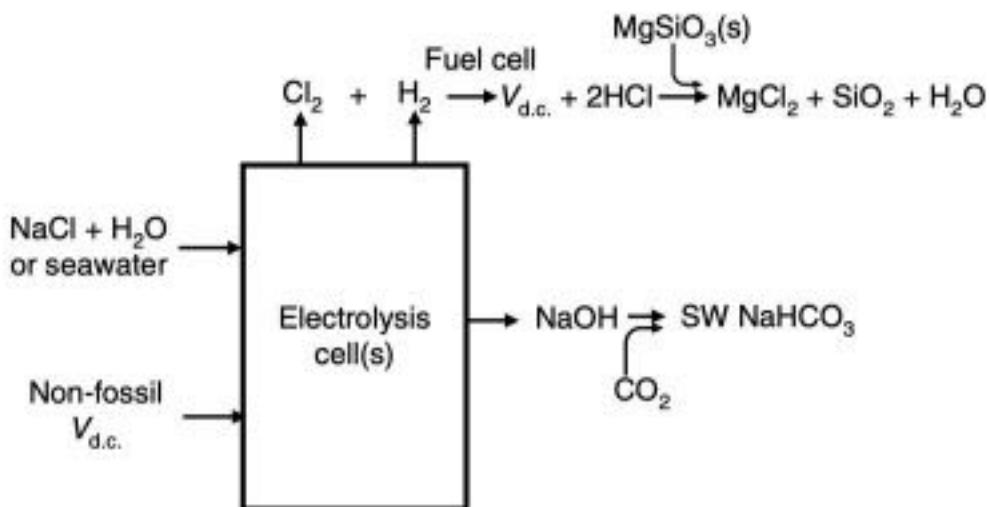
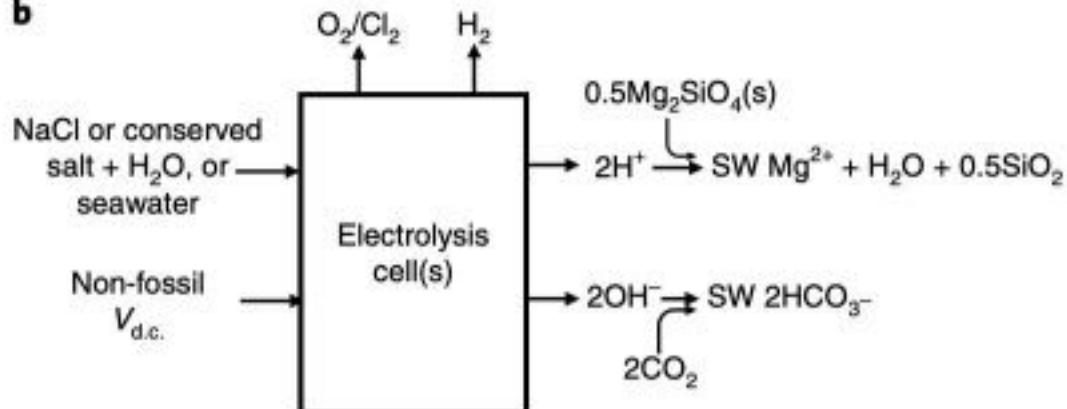
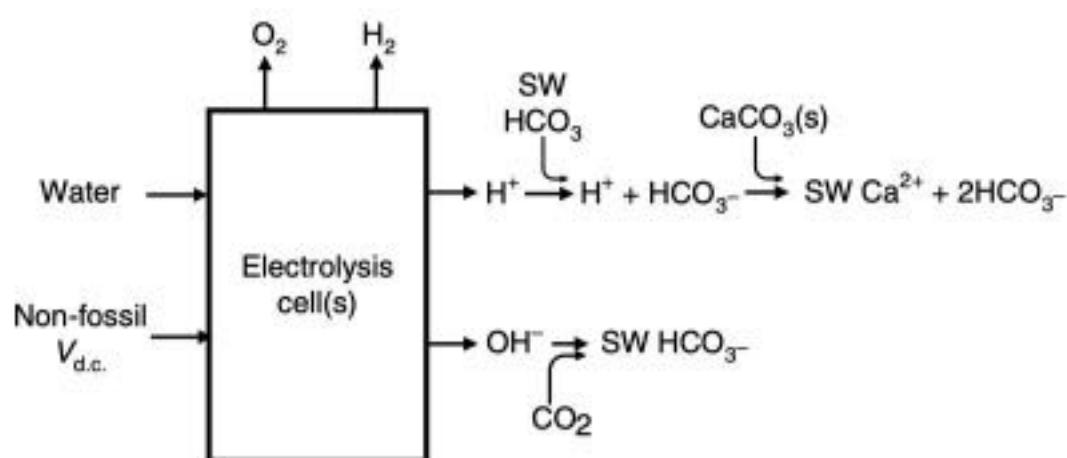
a**b****c**

Fig a. Central to these processes is the splitting of water at a cathode to form H₂ (gas) and OH⁻, with the generation of O₂ (gas) or Cl₂ (gas) and H⁺ at the anode. In one approach (House et al, 2007) the Na⁺ + OH⁻ produced during electrolysis of a NaCl solution (**chloralkali process** – see above) is used to absorb atmospheric CO₂ and convert it to NaHCO₃ (plus, via chemical equilibrium reactions, a smaller amount of dissolved Na₂CO₃). The H₂ and Cl₂ gases generated are reacted in a fuel cell to produce electricity and HCl (acid). The HCl is subsequently neutralized with alkaline silicate minerals to produce benign Mg and Ca chlorides and silica.

Fig b. In a second approach the H⁺ produced in the anolyte is directly neutralized with alkaline carbonate or silicate minerals, forcing the remaining electrolyte to accumulate OH⁻, which is then used to absorb CO₂ from the atmosphere.

Fig c. A third method (Willauer, et al, 2017) employs membranes to separate the OH⁻ (alkaline) and H⁺ (acid) solutions produced in compartmentalized water electrolysis, with the latter then used to acidify seawater and thus convert a substantial portion of its resident, dissolved bicarbonate and carbonate to dissolved CO₂ (or carbonic acid, H⁺ + HCO₃⁻). This CO₂ can subsequently be degassed and sequestered from the atmosphere, or as will be explored here, converted (without degassing) to dissolved seawater bicarbonate (plus carbonate) via spontaneous reaction with solid carbonate minerals (Rau & Caldeira, 2019; Rau, 2011), thus effecting CO₂ sequestration. Simultaneously, the OH⁻ stream produced in the preceding electrolysis is also added to seawater to effect air CO₂ capture and storage as dissolved mineral (bi)carbonates in the ocean.

Rau et al (2018) calculated the energy requirements of the above three, a-c, approaches. We leave the details to the interested reader. However, they concluded that their approach is a negative-emissions energy strategy with the potential to greatly expand the global resource beyond that previously estimated for BECCS, with the added benefits of

- (1) lessening or avoiding land use and land ecology impacts,
- (2) increasing the quantity of CO₂ removal per unit of energy generated,
- (3) avoiding the expensive production and risky storage of concentrated CO₂ inherent in CCS, and

(4) achieving these benefits at estimated costs equivalent to or lower than BECCS.

Carbon storage occurs in NE H₂ by converting CO₂ to dissolved alkaline bicarbonates and carbonates that, when added to the already very large reservoir of these compounds in the ocean, provide long-term carbon sequestration while helping counter ocean acidification.

In contrast to the land-based approach described by Rau et al (2018), in this ship-based approach all the energy produced in the form of H₂ would be utilized onboard to provide locomotion and energy for electrolysis. We will ask our consultants - is this feasible? What percentage of the electricity used for electrolysis can be recouped with H₂ fuel cells? And, which of the electrolysis approaches, including electrolysis GDA, is most efficient? Which is best suited to a ship-based approach?

An Equatorial Project

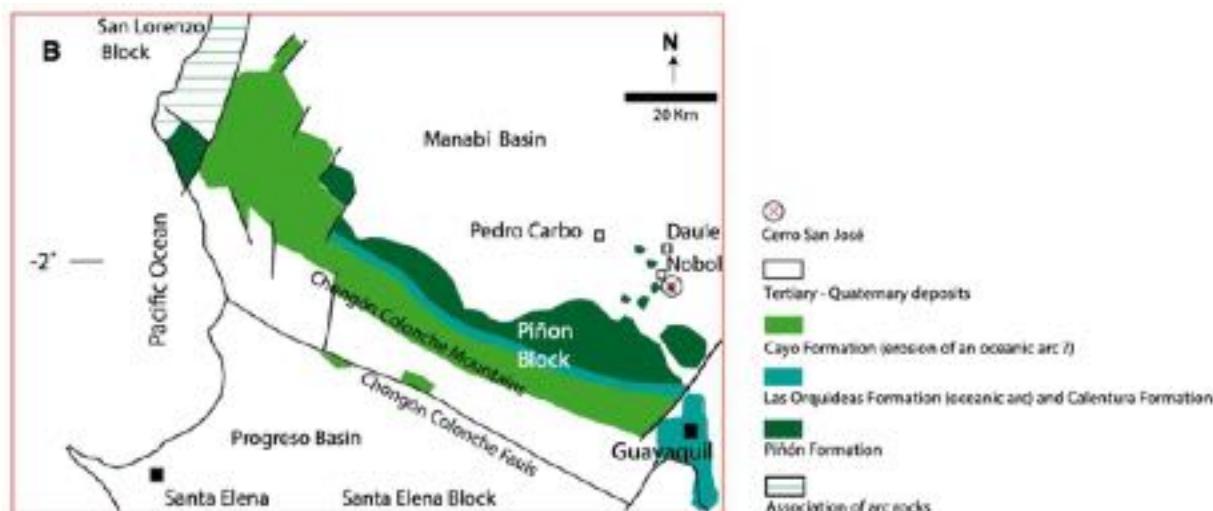
The above review identified an equatorial region along the equator west of Ecuador with the following characteristics:

- High levels of out gassing of CO₂ from the ocean to the atmosphere that needs to be reversed.
- High levels of salinity making electrolysis more efficient.

- A deep-sea thermal gradient conducive to the production of electricity by OTEC Ocean Thermal Energy Conversion.

- The availability of extensive ophiolite deposits in the nearby South American Countries (Villares et al 2020; Blanco-Quintero et al 2020; Bourgois, et al 1987; Spadea et al 1987; Kaeding, et al 1990) and New Caledonia.

There is also a deposit of ultramafic rock just north of Guayaquil, Ecuador that could supply the rocks for this project (see map). New Caledonia is also a possibility (see above).



Geological map of Ecuador of the Piñón ophiolite block north of Guayaquil.

These observations suggest an Equatorial Project in which the specialized ships described above, loading ultramafic rocks and operating out of Guayaquil, Ecuador, could address the high rate of out gassing in this area. Such highly focused projects may be much more effective than general ocean wide alkalization.

Protecting the Great Barrier Reef

Feng et al, (2016) concluded that EAO may be a method that could help to keep regional coral ecosystems within saturation states and pCO₂ values close to present-day values even in a high-emission scenario and thereby might ‘buy some time’ against the ocean acidification threat, even though regional EAO does not significantly mitigate the warming threat.

A distinct advantage of using ships as platforms for electrolysis EAO is that the efforts can be focused on critical area such as the Great Barrier Reef.

Long Term Effects of OAE.

Gonzales and Ilyina (2016) have modeled the effects of large scale OAE. The addition of 114 Pmol of alkalinity to the surface ocean stabilizes atmospheric CO₂ concentration to RCP4.5 levels under RCP8.5 emissions. This scenario removes 940 GtC from the atmosphere and mitigates 1.5 K of global warming within this century. The climate adjusts to the lower CO₂ concentration **preventing the loss of sea ice and high sea level rise. Seawater pH and the**

carbonate saturation state (Ω) rise substantially above levels of the current decade.

Pronounced differences in regional sensitivities to OAE are projected, with the Arctic Ocean and tropical oceans emerging as hot spots for biogeochemical changes induced by OAE. Thus, the CO₂ mitigation potential of OAE comes at a price of an unprecedented ocean biogeochemistry perturbation with unknown ecological consequences. All in all, the effects seem positive.

Studies of Weathering of in Oceans (Seawater)

Kheshgi, (1995). Ocean alkalinity might be raised by introducing the dissolution products of alkaline minerals into the oceans. **Naturally occurring soda ash (Na₂CO₃) is readily soluble and easily mined.** The world's production of soda ash in 2019 was 57 million metric tons. Increasing ocean alkalinity might have the environmental benefit of chemically buffering the oceans to the increased concentration of CO₂, although there might be impacts by contaminants or local pH effects which would have to be evaluated. **Increasing ocean alkalinity is a means by which CO₂ might be sequestered from the atmosphere.**

Lackner (2002) has expanded on the alkalinity approach. **Sequestration of waste carbon dioxide will require methods that can safely store several trillion tons of carbon dioxide.** Long-term storage of a gaseous substance is fraught with uncertainty and hazards, but carbonate chemistry offers permanent solutions to the disposal problem. Carbonates can be formed from carbon dioxide and metal oxides in reactions that are thermodynamically favored and exothermic, which result in materials that can be safely and permanently kept out of the active carbon stocks in the environment. Carbonate sequestration methods require the development of an extractive minerals industry that provides the base ions for neutralizing carbonic acid.

For carbon management applications, **the most important independent variable is alkalinity** because it very directly controls the amount of stored inorganic carbon. One may want to control its value by titrating ocean water with sodium carbonate (Kheshgi, 1995). (see above). By adding alkalinity to the surface water, one could maintain a constant PCO₂ over the water. **This strategy would minimize greenhouse gas impacts by effectively removing excess carbon dioxide from the air.** Changing the alkalinity would raise the uptake capacity of the surface ocean and ultimately of the full ocean. Any carbon management strategy that is based on increasing alkalinity could have the ocean take up 10,000 Gt of carbon with changes in PCO₂, [CO⁻³] and [H⁺] that could be held below 25%. It is remarkable that these changes, which could accommodate the disposal of most of the available fossil carbon, are smaller than those that have already occurred in surface waters due the increase in PCO₂.

Controlling the alkalinity of the ocean may be motivated not so much by a desire to eliminate the climate change impact of fossil fuel consumption but by the desire to correct the chemical imbalances caused by the dissolution of carbonic acid in the world's oceans. As a by-product of maintaining the oceans' carbonate ion concentration and pH as close to constant as possible, **the increased carbon uptake capacity of the oceans would remove nearly all the excess carbon dioxide from the atmosphere and retain it on geological timescales.**

The Lackner (2002) paper is very detailed. It adds some hope to the possibility that Increasing the alkalinity of the ocean in the area of the Great Barrier Reef would help to save the reef.

Henry (2008) In regard to the use of calcium carbonate to produce alkalinization of the ocean, Harvey (2008) concluded the following: CaCO_3 could be added to the surface layer in ocean regions where the depth of the boundary between supersaturated and unsaturated water is relatively shallow (250–500 m) and where the upwelling velocity is large (30–300 m/yr). The CaCO_3 would dissolve within a few 100 m depth below the saturation horizon, and the dissolution products would enter the mixed layer within a few years to decades, facilitating further absorption of CO_2 from the atmosphere. This absorption of CO_2 would largely offset the increase in mixed layer pH and carbonate supersaturation resulting from the upwelling of dissolved limestone powder. However, if done on a large scale, the reduction in atmospheric CO_2 due to absorption of CO_2 by the ocean would reduce the amount of CO_2 that needs to be absorbed by the mixed layer, thereby allowing a larger net increase in pH and in supersaturation in the regions receiving CaCO_3 . At the same time, the reduction in atmospheric pCO_2 would cause outgassing of CO_2 from ocean regions not subject to addition of CaCO_3 , thereby increasing the pH and supersaturation in these regions as well. Geographically optimal application of 4 billion t of CaCO_3 yr (0.48 Gt C/yr) could induce absorption of atmospheric CO_2 at a rate of 600 Mt CO_2 /y after 50 years, 900 Mt CO_2 /yr after 100 years, and 1050 Mt CO_2 /yr after 200 years. The time frames are daunting.

He examined the energy required to grind the limestone, the logistics of and energy use associated with dispersal by ship, and ecological impacts. The task would be enormous and would need to continue over a period of 100 years.

Hangx and Spiers (2009) The feasibility of spreading olivine on coast lines depends on the rate of olivine dissolution, the sequestration capacity of the dominant reaction, and its CO_2 footprint. Kinetics calculations show that offsetting 30% of worldwide 1990 CO_2 emissions by beach weathering means distributing of 5.0 Gt of olivine per year. For mean seawater temperatures. To obtain useful, steady state CO_2 uptake rates within 15-20 years requires a grain size of < 10 um. However, the preparation and movement of the required material poses major economic, infrastructural and public health questions. We conclude that coastal spreading of olivine is not a viable method of CO_2 sequestration on the scale needed.

This “**Green Beaches**” proposal entails the spreading of crushed olivine rock along large parts of the Earth’s coastlines, above the wave base, using coastal dumper barges and/or beach bulldozer equipment. Weathering is a slow process much skepticism exists in the scientific community regarding CO_2 sequestration by weathering approaches.

In contrast to the optimistic cheap tool of Schuiling and Krijgsman (2006), Hang and Spiers point out that with the **sand grain size of the Schuiling report it would take 370 to 6,010 years for the complete dissolution of olivine**. Dissolution is significantly accelerated with grain sizes of >10 um but achieving that small size adds considerable expense to EW. Thus, one of their conclusions is that mining, crushing and grinding of olivine to a grain size of <10 um will reduce process efficiency by 5-11% for pure olivine and by 10-20% for typical olivine rock. This does not seem unsurmountable. An additional 0.1 to 1% efficiency reduction will be generated per 100 km of transport of one ton of crushed olivine rock by ship, train, or truck. Typical transport distances in Europe would be ~1000 km.

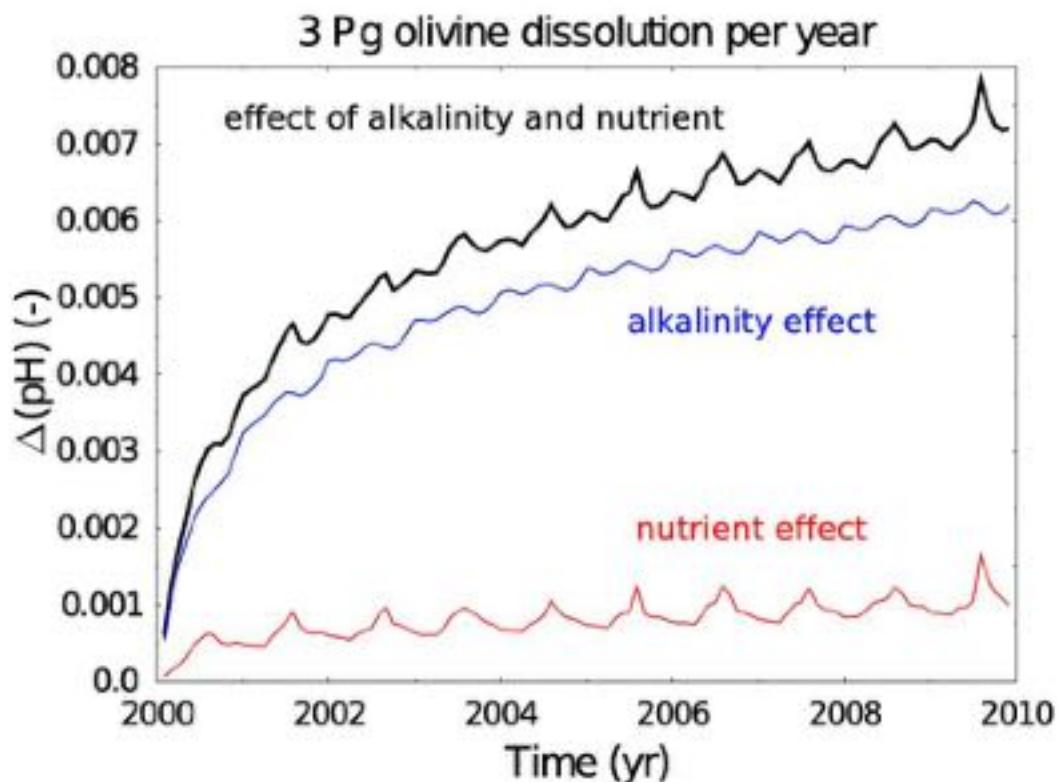
They concluded that coastal spreading of olivine sand is not a viable method of CO_2 sequestration on the scale needed. The method certainly cannot replace CCS technologies as a means of controlling atmospheric CO_2 concentrations.

Terrestrial spreading of crushed olivine in tropical areas is more promising than beach reaction, **especially on land with acidic soils**. However, beach weathering could contribute perhaps a 1% equivalent reduction as a niche activity, particularly in tropical regions where reaction rates are accelerated. More research on costs, logistics and seawater reaction rates is needed to clarify the possible contribution.

It is surprising that the grinding of olivine would only decrease efficiency by 5 to 20%. This seems doable.

Kohler et al (2013); Hauck, et al, (2014) concluded that if dissolved in the surface ocean, **olivine sequesters 0.28 g carbon per g of olivine dissolved, similar to land-based enhanced weathering**. Silicic acid input, a byproduct of the olivine dissolution, alters marine biology because silicate is in certain areas the limiting nutrient for diatoms. As a consequence, their model predicted **a shift in phytoplankton species composition towards diatoms**, altering the biological carbon pumps. Enhanced olivine dissolution, both on land and in the ocean therefore needs to be considered as ocean fertilization. From dissolution kinetics they calculate that **only olivine particles with a grain size of the order of 1 µm sink slowly enough to enable a nearly complete dissolution**. The energy consumption for grinding to this small size might reduce the carbon sequestration efficiency by ~30%.

The following figures shows the effect of ocean pH of the placement of 3 Pg or 3 billion tons of olivine per year.



The placement of large amounts of olivine into the ocean is not without potential problems. Its limitations are: distributing 3 Pg olivine per year: full-time commitment of more than **300 large ships**. **This would sequester approximately 9% of anthropogenic CO₂ emissions.**

Some of the risks are: Dissolution of heavy metals possible - toxicity? Impact on marine species distribution. Potential for extension of anoxic or sub-oxic regions. Environmental and social problems with mining of olivine.

Renforth and Henderson (2017) Assessing ocean alkalinity for carbon sequestration.

Carbon storage in the ocean as bicarbonate ions (by increasing ocean alkalinity) has received very little attention. Seawater has a high alkalinity (2.5 mEq/kg) which, coupled to the large volume of the ocean, makes oceanic inorganic C by far the largest C reservoir in the ocean-atmosphere-biosphere system (\approx 42,000 Gt C (Ciais et al., 2014). The oceans have a sufficient capacity to sequester copious quantities of CO₂. **It may be possible to sequester hundreds of billions to trillions of tons of C** without surpassing postindustrial average carbonate saturation states in the surface ocean. When globally distributed, the impact of elevated alkalinity is potentially small and may **help ameliorate the effects of ocean acidification**. However, the local impact around addition sites may be more acute but is specific to the mineral and technology.

The alkalinity of the ocean increases naturally because of rock weathering in which >1.5 mol of carbon are removed from the atmosphere for every mole of magnesium or calcium dissolved from silicate minerals (e.g., wollastonite, olivine, and anorthite) and 0.5 mol for carbonate minerals (e.g., calcite and dolomite). These processes are responsible for naturally sequestering 0.5 billion tons of CO₂ per year. Alkalinity is reduced in the ocean through carbonate mineral precipitation, which is almost exclusively formed from biological activity.

Most of the previous work on the biological response to changes in carbonate chemistry have focused on acidifying conditions. More research is required to understand carbonate precipitation at elevated alkalinity to constrain the longevity of carbon storage. A range of technologies have been proposed to increase ocean alkalinity (accelerated weathering of limestone, enhanced weathering, electrochemical promoted weathering, and ocean liming), the cost of which may be comparable to alternative carbon sequestration proposals (e.g., \$20–100 tCO₂). There are still many challenges that warrant research to address these.

The oceans contain \approx 38,000 Gt C, some 45 times more than the present atmosphere, and oceanic uptake has already consumed close to 40% of anthropogenic C emissions. So, **the issue is not capacity, but rather a question of how to accelerate oceanic uptake and storage in a safe and cost-effective way**. Given the increasing reliance of future climate scenarios on negative emission, and the size of C sequestration that may be required, it is important to explore and understand the feasibility of all possible C sinks, including acceleration of the natural oceanic sink. Sequestration of inorganic C in the ocean is the least represented climate mitigation strategies in the literature (Bellamy et al., 2012).

Alkalinity storage in the ocean raises issues around environmental impact, quantification, monitoring, governance, and longevity, all of which were explored in detail in this review.

Storage of C by increasing ocean alkalinity requires the extraction, processing, and dissolution of minerals. This results in chemical transformation of CO₂ and sequestration as bicarbonate and carbonate ions (HCO₃⁻ and CO₃²⁺) in the ocean. Dissolution of a mole of Ca²⁺ or Mg²⁺ sequesters close to 2 mol of C. Examination of several natural minerals showed that **olivine (forsterite)** Mg₂SiO₄ was the most efficient in terms of grams CO₂ sequestered per gram of mineral (**1.25**). This compared to magnesite MgCO₃ (0.52), Calcite CaCO₃ (0.44), Dolomite CaMg(CO₃)₂ (0.48) and anorthite CaAl₂Si₂O₈ (0.32). The gCO₂/g mineral is higher for man-processed minerals. These include Lime CaO (1.57), Portlandite Ca(OH)₂ (1.19), Periclase MgO

(2.18), and Brucite $Mg(OH)_2$ (1.51). However, these would not be available in very large quantities.

As shown previously, on land olivine, CO_2 and water produce magnesium carbonate:



If the cations (Mg^{++} , Ca^{++}) are transported to the ocean, they increase the alkalinity (see above - alkalinity) and lead to transfer of CO_2 to HCO_3^- and CO_3^{2-} . The resulting decrease of dissolved CO_2 causes uptake of atmospheric CO_2 by air-sea gas exchange.

Addition of sufficient Ca^{2+} to fully compensate for present anthropogenic emission of 10 Gt C/yr requires addition of 20 Gt Ca^{2+} /yr. This is ≈ 20 times the annual riverine input of Ca^{2+} , a very significant perturbation, and obviously a very substantial undertaking in engineering terms. The large volume of the ocean and its high Ca^{2+} concentration, however, mean that the oceanic perturbation is very much smaller and only a 0.9 mmol kg/yr increase in Ca^{2+} is required. Even if considering the surface ocean alone this annual addition is less than a 0.3% increase in total Ca^{2+} .

Rayner et al. (2013) have laid out a set of guiding (“Oxford”) principles for geoengineering, including (1) that it be regulated as a public good, (2) public participation in decision-making, (3) disclosure of research and open publication of results, (4) independent assessment of impacts, and (5) governance before deployment.

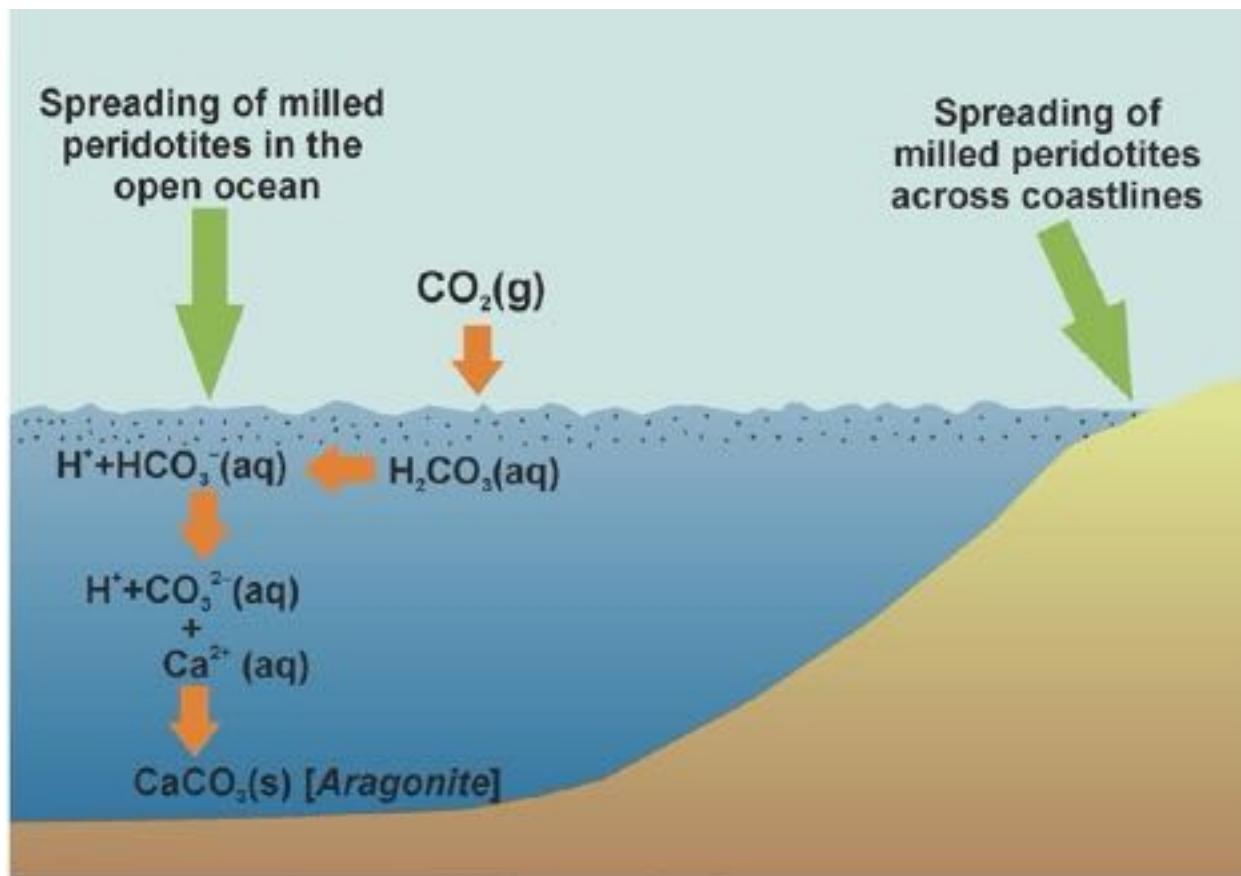
In conclusion, a range of techniques have been proposed for increasing ocean alkalinity, which exploit numerous reaction pathways. However, all require the extraction, processing, and reaction of rocks. It may be possible to achieve CO_2 :rock mass ratios > 1 using ultrabasic minerals. It may also be possible to use faster dissolving carbonate minerals for alkalinity addition (CO_2 :rock mass ratio ~ 0.5). While some components of these processes already operate at a large scale (e.g., the production of lime), generally, the overall technologies have not developed beyond desk-top technoeconomic assessment or bench scale laboratory work. However, this work suggests some of the proposals to have a range of energy requirements and financial costs comparable to more widely studied alternatives (e.g., 1–10 GJ t CO_2 /yr and \$50–150 t CO_2 /yr). However, upscaling these processes to have an impact on anthropogenic CO_2 emissions (i.e., billions of tons CO_2 /yr) is a considerable challenge.

Finally, the modification of the ocean raises issues surrounding regulation, monitoring, and the distribution of impact (Rayner et al, 2013). The London Convention/Protocol was created to limit dumping of materials in the ocean and has been amended (yet to be ratified) to include marine geoengineering proposals. More work is required to develop governance for ocean alkalinity carbon storage, but this should be informed by, and tailored to, the potential harms and benefits of specific alkalinity addition approaches.

Griffioen (2017) examined the effect of Fe rich versus Mg rich olivine. They concluded the efficiency of olivine weathering depended on the Mg/Fe fractions of olivine and precipitation of secondary minerals. For Fe-rich olivine, CO_2 may be released to the atmosphere and ocean pH might decrease during oxic olivine weathering. Ocean alkalinization only happens when more than 1 mol/kg H_2OMg -rich olivine weathers. The abundance of Mg compared to Fe depends on the rock but is about 90% in the most abundant dunite.

Maintenance of supersaturation for calcite or aragonite as holds in seawater reduces the efficiency by about a factor of two compared to the efficiency without secondary precipitation. Precipitation of sepiolite as Mg silicate reduces the efficiency even more.

Rigopoulos et al (2017) The following figure is from Rigopoulos et al: (2017) Carbon sequestration via enhanced weathering of peridotites and basalts in seawater.



This study was designed to assess the potential drawdown of CO_2 directly from the atmosphere by the enhanced weathering of peridotites and basalts in seawater. Experimentally measured dissolution rates by Wolff-Boenisch et al. (2011) suggested that ground mafic and ultramafic rocks could lead to the efficient carbon dioxide mineralization in seawater.

In the Rigopoulos et al (2017) study, pulverized, and ball-milled dunite, harzburgite and olivine basalt were reacted in artificial seawater in batch reactor systems open to the atmosphere for two months. The results demonstrate that the **ball-milled dunite and harzburgite changed dramatically the chemical composition of the seawater within a few hours, inducing CO_2 drawdown directly from the atmosphere** and ultimately the precipitation of aragonite (see above figure). In contrast, pulverized but un-milled rocks, and the **ball-milled basalt, did not yield any significant changes in seawater composition during the two-month experiments**. Zhang et al (1997) reported that **ball mill results in a structural change from a crystalline state into an amorphous one**. This change is attributed to local disordering around magnesium in the structure. This disordering leads to enhancement of extraction of both magnesium and

silicon from the mechanically activated serpentine by the acid solutions. Concentrations of both elements in the mother solutions increase with an increase in grinding time.

These results demonstrate that **ball-milling can substantially enhance the weathering rate of peridotites in marine environments**, promoting the permanent storage of CO₂ as environmentally benign carbonate minerals through enhanced weathering. The precipitation of Mg-silicate clay minerals, however, could reduce the efficiency of this carbon sequestration approach over longer timescales.

What is ball-milling?

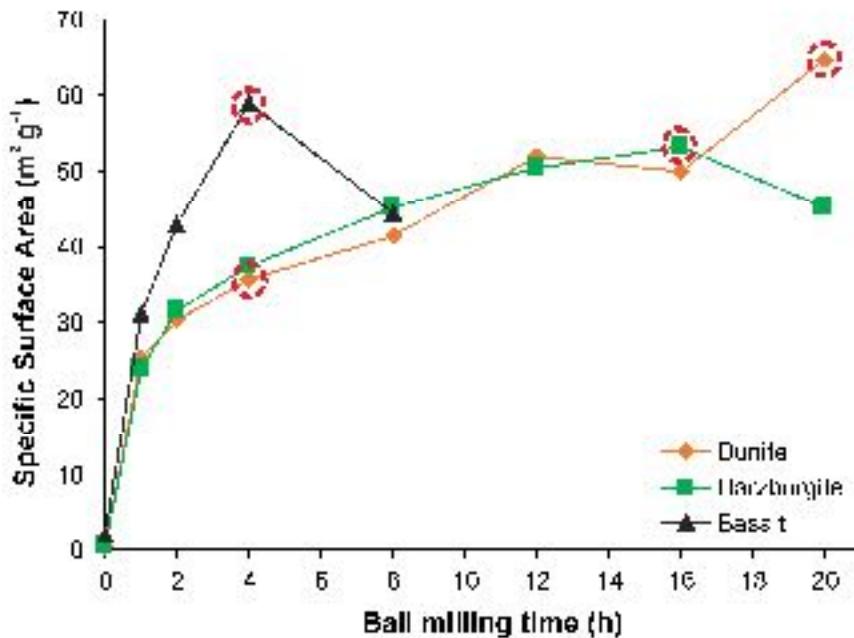


A ball mill is a type of grinder used to grind or blend materials for use in paints, pyrotechnics, ceramics, and selective laser sintering. It works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell. The process of grinding is called **communition**.

A ball mill consists of a hollow cylindrical shell rotating about its axis. The axis of the shell may be either horizontal or at a small angle to the horizontal. The grinding media are the balls, which may be made of steel (chrome steel), stainless steel, ceramic, or rubber. The inner surface of the cylindrical shell is usually lined with an abrasion-resistant material such as manganese steel or rubber lining. Less wear takes place in rubber lined mills.

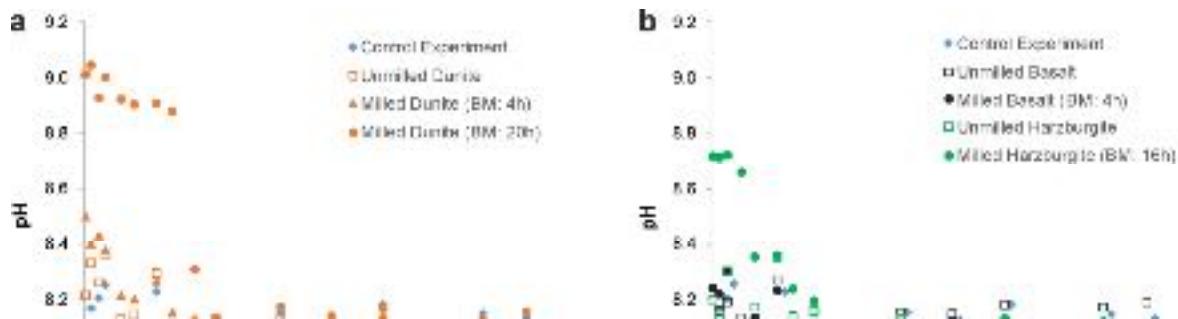
Fuerstenau, and Abouzeid (2002) examined the relative of different machines and factors. The required energy for comminution is proportional to the new surface produced. Efficiencies for the most commonly used mills ranged from 7–32%. In some cases the efficiencies are as low as .15%. The wet grinding in tumbling mills is more efficient than the dry grinding. One reason for this is that water is adsorbed on the newly created surfaces and prevents the fines from agglomerating. The second reason is that the fine particles produced during comminution remain suspended in the aqueous medium, thereby increasing the chance for the coarser particles to be broken by the tumbling media.

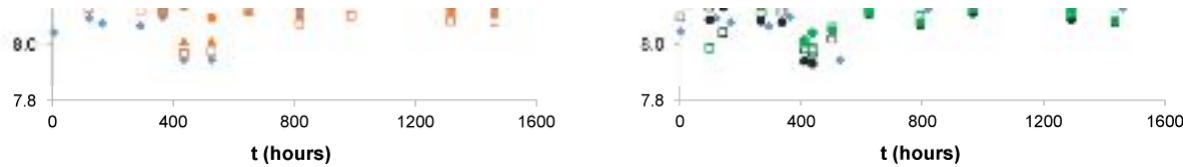
The effect of various times in the ball-mill was measured by the BET method (adsorption of N₂ at 77 K) and was carried out in a Micromeritics Gemini III Surface Area and Pore size Analyzer in order to determine the specific surface area (m²/g).



BET (m^2 / g) specific surface area versus ball milling time for the studied rock materials (red circles show the milled samples used during the experiments). The BET values for the milled basalt and dunite samples were acquired from Rigopoulos et al. (2015) and Rigopoulos et al. (2016), respectively.

This showed that it takes about 12 hours to grind these rocks to a size that maximizes the desired effect. The following figure shows that in seawater, milled dunite (a) and milled Harzburgite (b) show a pH of 8.7 to 9.0. Milled basalt and the controls showed a pH of 8.0 to 8.2. This is the pH range of natural seawater (Marion et al., 2011).





Temporal evolution of the reactive fluid pH: (a) Control experiment, and experiments with unmilled and milled dunite; (b) Control experiment, and experiments with unmilled and milled basalt and harzburgite.

This indicated that **only the 20-hr milled dunite (olivine) showed an increase in alkalinity to pH 9.0** starting after 6 hours. After several hundred hours the pH decreased back to @ 8.2. These experiments provide information as to the relative effect of these three milled minerals, dunite, harzburgite and basalt, in combating ocean acidification. Dunite was most effective, harzburgite next most, and basalt was ineffective. The conclusions were:

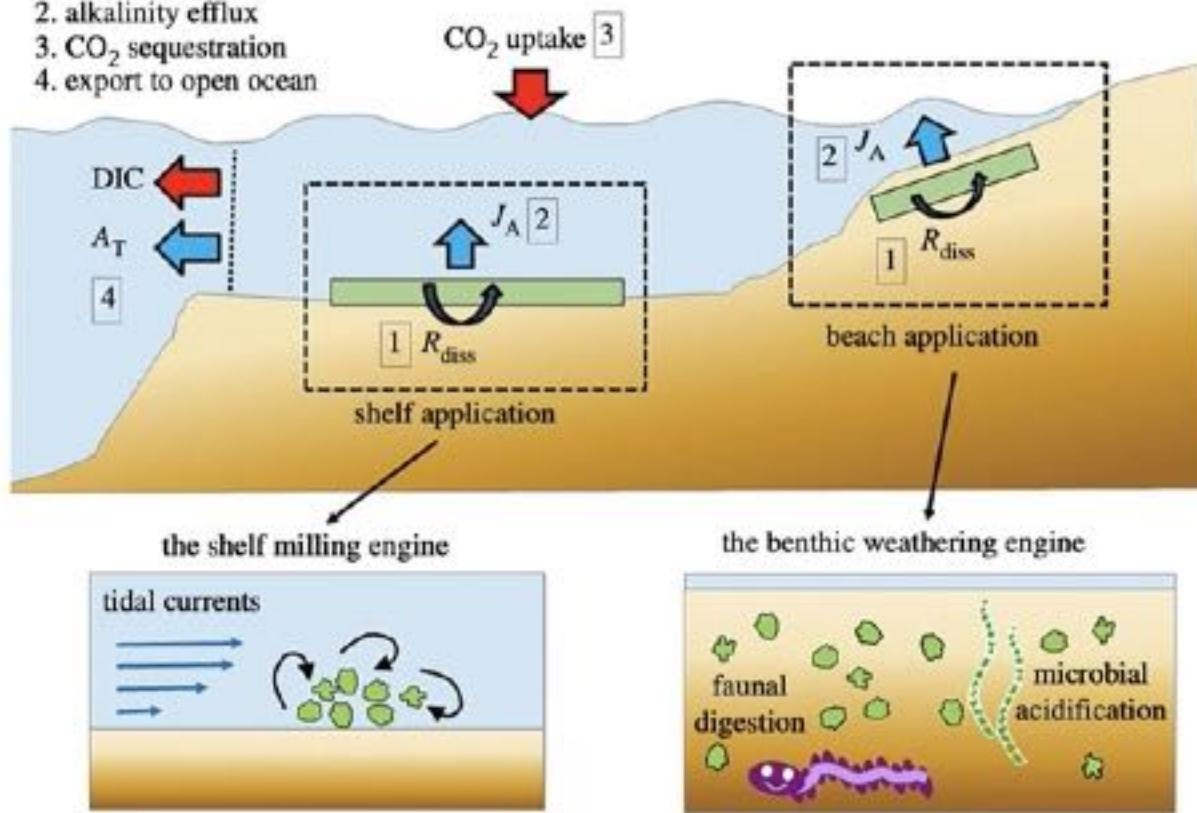
- Peridotites (olivine and mafic pyroxene) induced CO₂ drawdown directly from the atmosphere via mineralization.
- The basalt did not yield any significant changes in seawater composition.
- The precipitation of sepiolite could reduce the carbon sequestration efficiency.

So, **what is sepiolite?** It is also known as meerschaum, is a soft white clay mineral, often used to make tobacco pipes (known as meerschaum pipes). It is a complex magnesium silicate, a typical chemical formula for which is Mg₄Si₆O₁₅(OH)₂·6H₂O, it can be present in fibrous, fine-particulate, and solid forms. Only small amounts of it were formed in the grinding process.

Meysman and Montserrat, (2017) These authors discuss the potential of applying EW in coastal environments, both beaches and shelf, as a climate change mitigation option. By deliberately introducing fast-weathering silicate minerals onto coastal sediments, alkalinity is released into the overlying waters, thus creating a coastal CO₂ sink. Compared with other NETs, **coastal EW has the advantage that it counteracts ocean acidification, does not interfere with terrestrial land use and can be directly integrated into existing coastal management programmer with existing (dredging) technology.**

enhanced silicate weathering in the coastal zone

1. olivine dissolution
2. alkalinity efflux
3. CO_2 sequestration
4. export to open ocean



Two ESW (Enhanced Silicate Weathering) application scenarios have been proposed: (a) spreading coarse particles into high-dynamic shelf environments where particles are crushed during bedload transport ('shelf milling') and (b) spreading finer olivine sand onto beaches and shallows, where dissolution is enhanced through biotic processes in the seabed ('benthic weathering engine').

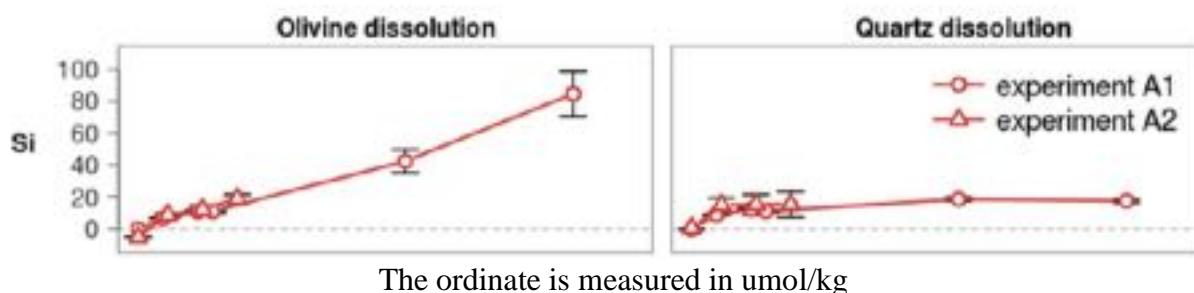
The seabed is characterized by various forms of biological activity, which could induce higher dissolution rates compared with sterile laboratory conditions. Such biological enhancement of silicate weathering has been extensively documented in terrestrial soils, giving rise to the 'mycorrhizal weathering engine' concept. The authors propose the concept of the 'benthic weathering engine', where both microorganisms and invertebrate fauna act as agents of enhanced weathering in marine sediments. Together, the interplay of microbial metabolism and macrofaunal bioturbation could substantially increase the rate of olivine dissolution under *in situ* conditions.

Dedicated experiments are needed (i) to more precisely determine the weathering rate under *in situ* conditions within the seabed and (ii) to evaluate the ecosystem impacts—both positive and negative—from the released weathering products.

Montserrat, F. et al (2017) The authors specifically address a number of questions related to the application of enhanced silicate weathering (ESW) in natural coastal environments: (1) What is the rate of olivine dissolution in natural seawater and how does this differ from

artificial seawater? (2) Does olivine dissolve stoichiometrically in natural seawater? (3) What dissolution products can be used to efficiently monitor the dissolution rate of olivine in coastal sediments, i.e., quantify the efficiency of enhanced silicate weathering? (4) To what extent does secondary mineral formation diminish the CO₂ sequestration efficiency of olivine dissolution in seawater?

Commercially available olivine sand ($Mg^{2-x}Fe^xSiO_4$) and lab-grade quartz (SiO_2) were used in slurry dissolution experiments. The olivine sand (particle size quantiles: D₁₀ = 91 μm , D₅₀ = 143 μm , D₉₀ = 224 μm) had a molar Mg-to-Fe ratio of 0.94:0.06, characterizing the olivine as forsterite-94 (Fo₉₄). The Ni content was estimated at 0.0075 mol Ni/mol olivine. The olivine or quartz were placed as a slurry of into borosilicate glass bottles and placed on a rotating shaking platform. The fluids were filtered seawater (FSW), artificial seawater (AFW) with or without Ca or Mg. The following figure shows the rate of silicon release over a period of 100 days for olivine and quartz.



The main consequences of forsterite olivine dissolution are increases in Mg²⁺, Si, TA (total alkalinity), DIC (dissolved inorganic carbon), Fe⁺², and Ni⁺², and their ecosystem effects should be thoroughly assessed.

While increases in alkalinity and DIC are a desired effect for climate engineering purposes, the increase in Mg²⁺ is not expected to pose a significant threat because of the high background concentration in seawater. Increases in dissolved Si and dissolved Fe can stimulate primary production and thus lead to additional CO₂ sequestration, as recently assessed by model analysis. However, the ultimate impacts on coastal food webs of fertilizing by olivine dissolution are uncertain and need further investigation.

Nickel Issues The impact of increased nickel flux on marine ecosystems is a matter of potential concern. Ecosystems is summarized on the Web site of the UK Marine Special Areas of Conservation (<http://www.ukmarinesac.org.uk/>) and established for the UK at a chronic concentration of the ecotoxicology of nickel in marine organisms and 0.25 $\mu mol/L$. Nickel toxicity has been reported in a number of cases: negative effects on spawning in mysid shrimps at 2.4 $\mu mol/L$, DNA damage with associated physiological and cytotoxic effects in the blue mussel *Mytilus edulis* at 0.3 $\mu mol/L$, disrupting ionoregulatory functions in the green crab *Carcinus maenas* between 8.5 and 51 $\mu mol/L$ in very low-salinity seawater (0.006 PSU), and organ oxidative stress in the killifish *Fundulus heteroclitus*.

The potential toxicity of nickel, combined with rather large uncertainties about the magnitude and direction of its response effects, make it paramount to further investigate its ecotoxicological effects within the framework of large-scale application of olivine in coastal environments.

Before beginning any field-scale application, there should be proper field trials in quasi-contained conditions, such as mesocosm setups, which can be upscaled in, e.g., tidal harbor basins. In the case that a mesoscale field trial ($\sim 100 \text{ m}^2$) would be undertaken, common dredging equipment would be used to apply the olivine into the (coastal) environment. The same equipment and expertise can be used to remove the olivine sand, should any acute unforeseen situation develop.

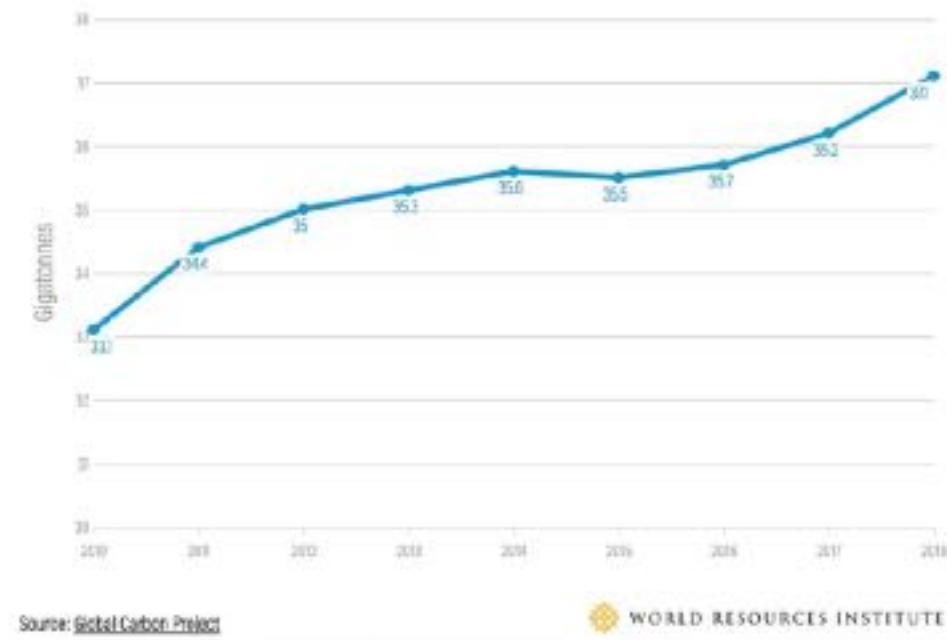
The CO₂ sequestration induced by ESW is governed by the acid–base thermodynamics of seawater, which are well understood, therefore rendering the containment of CO₂ in the ocean highly predictable. The central premise of ESW is that it increases the ocean's alkalinity, enabling more CO₂ to be dissolved into seawater at any given pCO₂ compared to the situation in which no alkalinity is added to the ocean.

If ESW is ever to be applied in a geo-engineering framework, it is of paramount importance to investigate the effects of all of these natural processes on the dissolution of olivine in coastal environments.

How much of the Problem of Removing CO₂ from the Atmosphere can be solved by Enhanced Weathering?

A. What are the Annual CO₂ Emissions due to Fossil Fuels?

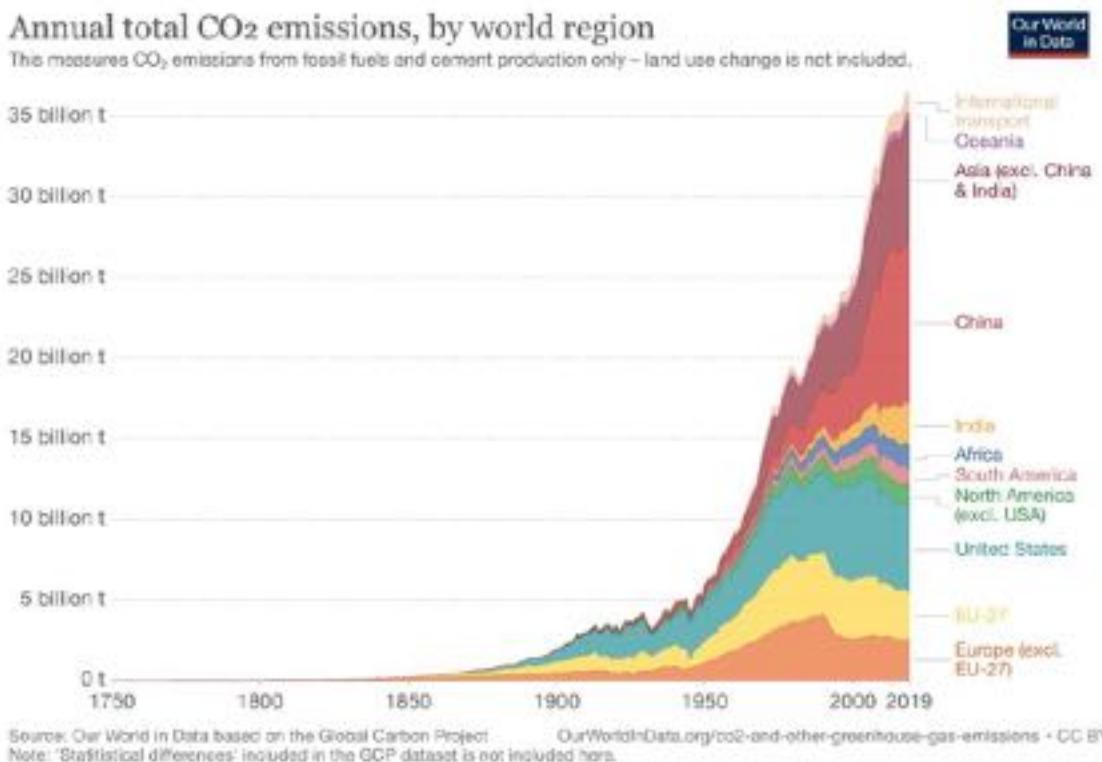
A common complaint about Enhanced Weathering and indeed any NET is that it accounts for only a small fraction of the total CO₂ emitted per year. Thus, to understand the magnitude of the problem it is **first necessary to determine the amount of CO₂ emitted per year, world-wide**. The following shows the yearly, global rates for fossil fuels from 2010 to 2018.



The rate of emissions appeared to be leveling off from 2014 to 2016, but then increased significantly from 2016 to 2018. The levels in 2019 were **36.8 gigatons**. They were anticipated to drop by at least 7% in 2020 due to the pandemic.

In his book *How to Avoid Climate Disaster* Bill Gates quotes a figure of **51 gigatons**/year. This includes all greenhouse gases and land use emissions of CO₂. Most discussions of NET state that removing 10 gigatons/year by mid-century, is a reasonable goal.

The following figure shows the contribution of each major country.



Based on these figures a rate of emissions from fossil fuels of approximately 37 billion tons/year provides a reasonable estimate.

B. Estimates of the Amount of CO₂ that could be removed by EW.

a. Beerling et al. The Beerling et al (2020) paper has been widely quoted in this review. In this paper Beerling estimated that annually EW could remove 0.5 to 2 Gt CO₂/yr. This was similar to other NET technologies such as direct air capture and storage, biochar, soil organic carbon sequestration, and afforestation/reforestation.

Beerling et al (2018) and Kantola, et al (2017) On the basis of basalt applications of 10 to 50 t ha ^{-/yr} to 70×10^6 ha of the annual crops corn/soy in the corn belt of North America could sequester 0.2–1.1 PgCO₂, 0.2 or 1.1 gigatons up to 13% of **the global annual agricultural emissions**, in the long run.

Beerling, D. J. et al. (2016) Provisional estimates suggest that amending two-thirds of the most productive cropland soils (9×10^8 ha) with basalt dust at application rates of 10–30 t/ha/yr could perhaps extract 0.5–4 PgCO₂/yr, or **0.5 to 4 gigatons/yr** by 2100 depending on climate, soil and crop type.

b. Renforth (2012) A maximum carbon capture potential of ~0.3 tCO₂/t is suggested for basalt, assuming a sufficiently fine particle size for effective dissolution on decadal timescales.

c) **Strefler et al (2018)**. Our results show that enhanced weathering is an option for carbon dioxide removal that could be competitive already at 60 US \$/t CO₂ removed for dunite, but only at 200 US \$/t CO₂ removed for basalt. The potential carbon removal on cropland areas could be as large as **95 Gt CO₂/year for dunite** and 4.9 Gt CO₂/year for basalt. The best suited locations are warm and humid areas, particularly in India, Brazil, South-East Asia and China, where almost 75% of the global potential can be realized.

d) **Hartmann & Kempe (2008)** report a theoretical global maximum potential of 65×10^6 t sequestered C/year if applied homogenously on all agricultural and forested areas of the world. This is equal to 3.67×65 or 238×10^6 tons of CO₂.

e) **Moosdorf et al (2014)** They stated that **very large amounts of rock would be needed** to control or reduce the atmospheric CO₂ concentrations substantially with enhanced weathering. Before enhanced weathering could be applied at large scales, more research is needed to assess weathering rates, potential side effects, social acceptability, and mechanisms of governance.

Other data on this question are given in the section **Negative Thoughts about Negative Emission Technology** (see below).

Who can do the research and serve as advisors to answer the questions listed below?

We would like to bring onboard a number of the authors listed in the above papers as advisors. We would like them to read this presentation for accuracy and answer the attached questions as best as possible.

Recently Elon Musk has also stepped into the NET breach with substantial prize money. However, it will be April 2024 before we learn which one of the many NETs he proposes to support. **The criteria for winning the Musk X-prize are very severe and we probably will not attain them to the satisfaction of the judges.** However, if we can at least meet many of them I would consider that a success. Regardless of the outcome, the Comings Foundation will continue to fund the work of attempting to move this NET from theory to practice. The details about the Musk Prize are given in **Appendix D**.

Negative Thinking About EW Negative Emissions Technology

To ensure that we are not guilty of having our heads in the clouds about EW NET it is important to maintain transparency about the difficulty of the task. The following are some of the many published comments about the difficulties of EW NET.

EFI Energy Futures Initiative Clearing the Air. A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies. Ernest J. Moniz, Chair (2019) Former Head DOE.

To be effective, technological CDR ultimately needs to be deployed at very large scale. The 2018 National Academies of Sciences, Engineering, and Medicine (NASEM) report entitled Negative Emissions Technologies and Reliable Sequestration: A Research Agenda identified the need for CDR at a scale of approximately **10 billion metric tons (GtCO₂) per year globally by midcentury and 20 GtCO₂ per year globally by 2100 to achieve climate goals while accounting for economic growth.** Capturing carbon from the environment at that scale would require the creation of new industries comparable in size to the steel, concrete, and petroleum

industries of today. For example, 1 GtCO₂, when liquefied during subsurface sequestration, is nearly 9 billion barrels of supercritical CO₂, **equivalent to twice the current annual U.S. domestic oil production.**

Ciais, et al. (2013) in Fifth Assessment Report of the Intergovernmental Panel on Climate Change

It is likely that Carbon Dioxide Removal (CDR) would **have to be deployed at large-scale for at least one century to be able to significantly reduce atmospheric CO₂.** In addition, it is virtually certain that the removal of CO₂ by CDR will be partially offset by outgassing of CO₂ from the ocean and land ecosystems.

Editorial in Nature (2018) Volume 554:404, February

Negative Thinking – How work on rocks draw carbon from the air shows the scale of the emissions challenge.

“...the effort required is astounding.”

“grinding up 10–50 tons of basalt rock and applying it to each of some 70 million hectares — an area about the size of Texas — of US agricultural land every year would soak up only 13% of the annual global emissions from agriculture. That still leaves an awful lot of carbon up there, even after all the quarrying, grinding, transporting and spreading.”

“It’s not hard to see why many climate scientists have dismissed the near-impossible scale of required negative emissions as “magical thinking”. Or why the European Academies’ Science Advisory Council said in a report this month: “Negative emission technologies may have a useful role to play but, on the basis of current information, not at the levels required to compensate for inadequate mitigation measures.”

“The IPCC is now working on a report on strategies to keep warming to under 1.5 °C, which is due to be published later this year. By necessity, those strategies will lean heavily on negative emissions. **Scientists must continue to spell out to policymakers the harsh reality of what this would involve, and in the strongest possible terms.**”

Schuiling and Krijgsman (2006) By the authors calculations, in order to neutralize the CO₂ currently in the atmosphere, we need to spread a layer of olivine over the whole surface of the earth at about 0.12 cm thickness. If we limit the olivine spreading to the **land mass, the thickness of the layer would become 0.4 cm. This is huge!**

Hartmann and Kempe (2008) What is the maximum potential for CO₂ sequestration by “stimulated” weathering on the global scale?

Of all the negative thinking articles, this somewhat obscure one in Naturwissenschaften, is the most negative of them all. It is paraphrased as follows.

Natural chemical weathering of silicate rocks is a significant sink for soil and atmospheric CO₂. Previous work suggested that natural chemical weathering may be stimulated by applying finely ground silicate rocks to agricultural areas or forests [enhanced weathering (EW)]. However, it remains unknown if this technique is practical to sequester globally significant amounts of CO₂ under realistic conditions. Applying first estimates of “normal

treatment” amounts from a literature review, we report here a theoretical global maximum potential of 65×10^6 tons of sequestered C/year, if EW would be applied homogenously on all agricultural and forested areas of the world. This is equivalent to **0.9% of anthropogenic CO₂** emissions (reference period 2000–2005). First, however, the assumed application of EW on most of the considered areas is not economically feasible because of logistic issues, and second the net-CO₂ sequestration is expected to amount to only a fraction of consumed CO₂ due to the energy demand of the application itself (currently ~11%). Unless progress in application procedures is provided, the recent realistic maximum net-CO₂-consumption potential is expected to be **much smaller than 0.1% of anthropogenic emissions**, and the EW would thus not be one of the key techniques to reduce atmospheric CO₂ concentration.

One can only think, after reading this – “why bother?”

Kohler et al (2010) also illustrated the magnitude of the problem. They calculated that at least 3 Gt of olivine per year must be distributed over tropical soils annually for Enhanced Weathering to consume 1 Gt C/yr. To put this into context at a local scale, global dissolution of 3 Gt of Mg-olivine per year would mean the distribution and dissolution of up to 600 g/m²/yr of olivine **throughout the whole catchment area of the Amazon**. In addition, these estimates do not address the difficulties in distributing olivine powder in remote land areas covered with dense tropical rain forests and neglect a crucial limitation of the chemistry of olivine dissolution, due to the saturation of waters with silicic acid (H₄SiO₄), which would restrict further dissolution of olivine.

Kohler et al (2013) pointed out that it would require **300 large tankers of olivine** put in the ocean each year to normalize ocean acidity. That is huge. Would this be decreased using electrolysis?

Anderson and Peters, (2016) The trouble with negative emissions. Reliance on negative-emission concepts locks in humankind’s carbon addiction. Science 354:182-183.

“Negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble. There is a real risk they will be unable to deliver on the scale of their promise.”

They raise a common concern about NET, that they would lower the pressure to decrease emissions. However, **most NET proposals include the conclusion that a stark reduction of emission is still critical.**

Nemet et al, (2018) Negative emissions—Part 3: Innovation and upscaling.

Given that the broader innovation literature consistently finds long time periods involved in scaling up and deploying novel technologies, there is an urgency to developing NETs that is largely unappreciated. This challenge is exacerbated by the thousands to millions of actors that potentially need to adopt these technologies for them to achieve planetary scale. This urgency is reflected neither in the Paris Agreement nor in most of the literature we review here. If NETs are to be deployed at the levels required to meet 1.5 °C and 2 °C targets, then important post-R&D issues will need to be addressed in the literature, including incentives for early deployment, niche markets, scale-up, demand, and—particularly if deployment is to be hastened—public acceptance.

Taylor et al, (2015) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change 6: 404, April.

Despite maximization of weathering by applying ground ultramafic rocks in **weathering hot spots in the tropics**, they estimated implementation costs (combined capital and operational) for achieving an initial 50 ppm drawdown of atmospheric CO₂ are **\$60–600 trillion** for mining, grinding and transportation, assuming no technological innovation, with similar associated additional costs for distribution. These costs are detailed in the following tables.

Supplementary Table S10. Estimated combined capital and operational costs associated with mining, grinding, transport and spreading of material from the air. Cost in US dollars (\$US) converted from Great British pounds (GBP) assuming an exchange rate of 0.63 GBP per \$US. This table has been adapted from Renforth *et al.*¹²².

	\$US tonne ⁻¹	\$US tonne ⁻¹
	lower	upper
Excavation/drilling	0.79	0.79
Grinding (communition)	5.40	64.60
National transport	8.57	9.21
International transport	42.86	46.03
Air-spreading	80 ^a	155 ^b
Total	162.50	325.83

^a Taken from Wickström *et al.* Swedish Forest Agency¹²³ 10-year catchment liming project

^b Estimate taken from whole-catchment lime application by aircraft reported in Donnelly *et al.*¹²⁴.

It is of note that the major expenses are International transport and Air-spreading. If the ultramafic rocks can be obtained locally, and the expense of air-spreading cut, and use the lower estimates, the costs could be as low as \$12 trillion, still a huge amount.

Supplementary Table S11. For application in tropical weathering hotspots (20 Mkm²) under RCP8.5 – expenditure (trillions of US dollars) required for initial consumption of 50 ppm atmospheric CO₂ based on the tonnage of rock required.

Application scenario	Year achieved	Initial 50 ppm CO ₂ drawdown					
		Rock required (Pg)	Rock prep. & transport		Spreading costs		
			lower	upper	Cost (Tn US\$)	Cost (Tn US\$)	
1 kg Harz. m ⁻² yr ⁻¹	2064	1,180	68	142	94	183	
5 kg Harz. m ⁻² yr ⁻¹	2034	2,900	167	350	232	449	
1 kg Basalt m ⁻² yr ⁻¹	2099	1,880	108	227	150	291	
5 kg Basalt m ⁻² yr ⁻¹	2054	4,900	282	591	392	760	

These costs are enormous!!!

These considerations make clear that the relatively modest resources of the Comings Foundation cannot begin to address the challenges of doing an NET that eliminates all the CO₂ necessary to fully combat global warming. There are two potential more modest possibilities.

Federal involvement

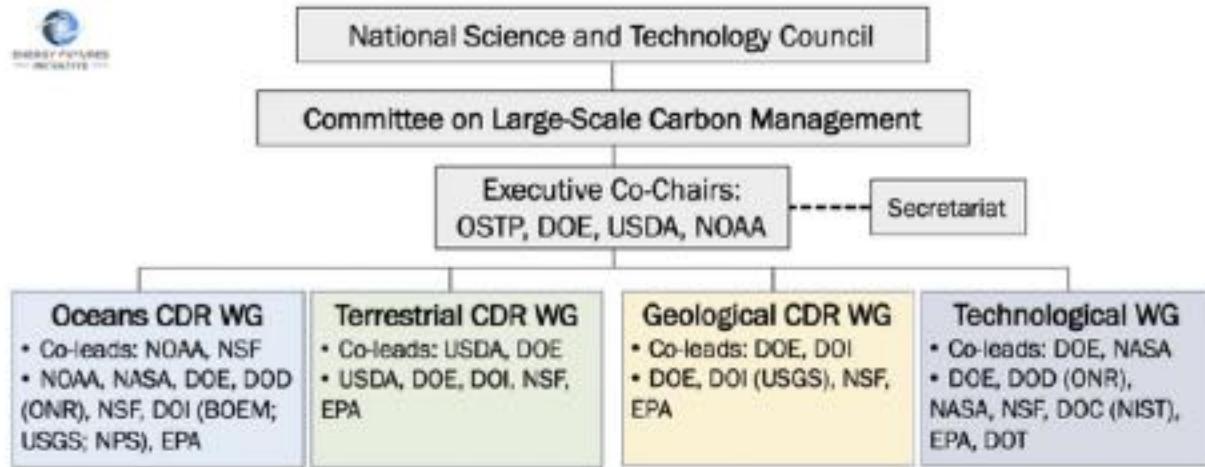
The magnitude of CDR is so immense that the authors of EFI (2019) proposed the involvement of following multiple federal entities. Involving the EPA will be important if large tracts of open mining are involved,

Federal Participation in CDR RD&D Initiative



He proposed the formation of a new entity the Committee on Large-scale Carbon Management utilizing these federal entities in the following manner.

Interagency Integration and Coordination



While the government involvement on such a scale has largely been lacking, the Biden administration has finally taken the issue of climate change seriously. However, until significant government involvement takes hold, it will be incumbent upon private entities and foundations to initiate the beginnings of the development required.

Perhaps Not Hopeless

Despite the many negative opinions shown above, The Energy Futures Initiative (2020) article entitled: *Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management*, makes the following key statements.

1. Carbon mineralization provides a **pathway to near permanent isolation of carbon dioxide (CO₂)** from the environment.
2. Technological enhancements can expand and accelerate natural carbon mineralization, making it feasible **to achieve gigaton (Gt) scale CO₂ removal (CDR)**.
3. Carbon mineralization has several co-benefits that enhance its attractiveness. They make a number of recommendations.
4. Each pathway has the scaling potential to achieve Gt-scale CDR within a cost range of less than \$100 per ton of CO₂.

In Conclusion,

- by using zero carbon dedicated sources of energy for grinding,
- by using commercial waste sources of silicates (tailings),
- by transporting by tanker if using Norwegian olivine is necessary,
- by recovering nickel from olivine,
- by factoring in the increases in crop yield,
- by factoring in the decrease in pH of the soil,
- by combating CO₂ emissions from soils,
- by combating N₂O emissions from the soil and ocean,
- by combating ocean acidification,
- by increasing ocean alkalization,
- by emphasizing the utilization of CO₂ weathering “hot spots”,
- by focusing on areas of oxisols and ultisols,
- by using ships for OAE designed to be carbon negative,
- by using the same ships for on-board grinding of rocks,
- by using carbon credits,
- by partnering with government agencies such as the Department of Agriculture, the U.S. Geological Service and others,

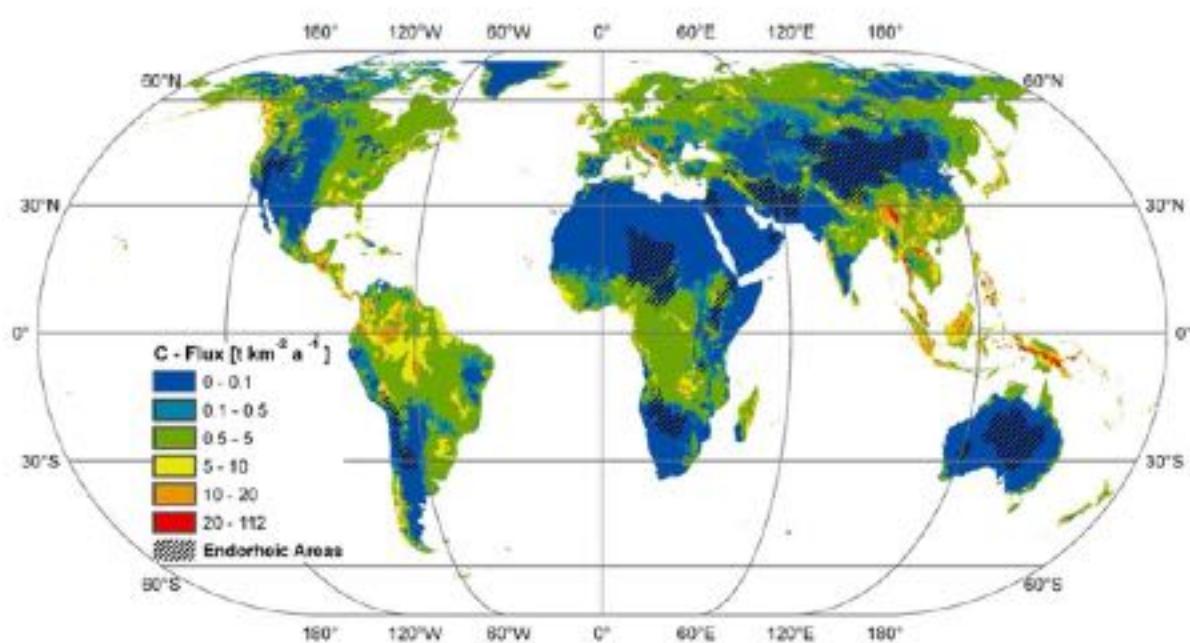
the prospects of using of enhanced weathering of cropland, non-cropland and oceans, could be significantly increased and its cost decreased.

More Realistic Comings Foundation Projects

Given the magnitude of above problems the Comings Foundation, and probably the worldwide EW effort, will clearly need to support some more modest objectives. The following are seven possibilities for these more modest projects. The 7th is **The Grand Plan**.

1. EW in South America Hot Spots. The Comings Foundation could support the spreading of finely ground olivine on hot spot areas in a South American country such as Columbia. Focusing on moist tropics produces 29 times more rapid weathering than dry, temperate climates, and focusing on tropical “weathering hot spots” leads up to a further 5-10-fold increase in weathering. This suggests that the exclusive use of hot spots would produce a weathering rate of 29 x 5 or 145 x that of temperate dry areas in the US. Clearly these would be the areas to use. **This might dramatically change some of the above negative thoughts about EW.**

Hartmann et al (2009a) published **hot spot map for the world**.



Compare this with the following Hartmann et al (2013) map of identified sources of mafic like basalt or gabbro in South America.



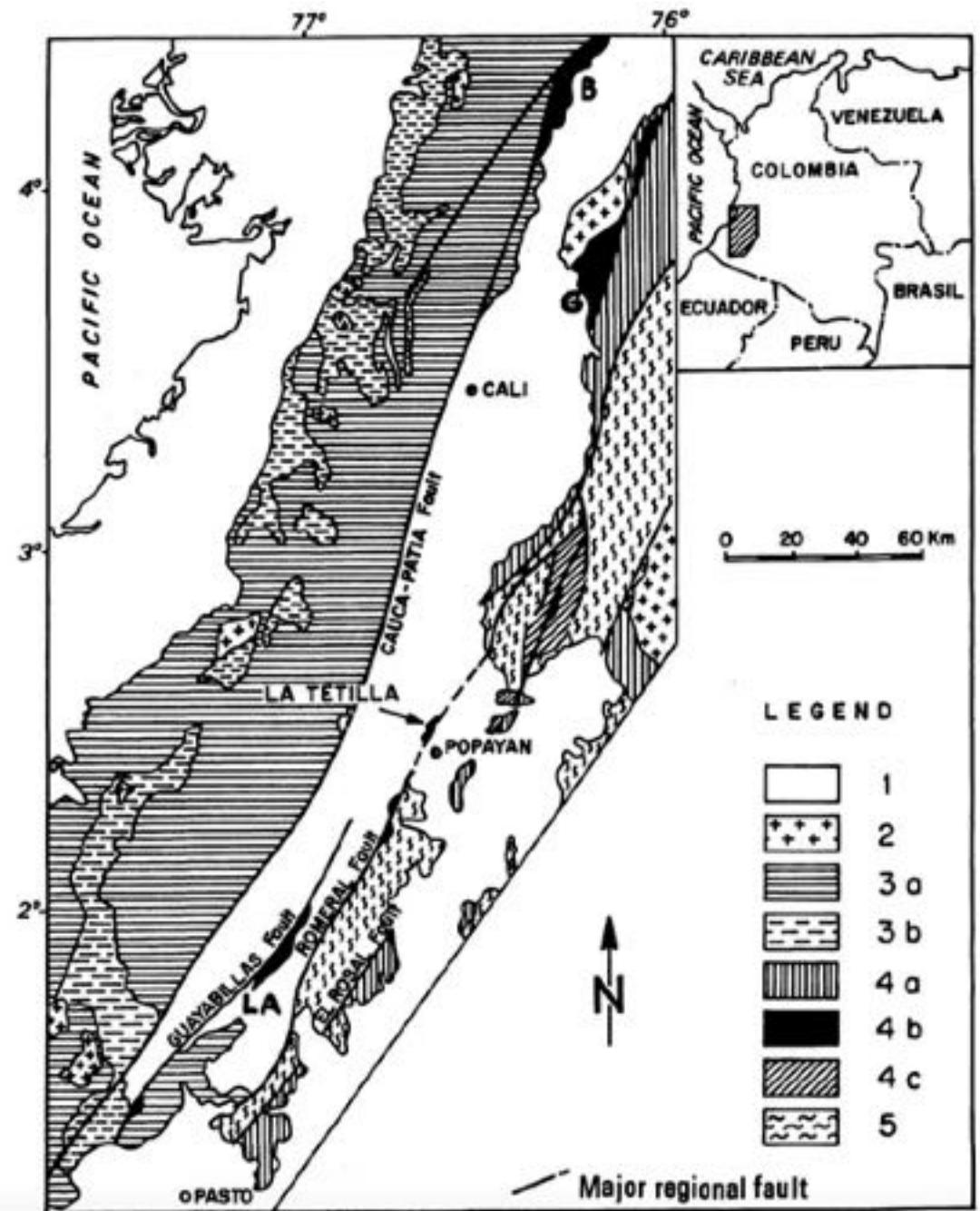
The ideal site for using mafic rocks to sequester CO₂ would be places where there are both weathering hot spots and sources of mafic rocks, preferably in the Western hemisphere. Comparing the above two maps identifies Columbia (below) as such a country.



The following are two geological maps of ophiolite deposits in Colombia, both showing areas close to the Pacific. For orientation, the first shows regions just north of Cali (see above map).

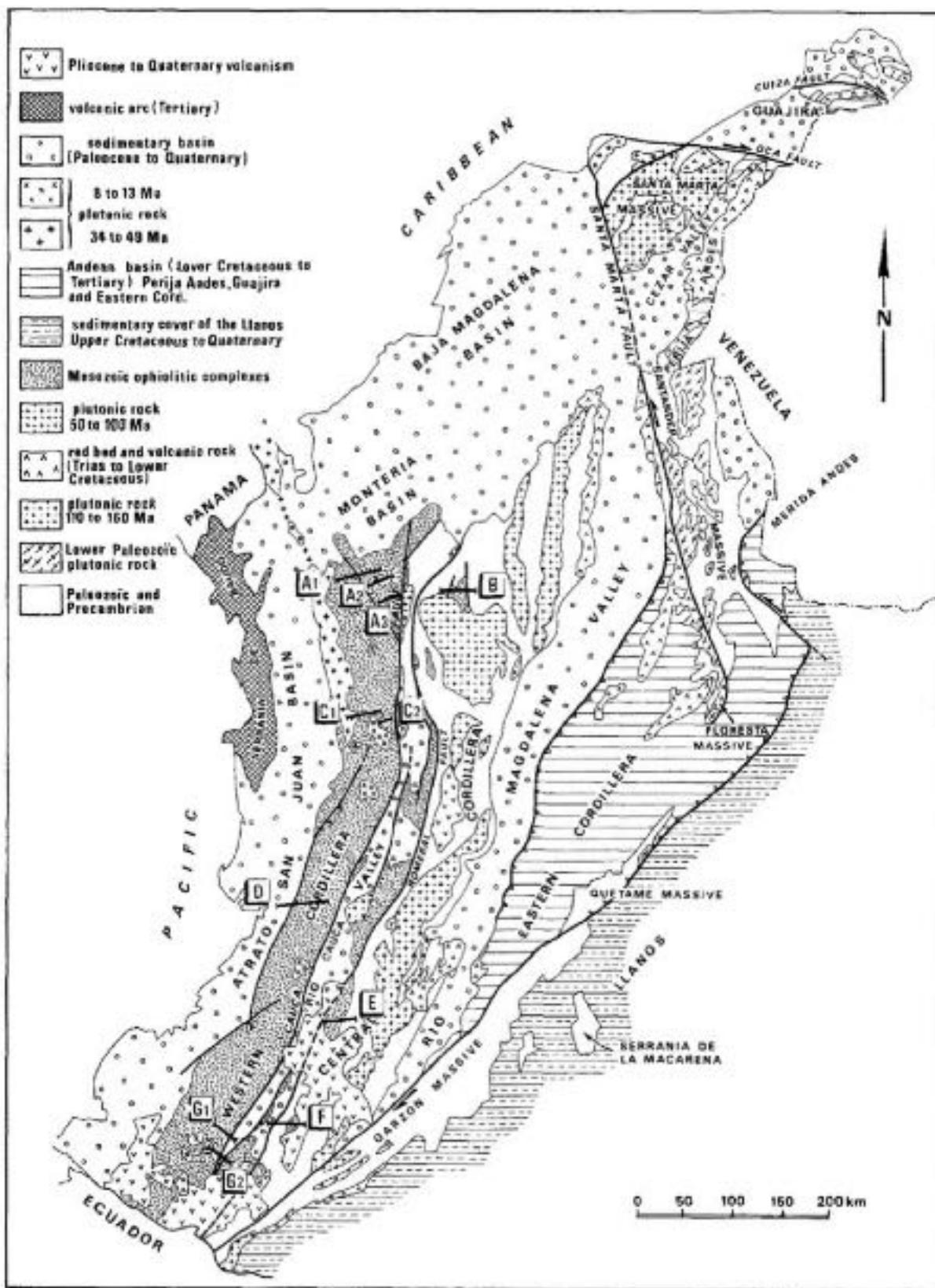
The first is from Spadea, P. et al.(1987) Ophiolite Complex from La Tetilla, Southwestern Colombia. The following is the legend.

Simplified geologic map of Southwestern Colombia. 1 = Quaternary-Neogene continental (volcanogenic p.p.) and marine deposits. 2 = Mesozoic intrusive. 3 = Volcanic-sedimentary complexes from Western Cordillera (Mesozoic): 3a. Basalt, chert, and terrigenous sedimentary rocks; 3b. Metasedimentary rocks. 4 = volcanic and plutonic complexes from Romeral Zone (Mesozoic): **4a. Mafic volcanism; 4b. Mafic-ultramafic plutonic: (B = Bolivar Complex; G = Ginebra Complex; LA = Los Azules Complex); 4c. High-pressure metabasites.** 5 = Metamorphic and plutonic rocks from Central Cordillera (Paleozoic).



The black regions are the location of **Mafic-ultramafic plutonism**.

The second map is from Bourgois, J. et al (1987) Geological history of the Cretaceous ophiolitic Complexes of Northwestern South America (Colombian Andes). *Tectonophysics*. 143:307-327.

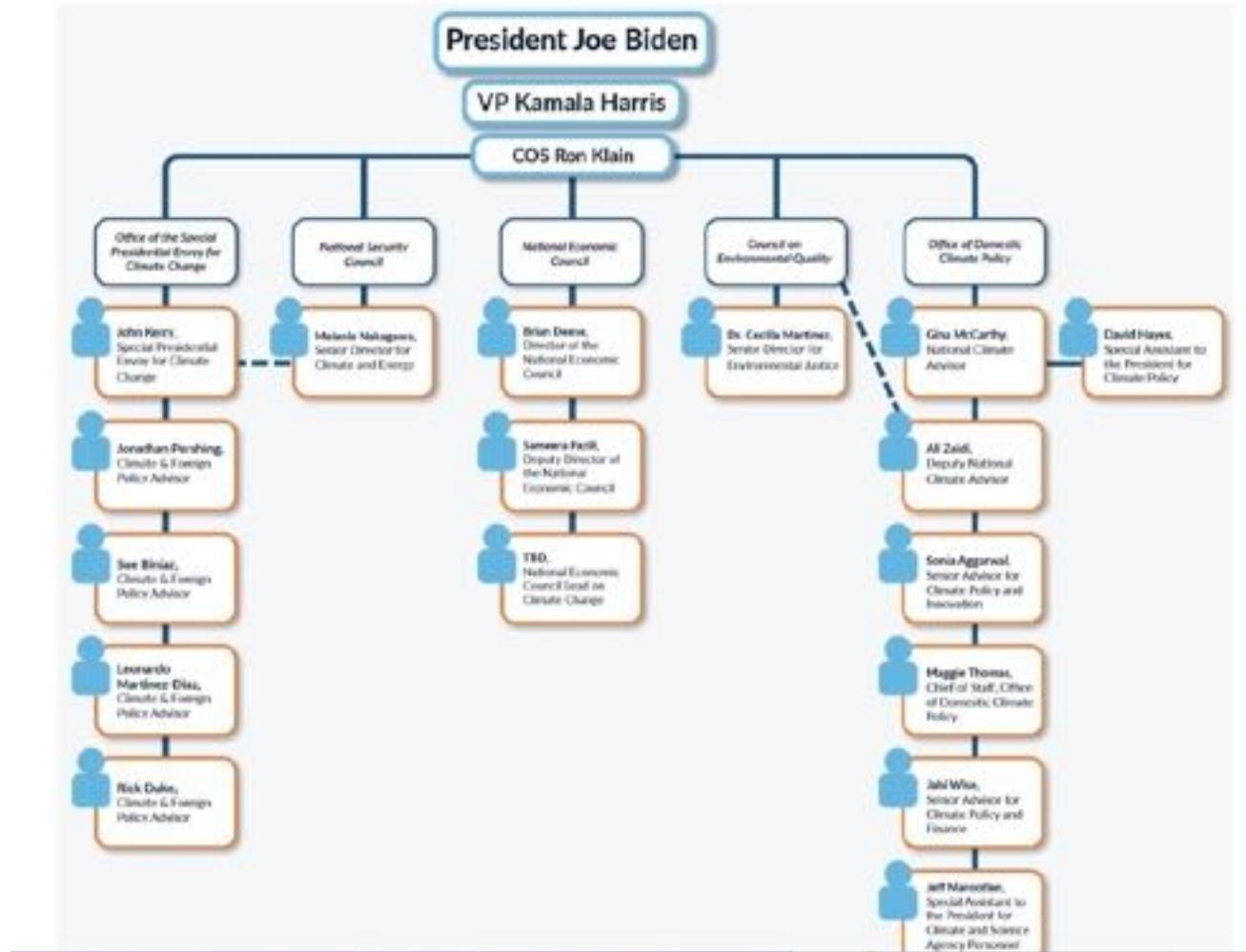


This shows that the Western Cordillera containing ophiolitic complexes runs along the Pacific Ocean from Panama to Ecuador.

These two maps show that Columbia has extensive deposits of ophiolites suitable both for research using ground ultramafic rocks on the crop and non-cropland, and the ocean.

It is clear that in order to pursue this area of research we would need a special team, preferably including hot spot specialists such as Hartmann, and working with the U.S. Office of the Special Presidential Envoy for Climate Change headed by John Kerry. As shown in the following diagram, within this team there is considerable emphasis on Foreign Policy.

Key Figures in President Biden's Climate Team



We would next ask the Biden Climate Team for assistance in working with Columbia. Are they willing to mine the mafic rocks and to have the following research site set up?

Research Plan for Comparing Efficacy of Weatherization in Hot Spots to US

Croplands. We would propose to use an area in Columbia of up to 200 acres, close to a river. The site would be divided into two halves, one half as non-cropland, the other half planted with different crops. In each, multiple subsites would be laid out, with a clear region of demarcation

between them. Each of these subsites would be layered with a different thickness of finely ground olivine or other silicates. Since studies in Oman indicated carbonization extended down 100 meters, these layers could be quite thick. The sites would be monitored for months to years to determine the composition of the rocks over time. We would also monitor the closest river over time to identify the rate of weathering and weathering products. We would assume that the testing of samples, both on the different sites and from the river, would utilize a common laboratory for the analyses. We would also set up two additional sites in the US, one in a temperate wet area such as in Southern states, and another in a temperate dry area. All sites would be set up in an identical fashion. This would allow us to compare the results for these different types of areas. Such a research program would answer many important questions about the use of EW on croplands or non-croplands in the US. An additional aspect of the study would involve planting **nickel hyper accumulators**, such as those in the *Alyssum* family, to determine if nickel can be economically extracted from olivine or related silicates.

Such a research project could be used to satisfy part of that Columbia's obligation for assisting with the Paris Accord or later accords. Columbia might also provide the research site and local personnel free of charge and provide other financial assistance to the project. This could be one of the projects submitted to the Musk Prize for assistance with funding (see Appendix D). The US Dept of Agriculture and the Biden Climate team might also help with funding. Several million dollars from the Comings Foundation could get the project started.

The Carbon 180 Zero then Negative - The Congressional Blueprint for Scaling Carbon Removal, May 2021, proposed as their action #11 - Create an RD&D program for enhanced CO₂ mineralization. **This would be just such a research program.**

2. Adding finely ground olivine to standard fertilization practices in the US.

Perhaps the equation could be turned upside down. Van Straaten, (2002), in his book *Rocks for Crops, Agrominerals for sub-Saharan Africa*, reported on the use of rocks and minerals as low-cost, locally available geological nutrient resources for agricultural development, with no thought to how they could sequester CO₂. When used in combination with leguminous tree fallows that fix atmospheric nitrogen, farmers were able to replenish the productivity of their soils using resources naturally available in Africa. This was a great contribution to overcoming hunger and opening the way for sustainable food production in Africa in ways that enhance their natural resource base. Agrogeology is broadly defined as 'geology in the service of agriculture.' Rocks for crops has also been done in many other countries.

Given the much lower weathering rate in dry, temperate regions like the U.S. compared to wet tropical ones, we could help to develop an industry consisting of obtaining, grinding and distributing finely ground olivine to U.S. farmers to supplement their normal fertilization practices, **and let the CO₂ sequestration chips fall where they may**. The advantage of adding mafic rocks to cropland is that they can combat soil acidity, add silicon, decrease N₂O production, and combat ocean acidity as stand-alone goals.

Other issues involve identifying the optimal sites for mining olivine, determining whether it is better to have a centralized facility near olivine mines for the grinding to take place or to have de-centralized facilities. If decentralized facilities were involved, it would allow for the investigation of the potential role of SCPP-PCR-CBGS (see above) at such multiple facilities to provide zero carbon power for the grinding and removal of methane and N₂O. An advantage of this approach is that if successful, the lessons learned from the research and development

involved could provide a blue-print for the dispersal of such an approach to many countries and farmlands world-wide.

3. Improving the Yield of Rice Farms. The net rice yield can be increased by 10% to 50% by application of silicon fertilizers, depending on the local conditions (Alvarez and Datnoff, 2001). Powdered silicate rocks have even been considered as an alternative to conventional fertilization in areas where fertilizers are not available or are too expensive for many farmers. The benefits include **dramatic increases in rice yields**, prevention of Fe and Mn toxicity, and better uptake of phosphorus. In China rice yields have increased up to 400% following treatment with Si containing materials. It also decreases the impact of several diseases. As such it can reduce the need for fungicides. It also decreases the effects of various arthropod pests. Si sources have residual effects that persist over time. Thus, yearly applications may not be needed. This would be an important accomplishment, since production increases will, come from yield increases because of lack of available land.

Rice farms are a major source of methane. One goal would be to determine if utilization of EW on rice farms would mitigate this problem

One could start with the rice farms in the U.S. These four regions produce almost the entire U.S. rice crop:

Arkansas Grand Prairie,
Mississippi Delta, (parts of Arkansas, Mississippi, Missouri, and Louisiana),
Gulf Coast (Texas and Southwest Louisiana), and
Sacramento Valley of California.

4. Saving the Great Barrier Reef in Australia. This would be addressed by placing ground olivine or similar mafic rocks into the waters around the Great Barrier Reef using the OAE ships (see below). There is considerable literature on relevant to large ophiolite deposits in Western and Eastern Australia (Aitchison 2017; Foster et al 2001; Spaggiari et al.2004, 2018; Moeskops and Davis, 1997). As outlined above there are also sites of ultramafic rocks in nearby New Guinea and New Caledonia.

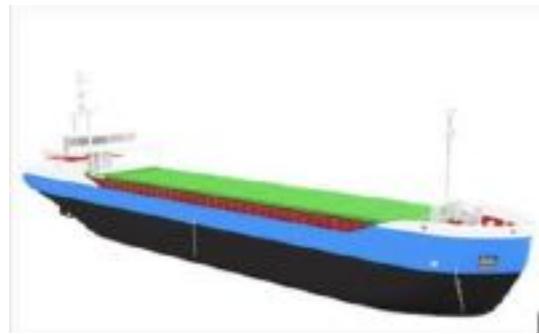
5. Decrease Atmospheric Methane. We will contract with a commercial engineering company to build and test the effectiveness of the **Solar Chimney Power Plant (SCPP)** and a **Photo-Catalytic Reactor (PCR)** for producing cheap electricity and remove methane from the atmosphere.

6. Develop blueprints for ships designed to distribute ultramafic rocks in the ocean using electrolysis techniques and renewable power.

As described above, one option for the alkalinization of the oceans is to build a fleet of specialized ships running on carbon free electricity and using electrochemistry for alkalinization. We will contact a ship design firm, such as **Bay Engineering** to assist in design proposals. The ship would at a minimum, need to comply with the International Maritime Organization Energy Efficiency Design Index (EEDI), but preferably do far better.

An OAE Research Ship

The following figure illustrates the general plan of an OAE research ship running on renewable power.



Model OAE Ship

(green = solar panels, blue and black = storage for crushed ultramafic rocks)

However, before we progress to large numbers of OAE ships it will be necessary to design and build the first one and perform a range of research studies. There are many design and other questions that need to be answered.

Power? Can on board solar panels and fuel cells and wind turbines provide enough power for the electrolytic methods and for on-board grinding of rocks? HCl-H₂ fuel cells? Standard O₂ H₂ fuel cells? Both? Are these enough to also power the ship moving slowly as it lays down alkalinization products? If not, can the addition of floating solar panels? (see Power Technology). Can OTEC also be used as a source of electricity? How much would such boats cost new? If a diesel engine is needed for some of the power use a new type of main engine a 7G80ME-C9.5 made by Dalian Marine Diesel (Tanker Operator, 2021)

Best rocks? Which are better, carbonate or silicate rocks? Is onboard grinding and pulverized machine possible? What is the optimal size of the ground rocks?

Heavy Metals One of the concerns about enhanced weathering, whether on cropland, non-cropland or the ocean, is the presence of heavy metals such as nickel and cadmium, in the ultramafic rocks. As noted in the section about On-board chemistry laboratory, the ship needs to have the onboard ability to test for these heavy metals both in the rocks before they are used, and test what goes into the ocean and finally, test the ocean after the OAE progresses. There should also be a developing database of the level of heavy metals in the different worldwide sources of mafic and ultramafic rocks. Finally, if the presence of these heavy metals is unavoidable, research needs to be carried out on the effects of these metals on marine life.

Efficiency What amounts of OAE and CO₂ sequestration could each boat accomplish? How many tons of rock should the boat carry? What would be the optimal balance between size, efficiency, carbon-free electricity and motors, and cost? What are the best electrolytic methods? Should the ships carry more than one method?

Effects on Ocean Chemistry? What are the effects these alkalinization projects on the ocean chemistry? This might be answered most easily by having the ship make multiple passes in a semi-enclosed bay. There are several possible locations including one of the many inlets in San Francisco Bay.

On-board chemistry laboratory Such a laboratory will be necessary to determine pH, salinity, alkalinity, temperature, pCO₂, pO₂, as well as all of the members of the carbonate cycle Ω carbonate, CO₂, H₂CO₃, HCO₃⁻ and CO₃²⁻ for ocean sampling. On board mass spectroscopy?

What other instruments? The use of Wave Gliders (Chavez, 2018) to measure surface pH and pCO₂ at significant distances from the ship would be a valuable addition to the instrumentation. There will be a need to assay heavy metals such as nickel, cadmium and others. How is that best done. Will the mass spectroscopy work for that?

Loading? How will the loading and storage of ultramafic rocks be carried out? Can the boat be designed to self-load? Is there a need for onboard loading towers? Can the companies that mine ultramafic rocks in Washington such as the Unimin Corp and Olivine Corp be utilized?

Governance? What governance agreements will be necessary? What departments in California need to be accessed to obtain permission to carry out this research in San Francisco Bay?

If the results with the initial research ship are positive, multiple countries and many ships could them be involved (see Grand Plan below). The goal is to provide a standardized set of blueprints for proven ships, so each country does not have to design its own.

7. The Grand Plan – World-wide Cooperation for EW.

Magnitude of the EW effort is so great that no single country can do it all. Thus – the Grand Plan. Multiple NETs (Negative Emission Technologies) are going to be required to prevent catastrophic global warming of the planet. Relying on any individual one will not work. Of the NETs - **Enhanced Weathering** using Magnesium and Iron mafic and ultramafic silicate rocks, such as olivine, either *in-situ* or *ex-situ*, is the safest and best NET in terms of very long-term sequestration of CO₂. The problem is huge and will require the combined efforts of many countries. To begin to execute this NET at anywhere close to what is needed, we need to cooperate with the Biden group and call on multiple countries to do the following:

- Put together in their country, an NET EW team of experts.
- Identify the location of mineable mafic and ultramafic rock deposits in their country.

As shown above, there are many possibilities other than olivine. I have been impressed that every time I examine in detail the location of ultramafic rocks in different countries, they are almost always close to the coast: Norway, United States, Columbia, Australia, New Guinea and New Caledonia. This is undoubtedly due to the mechanism of how they are produced, i.e., by the movement of tectonic plates. This costal location is ideal for spreading such rocks in the ocean as well as supplying other countries.

- Initiate the mining of those rocks.
- Develop a source of clean energy for the crushing and grinding of the rocks.
- Develop suitable methods of storing and transporting the ground rocks.
- Identify suitable ports and techniques for placing the ground rocks on ships.
- Identify for that country the most suitable use of this product – on cropland, non-cropland, in rivers, in the ocean, or simply supplying other countries.
- Those countries that have access to the ocean may prefer to put their ground rocks into the ocean. If so, the development, in conjunction with a Marine Engineering firm, of standardized plans for a ship using renewable energy to distribute rocks for alkalization, would be very beneficial. Determine if the country is willing to purchase one or more of the above-described ships.
- Determine the amount of credit they each country can receive for these efforts.
- Develop techniques for monitoring the efficiency and long-term effectiveness of CO₂ sequestration and risk assessments including assessing trace metals.

- While it is clear that the gravitas of the United States Government and the Biden group, will be necessary to get this international effort going, the Comings Foundation is willing to provide seed money for conferences and preliminary research including the design of the appropriate boats.

The Questions Section

A. Questions about mafic rock weathering on cropland

To begin this process, we propose to provide funds for several consultants to attempt to answer as many of these questions in sections A-C, as possible.

The Comings Foundation is interested in activating the use of EW on croplands, non-croplands and the oceans, switching from theory to practice. However, based on the above review it is clear that to totally correct for the CO₂ emissions would be a massive job and it is likely we could only take on bits and pieces and. **But what bits and pieces?** While there are many questions, there are four major ones.

- 1. How can a modest sized foundation, currently with \$2 to \$10 million to distribute each year, (possibly more later), best contribute to getting enhanced weathering of either crops or the ocean, started in the United States or the World?**
- 2. If our consultants had these funds what are the initial and subsequent steps they would take?**
- 3. For those areas of your expertise would you be willing to write a proposal relating to suggested research and be the principal investigator?**
- 4. Do you agree with the gist of the papers reviewed in Negative Thinking about Negative Emissions Technology? If you do, what part of the problem could we address. The section **More Realistic Comings Foundation Projects** attempts to answer that. Any other suggestions?**

Below is a list of some of the additional questions re: Weathering on Cropland and Non-cropland.

- Do you find any errors of fact in this document. If so, comment or correct them in red type and return a copy to us. You could also enter your answers to the questions directly on this document, also in red if you prefer.
- Following the thoughts of Bellamy and Geden (2019) that methods for CO₂ reduction do not have to be deployed at large global scales to be relevant for climate policy, and that every little bit helps, does this suggest despite the problems we should pursue EW on US croplands or elsewhere?
- As an example, one could set up a system to obtain olivine, fine grind it. Package it like fertilizer and distributed it for farmers to use in conjunction with fertilizer. This is one of the modified plans above.
- Even though EW is more efficient in hot and moist tropical and semi-tropical environments, is the addition of finely ground mafic rocks to U.S. croplands still valuable because of its addition of silicon to the soil, inhibition of N₂O release both on land and sea, increasing the pH of soil, and combating ocean acidification? Would emphasizing this NET in the hot, wet, temperate lands of the southern states help?
- What are the governing (regulation) issues, if any?

- Can we elicit the cooperation of the U.S. Dept of Agriculture to help?
- Which is better to use, olivine or basalt, in EW of crops in the U.S.?
- Where are stockpiles of aggregate waste mafic rocks that can be used?
- As stated by Beerling et al (2020) national inventories of the location, availability and extent of this resource are required to assess the potential contribution of this resource for EW. Do we need to develop a US inventory?
- Would it be cheaper to purchase commercially available olivine in the United States or Norway?
- How much would it cost per ton CO₂ if solar or wind energy, or other renewable, was used for grinding?
- Can CO₂ capture technologies, such as the water sensitive resins described by Lackner, be married to an olivine mine, thus enhancing mineralization and eliminating transportation costs?
- Should there be a centralized facility for mining and processing olivine or basalt? If so, where?
- Could carbon free sources of energy (solar, wind, nuclear) be made available in these areas?
- How to get farmers to switch from lime to basalt or olivine?
- Can we use the same companies that distribute lime to distribute crushed olivine?
- Schuiling and Krijgsman (2006) proposed mixing olivine or basalt with fertilizer. Is this reasonable? Would this increase farmers acceptance of weathering?
- If non-cropland is used, what is the thickness of the olivine or basalt that still effectively sequesters CO₂?
- Once we answer some of these questions, what are the prospects of spreading this technology to other countries?
- As described below, one source of power to grind the rock could come from a Solar Chimney Power Plant (SCPP). This also has the potential of combining this with a Photo-Catalytic Reactor (PCR) to also remove methane. Question: Can we engage an engineering company to build and test SCPPs-PCR. Will it work in the Midwest? Will using PCR really remove methane? If so, how much?
- Does the technique of Jang, et al (2021) of energy-efficient clathrate-based greenhouse gas-separation (CBGS), to remove atmospheric N₂O work? Is it economically feasible?
- A map above shows the worldwide distribution of olivine mines. Given that olivine weathers much rapidly in warm humid weather would it be possible to pick areas that a) mine olivine and b) are located in “hot spot” regions with warm humid weather to focus on EW of crops or non-croplands?
- In warm and humid areas, how thick can one coat non-croplands with olivine and still have efficient weathering? If the answer is a significant multiplier of the amount spread on cropland, this could dramatically enhance the prospects of EW as a solution to global warming.
- If carbon credits are in place, could that pay for much of EW using non-croplands?
- Could we purchase a number of acres in the southern states to use as a testing site to determine the maximum density of olivine that can effectively adsorb CO₂. Florida is already spending \$100 million on mitigation. They should be interested in this research.
- If we can't do these kinds of studies in the US where would be the best place to do them, taking into consideration which countries would be cooperative?
- What role can cooperative working with the U.S. Dept of Agriculture play in assisting with EW?
- As described above, one option is to purchase several hundred acres of non-cropland in low lying areas of a Central or South American country and spread finely ground olivine at sites of various levels of thickness. These different sites would be monitored over many months or years

for their effectiveness in sequestering CO₂. A part of this research would be to set up a comparable study in the US and compare the results. Do you concur that this is a reasonable research project? This is modified plan #1 above. If so, any comments on improving the study?

- What would be most effective, to have a centralized site where olivine or basalt is finely ground, using solar, wind, nuclear, or energy, then shipped to sites where it is used, or to do the grinding essentially onsite, again using clean energy?

B. Questions about putting mafic rocks directly into the ocean and electrolysis.

- The major question is: Which will be a more efficient way to use enhanced weathering – applying mafic rocks to croplands or by spreading finely ground olivine directly into the ocean, or both?
- The ocean approach has the advantage of directly combating ocean acidification and of bypassing the potential problems of obtaining the cooperation of farmers and spreading the rocks over large areas of cropland. Of course, both approaches can be used.
- Dissolution of olivine is slower at ocean pH than soil pH. Does this seriously impair the use of placing olivine directly in the ocean?
- Hartman et al (2013) emphasized the need for infrastructure to transport basalt or olivine over land distances and the carbon cost of this. Isn't this a good reason to emphasize direct spreading pulverized olivine in the ocean and using sources close to the ocean?
- Does the program above, concerning rescuing the Great Barrier reef sound doable? Are there adequate olivine deposits in or near Australia to accomplish this? Or would we have to rely on New Caledonia?
 - Is it reasonable to attempt to reduce ocean acidification over a limited area such as the great barrier reef. How quickly would this be eroded away by currents?
- In the Rigopoulos et al (2017) study, pulverized, and ball-milled dunite, harzburgite and olivine basalt were reacted in artificial seawater in batch reactor systems open to the atmosphere for two months. In contrast, pulverized but un-milled rocks, and the ball-milled basalt, did not yield any significant changes in seawater composition during the two-month experiments. Does that rule out using basalt on oceans? I would think so.
- Does paying the Bay Engineering Company to perform preliminary studies on the feasibility make sense? They were chosen because of their extensive use of computerized instruments and their wide range of services. See Appendix E.
 - As an example of an assessable ophiolite, in the area from North Carolina to Georgia, there are at least "25 large forsterite olivine deposits, remarkably sound and free from alteration minerals, occurring in a belt 175 miles long and 15 miles wide" (Project Vista). Can they be used?
 - Since the largest deposits of olivine in the U.S. are on the West and East coast of the U.S. would these be better sites to begin our ocean projects?
 - Can one or both of the U.S. olivine companies be of assistance? Utilizing these companies could solve the problem of where to get the olivine for enhanced weathering using the ocean or croplands.
 - An overriding major question is: How much CO₂ can be sequestered per year combining the use of cropland and non-cropland in the US, India and China, and other countries, plus the

oceans? Beerling et al (2020) hopes to achieve an average global goal of 0.5 to 2 gigatons of carbon dioxide (CO₂) per year by Enhanced Weathering of Croplands worldwide. The Musk prize has set a goal of 10 Gigatons per year. Thus, EW using croplands could account for up to 20% of this level of CO₂ sequestration. How much more can be sequestered by using the oceans? Or, by using non-croplands. This is a far greater percent of needed sequestration than suggested in many of the papers in the Negative Thinking section.

- The world's largest active olivine quarry is the Gusdal Pit in Norway (see above). No chemicals are needed to extract the rock, nothing is underground, the process is not mining, it is surface extraction. This raises the possibility of purchasing olivine on site, ensuring it is finely ground, and immediately distributing it into the ocean. Is this reasonable?
- An alternative mentioned above is loading Norwegian olivine on tankers, doing the grinding on the tanker, and distribute some in the ocean on the way to other ports. Is this reasonable?
- Does the use of boats to spread crushed carbonate or ultramafic rock into the ocean make sense?
- What percentage of the electricity used for electrolysis can be recouped with H₂ fuel cells?
- Which of the electrolysis approaches, including electrolysis GDA, is most efficient? Which is best suited to a ship-based approach?
- In regard to the Equatorial Project, is the increased uptake of atmospheric CO₂ following OAE sufficient to offset the outgassing of CO₂ in those equatorial regions? Or, put another way, can localized OAE combat the localized CO₂ outgassing?

C. Questions Relating to the Grand Plan and New Caledonia

- We believe involving many countries in this NET of EW for crops is the only viable way forward for this technology. Do you agree? According to Hartmann and Kempe (2008) even this may be a waste of effort and time.
- To make such a plan work we would need to have it headed by someone with gravitas in the field. Who would you recommend?
- Can we enlist the aid, cooperation and involvement of the Department of Agriculture? The Biden Climate Team?
- To spread out costs we would imagine that each country would fund their own efforts. Reasonable?
- We believe the Comings Foundation can best contribute to this effort by supporting some of the background research including answers to the many above questions.
- Relative to New Caledonia, this nation could become a major supplier of ultramafic rocks in the Pacific Area including for combating equatorial CO₂ outgassing. How do we get that started? It is a French Colony. Do we approach the President of France or the local government or do we start with one of the authors who have studies this area such as Pierre Gautier?

Appendices

Appendix A. A Short Course in Mineralogy

Because of the wide number of minerals mentioned above the following is a short course in the relevant mineralogy.

Mafic rocks **Ma** = magnesium **fic** = ferric iron containing.

Most mafic minerals are dark in color, and common rock-forming mafic minerals include olivine, pyroxene, amphibole, and biotite. Other common mafic rocks include basalt, diabase and gabbro.

Ultramafic rocks are igneous and meta-igneous rocks with a lower silica content (less than 45%), generally >18%, MgO high FeO, low potassium, and are composed of usually greater than 90% mafic minerals (dark-colored, high magnesium and iron content). The Earth's mantle is composed of ultramafic rocks.

Peridotite is a dense, coarse-grained igneous rock consisting mostly of the minerals olivine and pyroxene. Peridotite is ultramafic, as the rock contains less than 45% silica. It is high in magnesium (Mg^{2+}), reflecting the high proportions of magnesium-rich olivine, with appreciable iron.

Pyroxenes are a group of dark-colored rock-forming minerals found in igneous and metamorphic rocks throughout the world. They form under conditions of high temperature and/or high pressure.

Pyroxene minerals are defined by their chemical composition and crystal structure. Their generalized chemical composition is described by the formula XYZ_2O_6 where X can be Ca, Na, Fe^{++} , Mg, Zn, Mn or Li. Y can be Mg, Fe^{+++} , Cr, Al, Co, Mn, Sc, Ti or Vn. Z can be Si, Al or a combination of both. A wide range of cation substitutions can occur in the X and Y positions.

Augite, diopside, jadeite and spodumene are four of the best-known members of the pyroxene group; however, the pyroxene group has many other members.

Augite is a rock-forming mineral that commonly occurs in mafic and intermediate igneous rocks such as basalt, gabbro, andesite, and diorite. It is found in these rocks throughout the world, wherever they occur. Augite is also found in ultramafic rocks and in some metamorphic rocks that form under high temperatures. Augite has a chemical composition of $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$.

Andesite is the name used for a family of fine-grained, extrusive igneous rocks that are usually light to dark gray in color. They often weather to various shades of brown, and these specimens must be broken for proper examination.

Aragonite is a carbonate mineral, one of the three most common naturally occurring crystal forms of calcium carbonate, $CaCO_3$ (the other forms being the minerals calcite and vaterite). It is formed by biological and physical processes, including precipitation from marine and freshwater environments.

Basalt is a dark-colored, fine-grained, igneous rock composed mainly of plagioclase and pyroxene minerals. It most commonly forms as an extrusive rock, such as a lava flow, but can also form in small intrusive bodies, such as an igneous dike or a thin sill. It has a composition similar to gabbro. The difference between basalt and gabbro is that basalt is a fine-grained rock while gabbro is a coarse-grained rock.

Diopside is a rock-forming pyroxene mineral with a chemical composition of $MgCaSi_2O_6$. It occurs in igneous and metamorphic rocks at many locations around the world.

Diabase The name "diabase" is used for a dark gray to black, fine-grained, intrusive igneous rock that has a composition similar to basalt and gabbro. The difference between basalt, diabase, and gabbro is in their grain size - which was determined by their cooling rates.

Diorite is the name used for a group of coarse-grained igneous rocks with a composition between that of granite and basalt. It usually occurs as large intrusions, dikes, and sills within continental crust.

Dunite is an igneous rock, of ultramafic composition, with coarse-grained texture. It is 90% olivine.

Feldspar is the name of a large group of rock-forming silicate minerals that make up over 50% of Earth's crust. They are found in igneous, metamorphic, and sedimentary rocks in all parts of the world. Feldspar minerals have very similar structures, chemical compositions, and physical properties. Common feldspars include orthoclase ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$).

Fosterite is a form of white olivine rich in magnesium, with the formula Mg_2SiO_4

Jadeite is an aluminum-rich pyroxene, while nephrite is a magnesium-rich amphibole. Both can form jade. The two minerals have very similar physical properties in the eye of the average person. The chemical composition of jadeite is $NaAlSi_2O_6$ or $Na(Al,Fe^{3+})Si_2O_6$

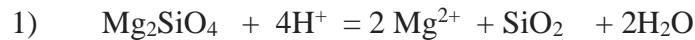
Gabbro is composed mainly of calcium-rich plagioclase feldspar (usually labradorite or bytownite) and pyroxenes (usually augite). Minor amounts of olivine might also be present in the rock.

Harzburgite, is an ultramafic, igneous rock. It is a variety of peridotite consisting mostly of the two minerals olivine and low-calcium (Ca) pyroxene (enstatite); it is named for occurrences in the Harz Mountains of Germany.

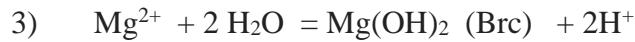
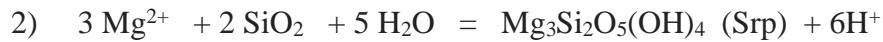
Olivine is the name of a group of rock-forming minerals that are typically found in mafic and ultramafic igneous rocks such as **basalt**, **gabbro**, **dunite**, **diabase**, and **peridotite**. They are usually green in color and have compositions that typically range between Mg_2SiO_4 and Fe_2SiO_4 . Many people are familiar with olivine because it is the mineral of a very popular green gemstone known as peridot.

Plagioclase is the name of a group of feldspar minerals that form a solid solution series ranging from pure albite, Na(AlSi₃O₈), to pure anorthite, Ca(Al₂Si₂O₈).

Serpentinization reaction, even in its simplest form (equation (1)), is the result of several simultaneous reactions that can be summarized as follows. First, olivine dissolves:



When the concentrations of dissolved species become sufficiently high, serpentine and brucite nucleate and precipitate according to:



Reactions (3) and (4) consume water and generate hydrogen ions (H⁺) that in turn promote forsterite dissolution (reaction 1). Eventually, the overall process reaches a steady state whereby the rates of Mg and SiO_{2(aq)} released from olivine dissolution (reaction 1) are balanced by their rates of consumption by serpentine (reaction 2) and brucite (reaction 3) formation.

Appendix B. Conversion Factors

International System of Units to U.S. customary units

Length

meter (m)	3.281 foot (ft)
kilometer (km ³)	0.6214 mile (mi)

Area

square kilometer (km ²)	0.3861 square mile (mi ²)
-------------------------------------	---------------------------------------

Volume

cubic meter (m ³)	35.31 cubic foot (ft ³)
cubic kilometer (km ³)	0.2399 cubic mile (mi ³)

Mass

kilogram (kg)	2.205-pound avoirdupois (lb)
metric ton (t) 1000kg	0.9842 ton long (2,240 lb)

Temperature

in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Appendix C Ophiolite Sites around the World (from Wikipedia)

Mediterranean and Peri-Arabic

Morais ophiolite complex, Portugal Internal Ligurian Ophiolites in Northern Apennines, Italy.
Troodos Ophiolite in the Troodos Mountains of Cyprus.
Kizildag ophiolite, southern Turkey Cap Corse ophiolite, Corsica, France.
Vourinos and Pindos Ophiolites in Northern Greece and their northern extensions.
Albania, Serbia and Bosnia Ronda peridotite,
Southern Spain Lherz Massif, France.
Beni Bousera ophiolite, Morocco.
Golyamo Kamenyane Complex, Bulgaria [2].
Semail Ophiolite in Oman and the United Arab Emirates.
Makran Ophiolite, Makran, Iran.
Pakistan Zagros ophiolite, Zagros mountains, Iran.
Iraq Zagros ophiolites, Zagros mountains, Iraq, includes; Cretaceous ophiolites (Mawat, Penjwen, Pushtashan, Hassanbig and Bulfat) and Eocene ophiolites (Rayat and Qalander).

Tibetan

Dongbo ophiolite Loubusa ophiolite
Purang ophiolite

Asia-Pacific

Zambales Ophiolite in western Luzon, Philippines.
Angat Ophiolite in eastern Luzon, Philippines.
Rapu-rapu Ophiolite Complex in eastern Philippines.
Southeast Bohol Ophiolite Complex in Bohol, Philippines.
Macquarie Island, Tasmania.
Australia Palawan Ophiolite.
Western Philippines.
Papuan ophiolite in Papua New Guinea Yakuno, Horokanai, and Poroshiri.
Three full ophiolite sequences in Japan Dun Mountain Ophiolite Belt,
South Island, New Zealand
Naga-Manipur Ophiolite Complex, India

North American Cordillera (a system or group of parallel mountain ranges together with the intervening plateaus and other features, especially in the Andes or the Rockies).

Coast Range Ophiolite, in the California.
Exposures straddle the coast from Santa Barbara County up to San Francisco. The formation then trends inland up to the southern end of the Klamath Mountains.[1a]
Coast Ranges from Santa Barbara through San Francisco Counties, California.
Kings River ophiolite, southwest Sierra Nevada foothills.
California Point Sal ophiolite, Point Sal, Santa Barbara County, Southern California.
California ophiolite-Smartville Block of the Sierra Nevada, and the Klamath Mountains.
Northern California Josephine Ophiolite.
Southern Oregon Canyon Mountain.
Sparta Complexes ophiolite, Northeastern Oregon.

Payson Ophiolite, Payson, Arizona.
Metchosin Igneous Complex ophiolite, southern Vancouver Island, British Columbia, Canada.
Ingalls Terrane ophiolite, Cascade Mountains, Washington
Fidalgo Complex ophiolite, Skagit County, Washington.

Mexico and the Caribbean

Olivos ophiolite, Chihuahua, Mexico.
Vizcaino ophiolite, Baja California Sur Mexico.
Cuban ophiolitic belt
Puerto Rican ophiolite

Andes

La Tetilla Ophiolite Complex, near Popayán.
Colombian Cordillera Occidental (Andes)
Famatinian Ophiolites, near Famatina in the Argentine Andes.
Tapo ophiolite, Peru [2]
Taitao ophiolite
Rocas Verdes ophiolites, Patagonian Andes, Chile [4]
Tortuga ophiolite complex
Sarmiento ophiolite complex

Brazil

Quatipuru ophiolite, Brazil.
Cerro Mantiqueiras Ophiolite, Rio Grande do Sul, Brazil

Eastern North America

Betts Cove, St. Anthony,
Little Port Advocate.
Gander River, Pipestone Pond.
Great Bend and Annieopsquotch ophiolites in Newfoundland Bay of Islands.
Ophiolite in Gros Morne National Park, Newfoundland, named a UNESCO World Heritage Site
in 1987 because of its superbly exposed complete ophiolite stratigraphic sequence [6]
Thetford Mines ophiolite Complex (Thetford Mines, Cantons de l'Est, Québec, Canada) [7][8].
Asbestos ophiolite (Asbestos, Cantons de l'Est, Québec, Canada) [8]
Mont Orford ophiolite (Magog, Cantons de l'Est, Québec, Canada) [8].
Mont Albert ophiolite (Gaspésie, Québec, Canada) [9]
Maryland ophiolite in the central Appalachian orogen, Baltimore, Maryland. [10]

Northern Europe

Ballantrae Ophiolite Complex.
Girvan-Ballantrae area, SW Ayrshire, Scotland.
Jormua Ophiolite, Finland [1]
Karmøy ophiolite, Scandinavian Mountains, Norway [12]
Leka Ophiolite, Scandinavian Mountains, Norway [13]
Løkken Ophiolite, Scandinavian Mountains, Norway [13]
Nuttio Ophiolite, Finland [1]

Solund-Stavfjord Ophiolite, Scandinavian Mountains, Norway.
Lizard complex in Cornwall, United Kingdom [14].
Outokumpu Ophiolite, Finland [1]
Shetland Ophiolite, Unst and Fetlar, Shetland, Scotland [15]

References

- 1a. Bailey, E. H., Blake Jr, M. C. & Jones, D. L. (1970). "On-land Mesozoic oceanic crust in California Coast Ranges" (PDF). Professional Paper. **700C**: C70–C81. ISSN 2330-7102. Wikidata Q65798444.
1. ^ Jump up to: [a](#) [b](#) [c](#) [d](#) Peltonen, P. (2005). "Ophiolites". In Lehtinen, Martti; Nurmi, Pekka A. (eds.). *Precambrian Geology of Finland*. Elsevier Science. pp. 237–277. ISBN 9780080457598.
 2. ^ Jump up to: [a](#) [b](#) Fernando Gerville, Isabel Fanlo, Thomas N. Kerestedjian, Ricardo Castroviejo, Jose Maria, Gonzalez-Jimenez, Jose Alberto Padron, and José Feliciano Rodrigues. 2011. Alteration Mechanism of Chromite in Podiform Chromitites from two Metamorphosed Ophiolitic Complexes: Golyamo Kamenyane (Bulgaria) and Tapo (Peru)
 3. ^ P. Spadea, M. Delaloye, A. Espinosa, A. Orrego and J. J. Wagner. Ophiolite Complex from La Tetilla, Southwestern Colombia, South America
 4. ^ Stern, Charles R.; De Wit, Maarten J. (2013). "Rocas Verdes ophiolites, southernmost South America: remnants of progressive stages of development of oceanic-type crust in a continental margin back-arc basin". In Dilek, Y.; Robinson, P.T. (eds.). *Ophiolites in Earth History*. Geological Society, London, Special Publications. pp. 665–683. [CiteSeerX 10.1.1.1026.5572](#).
 5. ^ LÉO A. HARTMANN and FARID CHEMALE-JÚNIOR. 2003. Mid amphibolite facies metamorphism of harzburgites in the Neoproterozoic Cerro Mantiqueiras Ophiolite, southernmost Brazil
 6. ^ Dewey, J.F.; Casey, J.F. (2013). "The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland". *Journal of the Geological Society*. **170** (5): 715–722. [Bibcode:2013JGSoc.170..715D](#). doi:[10.1144/jgs2013-017](#). S2CID 130035523.
 7. ^ Schroetter, J.-M.; Pagé, P.; Bédard, J.H.; Tremblay, A.; Béchu, V. (2003). "Forearc extension and sea-floor spreading in the Thetford Mines Ophiolite Complex". In Robinson, P.T.; Dilek, Y. (eds.). *Ophiolites in Earth's History*. Special Publications of the Geological Society. **218**. p. 231–251. doi:[10.1144/GSL.SP.2003.218.01.13](#). ISBN 9781862391451. S2CID 140632035.
 8. ^ Jump up to: [a](#) [b](#) [c](#) Schroetter, J.-M.; Bédard, J.H.; Tremblay, A. (2005). "Structural evolution of the Thetford Mines Ophiolite Complex, Canada: Implications for the southern Québec ophiolitic belt". *Tectonics*. **24** (1): n/a. [Bibcode:2005Tecto..24.1001S](#). doi:[10.1029/2003TC001601](#).
 9. ^ Dubacq, B.; Soret, M.; Jewison, E.; Agard, P. (2019). "Early subduction dynamics recorded by the metamorphic sole of the Mt. Albert ophiolitic complex (Gaspé, Quebec)" (PDF). *Lithos*. 334–335: 161–179. [Bibcode:2019Litho.334..161D](#). doi:[10.1016/j.lithos.2019.03.019](#).
 10. ^ Guice, George L.; Ackerson, Michael R.; Holder, Robert M.; George, Freya R.; Browning-Hanson, Joseph F.; Burgess, Jerry L.; Foustoukos, Dionysis I.; Becker, Naomi A.; Nelson, Wendy R.; Viete, Daniel R. (2021). "Suprasubduction zone ophiolite fragments in the central Appalachian orogen: Evidence for mantle and Moho in the Baltimore Mafic Complex (Maryland, USA)". *Geosphere*. The Geological Society of America. **17** (2): 561–581. [Bibcode:2021Geosp..17..561G](#). doi:[10.1130/GES02289.1](#).
 11. ^ Derbyshire, E.J.; O'Driscoll, B.; Lenaz, D.; Zanetti, A.; Gertisser, R. (2019). "Chromitite petrogenesis in the mantle section of the Ballantrae Ophiolite Complex (Scotland)" (PDF). *Lithos*. 344–345: 51–67. [Bibcode:2019Litho.344...51D](#). doi:[10.1016/j.lithos.2019.06.013](#).
 12. ^ Pedersen, R.B.; Dunning, G. (1997). "Evolution of arc crust and relations between contrasting sources: U-Pb (age), Nd and Sr isotope systematics of the ophiolitic terrain of SW Norway". *Contributions to Mineralogy and Petrology*. **128** (1): 1–15. [Bibcode:1997CoMP..128....1P](#). doi:[10.1007/s004100050289](#). S2CID 140175898.
 13. ^ Jump up to: [a](#) [b](#) [c](#) Furnes, H.; Dilek, Y.; Pedersen, R.B. (2012). "Structure, geochemistry, and tectonic evolution of trench-distal backarc oceanic crust in the western Norwegian Caledonides, Solund-Stavfjord

- ophiolite (Norway)". Geological Society of America Bulletin. 124 (7–8): 1027–1047. Bibcode:2012GSAB..124.1027F. doi:10.1130/B30561.1.*
14. [▲] Strachan, R.A.; Linnemann, U.; Jeffries, T.; Drost, K.; Ulrich, J. (2014). "Armorican provenance for the mélange deposits below the Lizard ophiolite (Cornwall, UK): evidence for Devonian obduction of Cadomian and Lower Palaeozoic crust onto the southern margin of Avalonia". International Journal of Earth Sciences. 103 (5): 1359–1383. Bibcode:2014IJEaS.103.1359S. doi:10.1007/s00531-013-0961-x. S2CID 129361445.
 15. [▲] Papapavlou, K.; Strachan, R.A.; Storey, D.; Bullen, D. (2021). "Tectonic significance of a supra-ophiolitic sedimentary cover succession, Unst, Shetland, Scottish Caledonides: insights from the U-Pb-Hf detrital zircon record". Journal of the Geological Society: jgs2020-169. doi:10.1144/jgs2020-169.

5 - Forearc extension and sea-floor spreading in the Thetford Mines Ophiolite complex

(link : https://scholar.google.com/citations?view_op=view_citation&hl=fr&user=sWm-LdoAAAAJ&cstart=20&sortby=pubdate&citation_for_view=sWm-LdoAAAAJ:B2rPIGFPLEC)

6 - Structural evolution of the Thetford Mines Ophiolite Complex, Canada: implications for the southern Québec ophiolitic belt

(link : https://scholar.google.com/citations?view_op=view_citation&hl=fr&user=sWm-LdoAAAAJ&cstart=20&sortby=pubdate&citation_for_view=sWm-LdoAAAAJ:u0Mu_IsstPMC)

Appendix D. The Musk X-prize (see Appendix D on web site)

Appendix E. Bay Engineering Inc <https://www.bayengineeringinc.com>

Naval Architecture

Including USACOE Naval Architectural Analysis, computer generated & faired hull lines, hull & appendage design, hydro-statics, hull girder strength, speed & power analysis, ship's motion studies, intact & damage stability analysis, lightship surveys, inclining experiments, trim & stability manuals, loading manuals & weight engineering.

Marine Engineering

Including main propulsion and auxiliary equipment selection and sizing, propulsion shafting including vibration and alignment analysis, anti-pollution system design, HVAC systems, hydraulic systems, machinery space arrangements and layout, diesel exhaust scrubbers, purchase technical specifications and test and trial memorandum.

Structural Design

Including scantling design in accordance with classification society requirements, hull strength & scantling reassessment, spud design, equipment foundation design, wood, steel & aluminum structural design.

Finite Element Analysis

Structural Analysis (both linear and non-linear) using finite element methods in 3D, including stress, vibration, buckling, and fatigue analysis, optimizing the structural design.

Outfitting Design

Including vessel general arrangements, navigation visibility, mooring, towing & anchor handling arrangements, cargo/stores handling design, ladder/stairway design, door/closures/gangway design, accommodations, commissary & public space arrangements, lifesaving & rescue boat arrangements, fire control & safety plans.

Mechanical Design

Including bulk cargo materials handling system design, pneumatic conveying and self-unloading conveyor design.

Piping Design

Including system diagrams with size & material, fluid flow analysis, piping arrangements, ballast water treatment system feasibility & design application, system modules & pipe spools, naval vessel fire-fighting & chilled water systems.

Electrical/Electronic System Design

Including ships power and lighting systems, electrical systems for manned as well as unmanned engine rooms, electronic communications and shipboard aids to navigation.

Software Technology We Utilize

AutoCAD, Rhino, Ship Constructor, MARIN, RISA-3D, FEMAP, NavCad, AutoDesk Nastran, NX Nastran, General HydroStatics, pipeflow, PIPE-FLO PROFESSIONAL, Propeller Series Package

Contact

Phone 920.743.8282 253 North First Avenue Sturgeon Bay, WI 54235

References

Alvarez, J., and L. E. Datnoff (2001), The economic potential of silicon for integrated management and sustainable rice production, *Crop Prot.* 20:43–48.

Aitchison, J. (2017) Ophiolites and Intra-Oceanic Island Arc Assemblages of Eastern Australia, New Caledonia and New Zealand. *ACTA GEOLOGICA SINICA* (English Edition) 91 (supp 1):1-3.

Amann, T. & Hartmann, J.(2019) Ideas and perspectives: Synergies from co-deployment of negative emission technologies. *Biogeosciences* 16, 2949–2960.

Anderson, K. & Peters, G. (2016) The trouble with negative emissions. *Science* 354:182-183.

Anonymous (2007) Olivine, in Mining, Exploration and Geoscience in NSW. NSW Department of Primary Industries. <http://www.dpi.nsw.gov.au/minerals/geological/industrial-mineral-opportunities>

Avery, W.H. and Wu, C. (1994) Renewable Energy from the Ocean: A Guide to OTEC. New York, Oxford University Press.

Bach et al, (2019) CO₂ Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. *Front. Clim.*, 11 October.

Ballerat-Busserolles, K., Wu, Y, and Carroll, J.J. (eds) (2018) *Cutting-Edge Technology for Carbon Capture, Utilization, and Storage*. Wiley 361pp

Bates, N. R., et al (2011), The ocean carbon cycle in the western Arctic Ocean: Distributions and air-sea fluxes of carbon dioxide, *Oceanography*, 24:186–201.

Bartholomew, TV and Mauter, MS (2021) Energy and CO₂ Emissions Penalty Ranges for Geologic Carbon Storage Brine Management. Environmental Science and Technology
<https://doi.org/10.1021/acs.est.0c06017>

Berge, ten H.F.M. et al (2012) Olivine Weathering in Soil, and Its Effects on Growth and Nutrient Uptake in Ryegrass (*Lolium perenne* L.): A Pot Experiment.
PLOS One 7: Issue 8, e42098

Beerling, D.J. et al (2018) Farming with crops and rocks to address global climate, food and soil security. Nature Plants, 4: 138-147.

Beerling, D. J. et al (2020). Potential for large-scale CO₂ removal via enhanced rock weathering with croplands. Nature 583, 242–248.

Beerling, D. J. et al. (2016) Defining the ‘negative emission’ capacity of global agriculture deployed for enhanced rock weathering. In American Geophysical Union Fall General Assembly abstract GC21J-04 (American Geophysical Union).

Bellamy, R. and Geden, O. (2019) Govern CO₂ removal from ground up. Nature Geoscience 12:874–879.

Blanco-Quintero et al (2020). The Peltetec ophiolitic belt (Ecuador): a window to the tectonic evolution of the Triassic margin of western Gondwana. Facultad de Minas. 10.6084/m9.figshare.13153542.v1

Blondes, M.S., et al (2019) Carbon dioxide mineralization feasibility in the United States: U.S. Geological Survey Scientific Investigations Report 2018–5079, 29 p., <https://doi.org/10.3133/sir20185079>.

Bourgois, J. et al (1987) Geological history of the Cretaceous ophiolitic Complexes of Northwestern South America (Colombian Andes). Tectonophysics. 143:307- 327

Breider, F. et al (2019) Response of N₂O production rate to ocean acidification in the western North Pacific. Nature Climate Change 9:954–958.

Berner RA, Kothavala Z (2001) GEOCARB III: A revised model of atmospheric CO₂ over phanerozoic time. Am J Sci 301(2): 182–204.

Boutin, J. et al (1999) Satellite sea surface temperature: a powerful tool for interpreting in situ pCO₂ measurements in the equatorial Pacific Ocean. Tellus 51B:490–508

Brown R.E., Brownlow J.W. & Krynen J.P. (1992). Manilla–Narrabri 1:250 000 Metallogenic Map SH/56-9, SH/55-12: metallogenic study and Mineral Deposit Data Sheets. Geological Survey of New South Wales, Sydney.

Bousquet R., El Mamoun, R., Saddiqi, O. & Goffé, B., (2008) Mélanges and ophiolites: was the Bou-Azzer's ophiolite suite (Morocco) a Franciscan-type wedge during the Pan-African orogeny? in The Boundaries of the West African Craton Eds Ennih, N. & Liégois, J.-P., Geological Society, London, Special Publications, 297: 233-247

Cao L, Caldeira K (2010) Atmospheric carbon dioxide removal: Long-term consequences and commitment. Environ Res Lett, 10.1088/1748-9326/5/2/024011.

Caldeira K. and Rau GH. 2000. Accelerating carbonate dissolution to sequester carbon dioxide in the ocean: geochemical implications. Geophys. Res. Lett. 27:225–28

Caldeira, K., and M. E. Wickett, 2005: Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. J. Geophys. Res. Oceans, 110, C09S04.

Ciais, P., et al. (2013) Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Coleman, R.G and Irwin, W.P.(eds) (1977) North American Ophiolites. State of Oregon Department of Geology and Mineral Industries Bulletin 95. U.S. Geological Survey.

Canadell and Schulze (2013) Global potential of biosphere carbon management for climate mitigation. Nature Communications 5:5282.

Chakraborty, K. et al (2018). Dominant biological control over upwelling on pCO₂ in sea east of Sri Lanka. Journal of Geophysical Research: Biogeosciences, 123:3250–3261.

Chavez et al (2018) Measurements of pCO₂ and pH from an autonomous surface vehicle in a coastal upwelling system. Deep–Sea Research Part II 151:137–146
<http://dx.doi.org/10.1016/j.dsr2.2017.01.001>

Chizmeshya, A., M., et al (2007). A Novel Approach To Mineral Carbonation:Enhancing Carbonation While Avoiding Mineral Pretreatment Process Cost. DOE Final Report 924162. Washington, DC: U.S. Department of Energy.

CO2.earth (2014). <https://www.co2.earth/global-co2-emissions>.

Carbon 180 (2021) Zero then Negative - The Congressional Blueprint for Scaling Carbon Removal, May. <https://carbon180.org>

Crawford, A. J et al (2003), 120–0 Ma tectonic evolution of the southwest Pacific and analogous geological evolution of the 600–220 Ma Tasman Fold Belt System, Geol. Soc. of Aust. Spec. Publ., 22, 377– 397.

Darst, M.R. et al (1991) Florida Wetland Resources U.S. Geological Survey Water Supply Paper 2425 and *T.E. Dahl, U.S. Fish and Wildlife Service, unpub. data, 1991*. FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 227 N. Brongaugh St., Suite 3015, Tallahassee, FL 32301; Regional Wetland Coordinator, U.S. Fish and Wildlife Service, 1875 Century Building, Suite 200, Atlanta, GA 30345

Davies, H. L. (1980), Folded thrust fault and associated metamorphism in the Suckling-Dayman Massif, Papua New Guinea, Am. J. of Sci., 280A, 171–191.

Davies, H. L. and Jaques, A. L. (1984) Emplacement of ophiolite in New Guinea. In Gass I.G. et al (eds) Ophiolites and Oceanic Lithosphere. The Geological Society, Blackwell Scientific Publications, Melbourne.

Davies, P.A. et al. (2018) Desalination as a negative emissions technology. Environmental Science: Water Research and Technology. Environ. Sci.: Water Res. Technol., 4:839-850

de Lannoy, C.-F. et al (2017). Indirect ocean capture of atmospheric CO₂: Part I. Prototype of a negative emissions technology. Int. J. Greenhouse. Gas Control 70:254–261.
<https://doi.org/10.1016/j.ijggc.2017.10.007>

Dessert, C., Dupré, B., Francois, L.M., Schott, J., Gaillardet, J., Chakrapani, G., Bajpai, S., 2001. Erosion of Deccan Traps determined by river geochemistry: impact on the global climate and the 87Sr/86Sr ratio of seawater. Earth Planet. Sci. Lett. 188, 459–474.

Dickson, A. G. (1981). An exact definition of total alkalinity and a procedure for the estimation of alkalinity and total inorganic carbon from titration data. Deep Res. 28A, 609–623. doi: 10.1016/0198-0149(81)90121-7

Dickinson, W.R. et al (1996). Alternate Origins of the Coast Range Ophiolite (California): Introduction and Implications. GSA Today 6.

Dilek, Y. and Newcomb, S. eds (2003). Ophiolite concept and the evolution of geological thought. The Geological Society of America. Special Paper 373.

Eisaman MD, et al. (2012) CO₂ extraction from seawater using bipolar membrane electrodialysis. Energy Environ Sci 5:7346–7352.

EFI Energy Futures Initiative (2019). Clearing the Air. A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies.

EFI Energy Futures Initiative (2020a). From the Ground Up. Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal.

EFI Energy Futures Initiative (2020b). Uncharted Waters. Expanding Options for Carbon Dioxide Removal in Costal and Ocean Environments.

EFI Energy Futures Initiative (2020c). Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management.

England, R.N. and Davis, H.L. (1973) Mineralogy of ultramafic cumulates and taconites from eastern Papua. *Earth and Planetary Science Letters*. 17: 416-425

Evans, W., B. Hales, and P. G. Strutton (2011), Seasonal cycle of surface ocean pCO₂ on the Oregon shelf, *J. Geophys. Res.*, 116, C05012, doi:10.1029/2010JC006625.

Feely, R.A. et al (2006) Decadal variability of the air-sea CO₂ fluxes in the equatorial Pacific Ocean. *J. Geophysical Research* 111: C08S90.

Feng, E.Y. et al (2016) Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification? *Environ. Res. Lett.* 11:074008.

Ferrer-González, M., and T. Ilyina (2016), Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations, *Geophys. Res. Lett.*, 43, 6493–6502, doi:10.1002/2016GL068576.

Field, C.B. & Mach, K.J. (2017) Rightsizing carbon dioxide removal. *Science* 356:706-707.

Foster, D. A. et al (2001) History of Orogeny and Accretion along the Eastern Australian Margin of Gondwana. Geological Assn Australia Annual Meeting Nov 5-8. Paper No. 87-0

Fox, D. (2021) Rare Mantle Rocks in Oman Could Sequester Massive Amounts of CO₂ - Scientific American. July 1. <https://www.scientificamerican.com/article/rare-mantle-rocks-in-oman-could-sequester-massive-amounts-of-co2/>

Franke W.A. & Teschner-Steinhardt R. (1994) An experimental approach to the sequence of the stability of rock-forming minerals towards chemical stability. *Catena*, 21:279-290.

Fuerstenau, D. W., and A. Z. M. Abouzeid (2002), The energy efficiency of ball milling in comminution, *Int. J. Miner. Process.*, 67(1-4), 161–185.

Gadikota, G., K. Fricker, S.-H. Jang, and A.-H. A. Park. 2015. Carbonation of Silicate Minerals and Industrial Wastes and Their Potential Use as Sustainable Construction Materials. In Advances in CO₂ Capture, Sequestration, and Conversion. Jin, F., L.-N. He and Y. H. Hu, eds. Washington, DC: American Chemical Society.

Gautier, P., B. et al (2016) The emplacement of the Peridotite Nappe of New Caledonia and its bearing on the tectonics of obduction, *Tectonics*, 35, doi:10.1002/2016TC004318.

Gibbons, J.M. et al. (2014) Sustainable nutrient management at field, farm and regional level: soil testing, nutrient budgets and the trade-off between lime application and greenhouse gas emissions. *Agri. Ecosys. Environ.* 188:48–56.

Goff F, Lackner KS. (1998). Carbon dioxide sequestering using ultramafic rocks. Environ. Geosci. 5:89–101

Goff F, Guthrie G, Lipin B, Fite M, Chipera S, et al. (2000). Evaluation of Ultramafic Deposits in the Eastern United States and Puerto Rico as Sources of Magnesium for Carbon Dioxide Sequestration. Rep. LA13694-MS. Los Alamos Natl. Lab., Los Alamos, NM

González, M. F., and T. Ilyina (2016), Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations, *Geophys. Res. Lett.*, 43: 6493–6502, doi:10.1002/2016GL068576.

Griffioen, J., (2017). Enhanced weathering of olivine in seawater: The efficiency as revealed by thermodynamic scenario analysis. *Sci. Total Environ.* 575, 536-544.

Guntzer, F. et al (2012) Benefits of plant silicon for crops: a review. *Agron. Sustainable Devel.* 32, 201-213.

Hangx, S. J. T.; Spiers, C. J. (2009) Coastal spreading of olivine to control atmospheric CO₂ concentrations: A critical analysis of viability. *Int. J. Greenhouse Gas Control* 3:757–767.

Hartmann, J., and S. Kempe (2008), What is the maximum potential for CO₂ sequestration by “stimulated” weathering on the global scale? *Naturwissenschaften*, 95, 1159–1164.

Hartmann, J. et. al. (2009a) Global CO₂ -consumption by chemical weathering: What is the contribution of highly active weathering regions? *Global Planet. Change* 69, 185-194.

Hartmann, J., et al, (2009b). Predicting riverine dissolved silica fluxes into coastal zones from a hyperactive region and analysis of their first order controls lithology. *International Journal of Earth Sciences* DOI 10.1007/s00531-008-0381-5 .

Hartmann, J., (2009). Bicarbonate-fluxes and CO₂ -consumption by chemical weathering on the Japanese Archipelago — Application of a multi-lithological model framework. *Chemical Geology* in press , DOI: 10.1016/j.chemgeo.2009.03.024.

Hartmann, J., and N. Moosdorf (2012), The new global lithological map database GLiM: A representation of rock properties at the Earth surface, *Geochem. Geophys. Geosyst.*, 13, Q12004. doi:10.1029/2012GC004370.

Hartmann, J. et al (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* 51, 113–149.

Harvey, L. D. D. (2008), Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone powder to upwelling regions, *J. Geophys. Res.*, 113, C04028, doi:10.1029/2007jc004373.

Hauck, J. et al (2014) Impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and the biological carbon pump. 20 August 2014, Climate Engineering Conference 2014, Berlin Alfred-Wegener-Institut.

Henning R.J. 1994. Olivine and dunite. In: Carr D.D. ed. Industrial minerals and rocks, 6th edition, pp. 233–246. Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado.

Hills CD, et al (2020) Mineralization Technology for Carbon Capture, Utilization, and Storage. *Front. Energy Res.* 8:142. doi: 10.3389/fenrg.2020.00142

Hinsinger, P. et al. (2001) Plant-induced weathering of basaltic rock: experimental evidence. *Geochim. Cosmochim. Acta* 65:137-152.

Hoatson, D.M. and Keays, R.R. (1989) Formation of Platiniferous Sulfide Horizons by Crystal Fractionation and Magma Mixing in the Munni Layered Intrusion, West Pilbara Block, Western Australia *Economic Geology* 84:1775-1804.

Hoatson, D.M. et al (2005) Proterozoic mafic–ultramafic intrusions in the Arunta Region, central Australia: Part 1: Geological setting and mineral potential. *Precambrian Research* 142: 93-133.

House, K. Z., C. H. House, D. P. Schrag, and M. J. Aziz, 2007: Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. *Environ. Sci. Technol.*, 41, 8464–8470.

Hoegh-Guldberg et al. (2007). Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science* 318:1737 - 1742.

Hunter, C.E. (1941) Fosterite Olivine Deposits in North Carolina and Georgia. North Carolina Department of Conservation and Development. Bulletin 41.

Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze (2013), Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO₂ and ocean acidification, *Geophys. Res. Lett.*, 40, 5909–5914, doi:10.1002/2013GL057981.

IPCC (2019). Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., et al (eds.)

Jang, J. et al (2021) Recovery of N₂O: Energy-Efficient and Structure-Driven Clathrate-Based Greenhouse Gas Separation. *Environmental Science and Technology* 55:3909-3917.

Jenkyns, H.C., (2010) Geochemistry of oceanic anoxic events: *Geochemistry, Geophysics, Geosystems* 11:Q03004. doi:10.1029/2009GC002788.

Kaeding, M. et al (1990) Geochemistry of the Taitao ophiolite and near-trench intrusions from the Chile margin triple junction. *J. South American Earth Sciences* 3:161-177.

Kantola, I.B. et al (2017) Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. Biol. Letts. 13:20160714.

Kantola, I.B., et al (2016). Climate change mitigation through enhanced weathering in bioenergy crops. American Geophysical Union, Fall General Assembly, abstract #H13B-1358.

Kheshgi HS. (1995). Sequestering atmospheric carbon-dioxide by increasing ocean alkalinity. Energy 20:915–22

Kohler, P., Hartman, J. & Wolf-Gladrow, D.A. (2010) Geoengineering potential of artificially enhanced silicate weathering of olivine. Proc. Natl. Acad. Sci. USA 107:20228-20233.

Köhler, P. et al (2013) Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology. Environ. Res. Lett. 8 014009

Kramer, D.A. et al (2019) Geological Mapping and Characterization of Possible Primary Input Materials for the Mineral Sequestration of Carbon Dioxide in Europe. Minerals 9:485; doi:10.3390/min9080485

Kramer, D.A. (2020) Current mining of olivine and serpentine. USGS, Reston, VA.

Kelemen, P.B. and Matter, J. (2008) *In situ* carbonation of peridotite for CO₂ storage. PNAS 105: 17295–17300.

Kelemen, P. et al (2019) An Overview of the Status and Challenges of CO₂ Storage in Minerals and Geological Formations. Front. Clim. 15. <https://doi.org/10.3389/fclim.2019.00009> (<https://doi.org/10.3389/fclim.2019.00009>)

Krevor, S.C. et al (2009) Mapping the Mineral Resource Base for Mineral Carbon-Dioxide Sequestration in the Conterminous United States. U.S. Geological Survey, Reston, Virginia. Data Series 414.

Lackner, K.S. (2002) Carbonate Chemistry for Sequestering Fossil Carbon. Annual. Rev. Energy Environ. 27:193–232. doi:10.1146/annurev.energy.27.122001.083433

Lampitt RS, et al. (2008) Ocean fertilization: A potential means of geoengineering? Phil Trans R Soc London A 366:3919–3945.

Lark, T.J. et al. (2020) Cropland expansion in the United States produces marginal yields at high costs to wildlife. Nature Communications| 11:4295 1-11. <https://doi.org/10.1038/s41467-020-18045-z>.

LeFevre, et al (2002) Observations of pCO₂ in the coastal upwelling off Chile: Spatial and temporal extrapolation using satellite data. J. of Geophysical Research: Oceans. 107:C6, 8-1 to 8-15

Lehmann, J. and Possinger, A. (2020) Atmospheric CO₂ removed by rock weathering. *Nature* 583:204-205.

Leonardos et. al., (1987) The use of ground rocks in laterite systems: an improvement to the use of conventional soluble fertilizers? *Chem. Geol.* 60 361–70

Lenzi, D. et al (2018) Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561:304-305.

Lewis, E., D. Wallace, and L. J. Allison (1998), Program developed for CO₂ system calculations. Carbon Dioxide Information Analysis Center managed by Lockheed Martin Energy Research Corporation for the US Department of Energy Tennessee. [Available at <http://cdiac.ornl.gov/oceans/co2rppt.html>]

Lewis, J.F. et al (2006). Ophiolite-related ultramafic rocks (serpentinites) in the Caribbean Region: a review of their occurrence, composition, origin, emplacement and Ni-laterite soil formation. *Geol. Acta* 4, 237–263.

Louvat, P., Allègre, C.J., 1997. Present denudation rates on the island of Réunion determined by river geochemistry: basalt weathering and mass budget between chemical and mechanical erosions. *Geochim. Cosmochim. Acta* 61, 3645–3669.

Lu, L et al (2015) Microbial Electrolytic Carbon Capture for Carbon Negative and Energy Positive Wastewater Treatment *Environmental Science & Technology* 49: 8193-8201

Ludwig W, et al (1998) Atmospheric CO₂-consumption by continental erosion: present-day controls and implications for the last glacial maximum. *Glob Planet Change* 17:107–120

Marion, G.M., Millero, F.J., Camoes, M.F., Spitzer, P., Feistel, R., Chen, C.-T.A., (2011). pH of seawater. *Mar. Chem.* 126, 89-96.

Matter, J.M., Kelemen, P.B., (2009). Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. *Nature Geoscience* 2: 837–841.

McGrail, B. P., et al (2006), Potential for carbon dioxide sequestration in flood basalts, *J. Geophys. Res.*, 111, B12201, doi:10.1029/2005JB004169.

Makowski, D. (2019) N₂O increasing faster than expected. *Nature Climate Change* 9:907–910.

Mathis, J. T., et al. (2012) Storm-induced upwelling of high pCO₂ waters onto the continental shelf of the western Arctic Ocean and implications for carbonate mineral saturation states, *Geophys. Res. Lett.*, 39, L07606, doi:10.1029/2012GL051574.

Maurizot, P., and M. Vendé-Leclerc (2009), Carte géologique de la Nouvelle-Calédonie à l'échelle 1/500000, Dir. de l'Industrie, des Mines et de l'Energie – Service de Géologie de Nouvelle-Calédonie, Bur. Rech. Géol. Min., France.

Maybeck, M. et al. (2006) Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage. *Global Biogeochemical Cycles* 20.

McNeil, B. et al (2003) Anthropogenic CO₂ Uptake by the Ocean Based on the Global Chlorofluorocarbon Data Set. *Science* 299: 235–239.

Meysman FJR, Montserrat F. (2017) Negative CO₂ emissions via enhanced silicate weathering in coastal environments. *Biol. Lett.* 13: 20160905. <http://dx.doi.org/10.1098/rsbl.2016.0905>

Montserrat, F., P. Renforth, J. Hartmann, M. Leermakers, P. Knops, and F. J. R. Meysman. (2017). Olivine dissolution in seawater: Implications for CO₂ Sequestration through enhanced weathering in coastal environments. *Environmental Science & Technology* 51(7):3960-3972. DOI: 10.1021/acs.est.605942.

Moosdorf, Nils, Renforth, Phil and Hartmann, Jens (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science and Technology* 48 (9) , pp. 4809-4816. 10.1021/es4052022 file

Moeskops, P.G. and Davis, G.R. (1977). Unusual sulphide replacement textures in altered olivine-rich rocks of the Bulong Complex near Kalgoorlie, Western Australia. *Mineralogical Magazine*, 41:473-479, December.

Ernest J. Moniz, E.J. Chair. (2019) (Former Head DOE). Energy Futures Initiative Clearing the Air. A Federal RD& D Initiative and Management Plan for Carbon Dioxide Removal Technologies. <https://www.ourenergypolicy.org/resources/clearing-the-air-a-federal-rdd-initiative>

NAS (2018) National Academies of Sciences, Engineering, and Medicine. Direct Air Capture and Mineral Carbonation Approaches for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop in Brief. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25132>.

NAS (2019) National Academies of Sciences, Engineering, and Medicine. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25259>

NAS (2015) National Academies of Sciences, Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. National Academies Press, Washington, D.C.

Nemet, et al (2018). Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.* 13:063003

O'Connor W.K., e al, (2000). Carbon dioxide sequestration by direct mineral carbonation with carbonic acid. *Proc. 25th Int. Tech. Conf. Coal Util. Fuel Syst.*, Mar. 6–9, pp. 153–64. Clearwater, FL

O'Conner, W.K. et al (2004). Energy and Economic Considerations for Ex-situ aqueous mineral carbonation. DOE/ARC-2004-028.

O'Connor, W. K., et al. (2005). Final Report: Aqueous Mineral Carbonation—Mineral Availability, Pretreatment, Reaction Parametrics, And Process Studies. DOE/ARC-TR-04-002. Albany, OR: Office of Process Development, National Energy Technology Laboratory, Office of Fossil Energy, US Department of Energy.

Oelkers, E. H. (2001) An experimental study of forsterite dissolution rates as a function of temperature and aqueous Mg and Si concentrations. *Chem. Geol.* 175: 485–494.

Oelkers, E.H. et al.(2018) Olivine dissolution rates: A critical review. *Chemical Geology* 500: 1-19

Olsen AA (2007) Forsterite Dissolution Kinetics Applications and implications for chemical weathering, Dissertation Virginia Polytechnic Institute. Available:
<http://scholar.lib.vt.edu/theses/available/etd-07052007-135551>.

Palandri, J. L., and Y. K. Kharaka. (2004). A Compilation of Rate Parameters of Water-Mineral Interaction Kinetics for Application to Geochemical Modeling. Open File Report 2004-1068. Washington, DC: U.S. Geological Survey.

Paquay, F. S., and R. E. Zeebe (2013), Assessing possible consequences of ocean liming on ocean pH, atmospheric CO₂ concentration and associated costs, *Int. J. Greenhouse. Gas Control*, 17, 183–188, doi:10.1016/j.ijggc.2013.05.005.

Paukert, A.N. et al (2012) Reaction path modeling of enhanced in situ CO₂ mineralization for carbon sequestration in the peridotite of the Samail Ophiolite, Sultanate of Oman. *Chemical Geology* 330-331:86–100

Paulmier, Aet al (2011) CO₂ maximum in the oxygen minimum zone (OMZ), *Biogeosciences*, 8: 239–252, <https://doi.org/10.5194/bg-8-239-2011>, <https://bg.copernicus.org/articles/8/239/2011/>

Paustian, K et. al. (2007) Agricultural soils as a sink to mitigate CO₂ emissions. *Soil. Use Manag.* 13, 230–244.

Percival, L.M.E., et al. (2016) Osmium isotope evidence for two pulses of increased continental weathering linked to Early Jurassic volcanism and climate change. *Geology* 44:759–762.

Philip A.E. et al (2021) The lithium and magnesium isotope signature of olivine dissolution in soil experiments. *Chemical Geology* 560:120008.
<https://doi.org/10.1016/j.chemgeo.2020.120008>

Project Vista. Olivine and Dunite Reserves and their position in ophiolites.
<https://legacy.projectvesta.org/wiki/olivine-and-dunite-reserves-and-their-position-in-ophiolites>

Pokrovsky, O. S.; Schott, J. (2000) Kinetics and mechanism of forsterite dissolution at 25°C and pH from 1 to 12. *Geochim. Cosmochim. Acta* 2000, 64 (19), 3313–3325.

Pokrovsky, O. S., and Schott, J. (2000). Forsterite surface composition in aqueous solutions: a combined potentiometric, elektrokinetic, and spectroscopic approach. *Geochim. Cosmochim. Acta* 64, 3299–3312. doi: 10.1016/S0016-7037(00)00435-X

Prentice IC, et al. (2001) Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, ed Houghton JT (Cambridge Univ Press, Cambridge, UK), pp 183–237.

Ragueneau, O., D. J. Conley, D. J. DeMaster, H.H. Dürr, N. Dittert (2010), Biogeochemical cycle of silicon on continental margins: Transformations along the land-ocean continuum and implications for the global carbon cycle, in, Carbon and Nutrient Fluxes in Global Continental Margins, Global Change – The IGBP Ser., edited by K. K Liu, L. Atkison, R. Quiñones, and L. TalaueMcManus, pp. 515–527, Springer–Verlag Berlin Heidelberg Germany.

Raich, J W, and Potter, C S. (1995) Global patterns of carbon dioxide emissions from soils on a 0.5-degree-grid-cell basis. *Global Biochemical Cycles* 9: 23-36.

Rau, G.H. and Baird, J.R. (2018) Negative-CO₂ -emissions ocean thermal energy conversion. *Renewable and Sustainable Energy Reviews* 95:265-273.

Rau, G.H., Caldeira K. (1999). Enhanced carbonate dissolution: a means of sequestering waste CO₂ as ocean bicarbonate. *Energy Convers. Manag.* 40:1803–13

Rau, G.H., Caldeira K. (2001). Enhanced carbonate dissolution: a means of sequestering Carbon Dioxide. Eleventh Annual Goldschmidt Conference.

Rau, G. H. & Caldeira, K. (2019) Enhanced carbonate dissolution: a means of sequestering waste CO₂ as ocean bicarbonate. *Energy Convers. Manag.* 40: 1803–1813.

Rau, G. H. (2008) Electrochemical splitting of calcium carbonate to increase solution alkalinity: Implications for mitigation of carbon dioxide and ocean acidity. *Environ. Sci. Technol.*, 42, 8935–8940.

Rau, G.H. (2011) CO² mitigation via capture and chemical conversion in seawater. *Environ. Sci. Technol.* 45, 1088–1092.

Rau, G. H. et al. (2013) Direct electrolytic dissolution of silicate minerals for air CO₂ mitigation and carbon-negative H₂ production. *Proc. Natl Acad. Sci. USA* 110:10095–10100.

Rau, G.H. et al (2018) The global potential for converting renewable electricity to negative-CO₂ -emissions hydrogen. *Nature Climate Change* 8:621–625.

Ray L.M. et al. (2020) Soil CO₂ emission in response to organic amendments, temperature, and rainfall.\ Scientific Reports 10:5849 | <https://doi.org/10.1038/s41598-020-62267-6>

Rayner, S., C. Heyward, T. Kruger, N. Pidgeon, C. Redgwell, and J. Savulescu (2013), The Oxford principles, *Clim. Chang.*, 121, 499–512, doi:10.1007/s10584-012-0675-2

Renforth, P. (2012) The potential of enhanced weathering in the UK. *Int. J. Greenhouse Gas Control* 10, 229–243.

Renforth, P., Kruger, T., (2013) Coupling mineral carbonation and ocean liming. *Energy Fuel.* 27, 4199–4207.

Renforth, P., Jenkins, B.G., Kruger, T. (2013) Engineering challenges of ocean liming. *Energy* 60, 442–452.

Renforth, P. et al (2015) The dissolution of olivine added to soil: Implications for enhanced weathering. *Applied Geochemistry* 61: 109–118

Renforth, P. and Henderson, G. (2017) The negative emission potential of alkaline materials *Rev. Geophys.* 55:636–674.

Renforth, P., and G. Henderson, G. (2017), Assessing ocean alkalinity for carbon sequestration, *Rev. Geophys.*, 55, 636–674, doi:10.1002/2016RG000533.

Renforth, P. (2019) The negative emission potential of alkaline materials. *Nature Communications* 10:1401. | <https://doi.org/10.1038/s41467-019-09475-5>

Revelle, R. & Hans E. Suess, H.E. (1957) Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO₂ during the Past Decades, *Tellus*, 9:1, 18-27, DOI: 10.3402/tellusa.v9i1.9075

Risien, C. M., & Chelton, D. B. (2008). A global climatology of surface wind and wind stress fields from eight years of QuikSCAT scatterometer data. *Journal of Physical Oceanography*, 38:2379–2413.

Rigopoulos, I., Petallidou, K.C., Vasiliades, M.A., Delimitis, A., Ioannou, I., Efstathiou, A.M., Kyratsi, Th., 2015. Carbon dioxide storage in olivine basalts: effect of ball milling process. *Powder Technol.* 273, 220-229.

Rigopoulos, I., Vasiliades, M.A., Ioannou, I., Efstathiou, A.M., Godelitsas, A., Kyratsi, Th., 2016. Enhancing the rate of ex situ mineral carbonation in dunites. *Adv. Powder Technol.* 27, 360-371.

Rigopoulos, I., Harrison, A.L., Delimitis, A., Ioannou, I., Efstathiou, A.M., Kyratsi, T., Oelkers, E.H., (2017). Carbon sequestration via enhanced weathering of peridotites and basalts in seawater, *Applied Geochemistry* (2017), doi: 10.1016/j.apgeochem.2017.11.001.

Rockstrom, J. et al. (2017) A roadmap for rapid decarbonization. *Science* 355, 1269-1271.

Roger Revelle's Discovery. <https://history.aip.org/climate/Revelle.htm>

Romanov, V, et al (2015) Mineralization of Carbon Dioxide: Literature Review. U.S. Department of Energy National Energy Technology Laboratory

Rosso, J. J.; Rimstidt, D. J. A high-resolution study of forsterite dissolution rates. *Geochim. Cosmochim. Acta* 2000, 64 (5), 797–811.

Sarma, V., et al (1998) The central and eastern Arabian Sea as a perennial source of atmospheric carbon dioxide, *Tellus B: Chemical and Physical Meteorology*, 50:179–184

Schuring, R. D. (2006). Mineral sequestration of CO₂ and recovery of the heat of reaction, in: Macro-engineering: a challenge for the future. In V. Badescu et al. (eds.), *Macro-Engineering: A Challenge for the Future*, p 21-29. Springer.

Schuring, R. D. and Krijgsman, P. (2006). Enhanced weathering: an effective and cheap tool to sequester CO₂. *Clim. Change* 74:349-354.

Schuring, R.D., de Boer, P.L. (2010). Coastal spreading of olivine to control atmospheric CO² concentrations: a critical analysis of viability. Comment: nature and laboratory models are different. *Int. J. Greenhouse Gas Control* 4, 855–856.

Schuring, R.D. (2013) Olivine as a Super-green Fuel. *Energy, Sustainability and Society* 3:18.

Schuring, O. (2018) Olivine. The Philosopher's Stone. Elmar Publishers.

Seaman, J.H. (2006) Mining. In *Encyclopedia of North Carolina*. Powell, W.S.(editor). University of North Carolina Press.

Sodal, J. (2015) Silicate weathering in soils: A solution for soil pH management? Master of Science Thesis Department of Earth Science University of Bergen.

Smith, I.E.M. (2013) The chemical characterization and tectonic significance of ophiolite terrains in southeastern Papua New Guinea. *Tectonics* 32: 159-170

Smith, et al. (2016) Biophysical and economic limits to negative CO₂ emissions. *Nat. Clim. Change* 6:42-50.

Spadea, P. et al. (1987) Ophiolite Complex from La Tetilla, Southwestern Colombia, South America. *The Journal of Geology* 95:377-395.

Spaggiari, C.V. et al (2004) Ophiolite accretion in the Lachlan Orogen, Southeastern Australia. Journal of Structural Geology 26: 87-112.

Spaggiari, C.V. et al (2018) Buried but preserved: The Proterozoic Arubiddy Ophiolite, Madura Province, Western Australia Precambrian Research 317: 137-158

Spawn, S.A. et al (2019) Carbon emissions from cropland expansion in the United States. Environ. Res. Lett. 14: 045009.

Strefler, J. et al (2018) Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environ. Res. Lett. 13.

Takahashi T, et al. (2009) Climatological mean and decadal change in surface ocean pCO₂ and net sea-air CO₂ flux over the global oceans. Deep Sea Res Part 2 Top Stud Oceanogr 56:554–577.

TankerOperator Newsletter. July 23, 2021. China launches one of the most energy efficient VLCCs ever built following CCS surveys.

<https://www.tankeroperator.com/news/china-launches-one-of-the-most-energy-efficient-vlccs-ever-built-following-ccs-surveys/12500.aspx>

Taylor, L.L. et al (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change, 6:402-406.

Taylor, L.L. et al (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Supplementary Material. Nature Climate Change, 6:402-406.

Taylor, et al (2017) Simulating carbon capture by enhanced weathering with croplands: an overview of key processes highlighting areas of future model development. Biol. Lett. 13: 20160868.

The Climate Source (2001) Mean Annual Precipitation in the US.
<http://www.climatesource.com>

Thompson, R. L. et al. (201) Acceleration of global N₂O emissions seen from two decades of atmospheric inversion. Nature Climate Change 9:993-998.

TNO (2008) TNO-U-R-0776/B Desk study on the feasibility of CO₂ sequestration by mineral carbonation. <http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/kamerstukken/2009/01/26/reactie-opbrief-van-hr-schuling-over-olivijn-rapport/kl2009006101aolivijnrapport.pdf>

Tubana, B.S., et al (2016) A review of silicon in soils and plants and its role in US agriculture: history and future perspectives. Soil Sci. 181:393–411.

USGS (2012) Limestone—A Crucial and Versatile Industrial Mineral Commodity.

<https://pubs.usgs.gov/fs/2008/3089/fs2008-3089.pdf>

USGS (2019) Making Minerals-How Growing Rocks Can Help Reduce Carbon Emissions.

de Verneil, A. et al (2021) Evaluating the Arabian Sea as a regional source of atmospheric CO₂: seasonal variability and drivers. Biogeosciences Discussions. <https://doi.org/10.5194/bg-2021-22>

Villares, F. et al (2020) The Peltetec ophiolitic belt (Ecuador): a window to the tectonic evolution of the Triassic margin of western Gondwana, International Geology Review, DOI: [10.1080/00206814.2020.1830313](https://doi.org/10.1080/00206814.2020.1830313)

van Straaten, P. (2002), Rocks for Crops: Agrominerals of sub-Saharan Africa, 338 pp., ICRAF, Nairobi, Kenya.

von Uexküll, H. R. & Mutert, E. (1995) Global extent, development and economic impact of acid. Plant Soil 171, 1–15.

Wignall, P. B. (2015) The Worst of Times. How Life on Earth Survived Eighty Million Years of Extinctions. Princeton Oxford University Press.

Willauer, H. D., et al (2017). Development of an electrolytic cation exchange module for the simultaneous extraction of carbon dioxide hydrogen gas from natural seawater. Energy Fuels 31:1723–1730.

Wilson, M.J., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. Clay Miner. 39:233–266.

Wogelius, R. A.; Walther, J. V. Olivine dissolution at 25°C: Effects of pH, CO₂, and organic acids. Geochim. Cosmochim. Acta 1991, 55 (4), 943–954.

Wolff-Boenisch, D., Wenau, S., Gislason, S.R., Oelkers, E.H., 2011. Dissolution of basalts and peridotite in seawater, in the presence of ligands, and CO₂ : Implications for mineral sequestration of carbon dioxide. Geochim. Cosmochim. Acta 75, 5510–5525.

Wood, S., Sebastian, K. & Scherr, S. J. (2000) Pilot Analysis of Global Ecosystems: Agroecosystems (world Resources Inst).

Zhang Q, Sugiyama K, Saito F. 1997. Enhancement of acid extraction of magnesium and silicon from serpentine by mechano-chemical treatment. Hydrometallurgy 45:323–31

Zeebe, R. E., and Wolf-Gladrow, D. A. (2001). CO₂ in Seawater: Equilibrium, Kinetics, Isotopes. Amsterdam: Elsevier.

Wolf-Gladrow, D. A., Zeebe, R. E., Klaas, C., Kötzinger, A., and Dickson, A. G. (2007). Total alkalinity: the explicit conservative expression and its application to biogeochemical processes. Mar. Chem. 106, 287–300. doi: 10.1016/j.marchem.2007.01.006

Xie, H. et al (2014) Mineralization of flue gas CO₂ with coproduction of valuable magnesium carbonate by means of magnesium chloride, Chinese Science Bulletin, 59 (2014) 28822889.