

Enhanced Weathering: The Best Method of Removing CO₂ from the Atmosphere

**A Plan to Halt Increasing Global Temperatures Despite Continued Emissions
MINE, GRIND, SPREAD and SEQUESTER**

By
David E Comings, M.D.
The Comings Foundation
From Theory to Action
www.thecomingsfoundation.org

Summary of the Summary

The opportunity to limit the impact of climate change is rapidly narrowing.
Antonio Guterres UN Secretary General, Aug 9, 2021

***We believe this document presents the only way to halt global warming
in a few years rather than many decades.***

There is universal agreement that solving the climate crisis will require both the reduction of CO₂ emissions and the removal of CO₂ from the atmosphere. In this extensive scientific review, we show that Enhanced Weathering (EW), consisting of spreading highly pulverized ultramafic rocks, such as olivine, on croplands, non-croplands and the ocean, is the best and safest approach to permanently removing gigatons of atmospheric CO₂. It greatly accelerates the natural method by which 99.94% of all the CO₂ ever produced on earth has been stored. However, if we want to sequester gigatons of CO₂ we need gigatons of ultramafic rocks. These rocks are very common, and deposits are present in virtually all countries but currently no one is mining them primarily for this purpose. We urge the U. S. Government or the UN to convene a meeting of all the countries of the world to begin mining, processing and using these rocks in their own country to save our planet from global warming. We also suggest that all countries pledge to both reduce emissions AND use these technically straight-forward methods to sequester the amount of CO₂ they are currently emitting + 30% each year. This would be very fair since they only sequester what they emit and this would quickly halt increasing temperatures and the level of CO₂ in the atmosphere would continually decrease.

In the book All We Can Save, Naomi Klein stated, "Young people around the world are cracking open the heart of the climate crisis, speaking of a deep longing for a future they thought they had but that is disappearing each day that the adults fail to act on the reality that we are in an emergency"

Queen Elizabeth said, "They talk but don't do."

It is time to do.



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INTERNATIONAL MINE, GRIND, SPREAD and SEQUESTER

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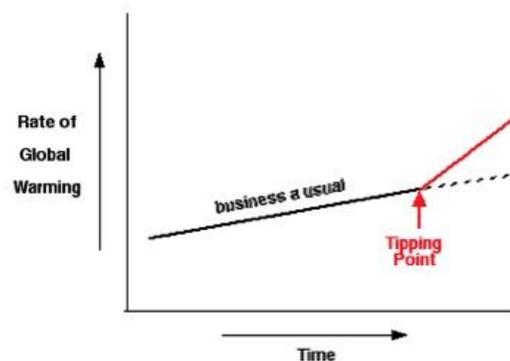
A Review and Proposals

Summary

We believe this document presents the only way to halt global warming in a few years rather than many decades.

All agencies involved in the control of global warming concur that simply cutting down on emissions will not be enough. In fact, the current level of atmospheric CO₂ is 420 ppm, significantly more than at the time of the first climate conference. There is wide agreement that the emission proposals at COP26 will not keep the earth's temperature below 1.5°C (Masood and Tollefson (2021). "A survey shows that many of the authors of the COP26 are anxious about the future and expect to see catastrophic changes in their lifetimes." (Tollefson, 2021). Tipping points are already upon us and are potentially very catastrophic.

A tipping point for global warming is a temperature at which events begin to happen that produce a positive feedback loop, accelerating further temperature rise above the previous rate. The following figure illustrates the effect of tipping points.



Many tipping points have been identified for climate change (Fabbri, et al 2021). They are all scary, but the following are some that are really scary.

1. *Plants switch from photosynthesis to respiration.* As global temperatures increase a point is reached at which all plants on earth begin to switch from photosynthesis (consuming CO₂ and producing oxygen), to respiration (consuming oxygen and producing CO₂). Duffy et al, (2021) state that at the current rate of temperature rise this process will be well underway by 2040.

2. *Melting permafrost.* A temperature at which the vast amounts of permafrost begin to melt with the release of huge amounts of methane, a greenhouse gas 80 times more potent than CO₂. This has already started in parts of Siberia (Shakhova, *et al.* 2010; Welch (2019); Kindy, 2021) and the North American arctic.

3. *Loss of albedo.* The frozen ice in the arctic, Greenland and the Antarctic reflect large amounts of solar radiation back into space, cooling the planet. The continued melting of our ice destroys this albedo effect (Riihelä, et al (2021). This melting also causes an increase in sea level with the displacement of hundreds of millions of people (NIC-NIE, 2021)

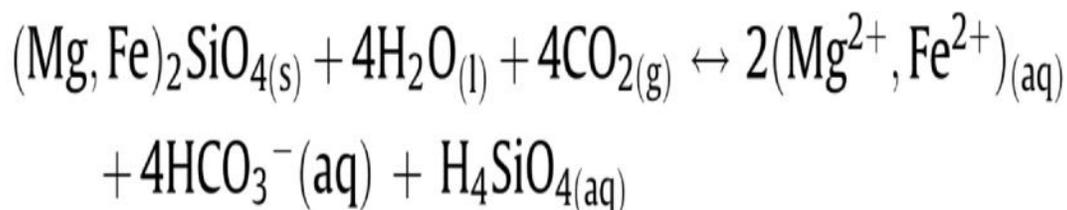
4. *Die off of phytoplankton.* It is rarely appreciated that phytoplankton in the ocean sequesters as much CO₂ as all the trees on land (Longhurst, et al 1995; Field, et al, 1998; MacRae, 2020). If these die off because of ocean acidification, which is progressing at a rapid rate, this huge reservoir of carbon dioxide will be lost.

5. *Collapse of the AMOC.* A collapse of the Atlantic Meridional Overturning Circulation would alter the North Atlantic air temperatures by 7°C. The AMOC is a critical part of the Earth's Climate System that transfers warm water northward (to Europe) and deep cold water southward (NIC-NIE, 2021).

The existence of these and other tipping points add additional urgency the need to quickly stop the rise in the mean earth temperature past 1.5°C. The proposals outlined in this document provide a pathway to rapidly halting this temperature rise despite the continued emissions of CO₂.

The Equation that Saved Planet Earth - Can Do It Again.

The atmosphere of Venus is 96.5% carbon dioxide resulting in a deadly temperature of 872 °F. By comparison, the atmosphere of the earth contains 0.04% CO₂ and has a temperature which is compatible with life. Schuiling (2013) pointed out that the difference between the two planets was the presence of water on earth which allowed the CO₂ to be permanently mineralized. It was based on the following equation where the left-hand compound is olivine, an ultramafic rock.



This reaction, sequestering CO₂, could only occur in the presence of water. The complete fate of the different parts of this equation are shown below.

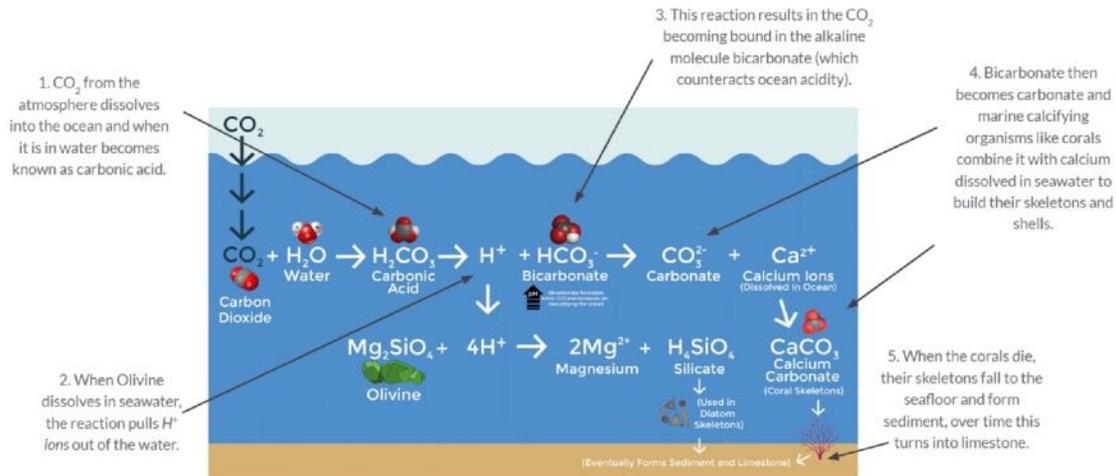


Figure from Project Vista

CO₂ from the atmosphere dissolves in water producing carbonic acid, H₂CO₃, which produces acid H⁺ and HCO₃⁻. Ultramafic minerals such as olivine, Mg₂SiO₄, combine with the H⁺ to produce silicates (H₄SiO₄) which are taken up by diatoms which die and fall to the ocean floor. The carbonic acid also produces carbonates, CO₃²⁺, which combine with calcium Ca²⁺ and Mg²⁺ to produce calcium carbonate, CaCO₃, which is used by corals and shells of other marine organisms, and Mg carbonate which also permanently stores CO₂. Combined, these and other reactions permanently store in mineral form 99.94% of all the CO₂ ever produced on earth and make the earth a livable planet. This reaction in nature takes thousands of years.

This equation saved the planet earth once and it can, with our help, save it again.

What is meant by, “With our help?” The speed of the above equation can be dramatically increased by grinding the ultramafic rocks to a fine powder and spreading them on croplands, non-croplands and the ocean. The different techniques of removing CO₂ from the atmosphere are called Negative Emission Technologies or NETs. One of the reasons these will be critical is that to date attempts to reduce emissions alone are not working. The US Military has identified the worldwide disruptions due to Climate Change as one of the greatest threats to US security.

In this review we show that the above equation in its accelerated form can be utilized in two NETs called Enhanced Weathering (EW) and Ocean Alkalinity Enhancement (OAE). These are the only NETs capable of permanently and safely storing gigatons (billions of tons) of CO₂ to reduce atmospheric CO₂ and ocean acidification.

The level of CO₂ in the atmosphere continues to rise. Firestorms are ravaging the western US and other countries such as Greece, Russia and Australia, the rate of melting of ice in Greenland, the Arctic and Antarctic is rapidly increasing, sea levels are rising and threatening cities, draughts and accompanying crop failures are increasing worldwide with widespread starvation, the temperature of both the air and water are rising, we are losing island nations such as Tuvalu, the warm waters are causing more violent hurricanes and tropical storms resulting in billions of dollars of destruction, glaciers and snow fields which supply 75% of the world’s fresh water for drinking and irrigation are rapidly melting, water reservoirs are at an all-time low and in some places result in loss of hydroelectric

electricity, electric automobiles still represent a tiny fraction of all cars, and renewable energy still represents a minor percent of total electricity production. In addition, the acidification of the oceans is threatening the food supply for billions of people. And, if you think this is bad, read David Wallace-Wells (2020) account what the world will soon be like if we do not get global warming under control. Sliding past 1.5°C and into 2°C and higher by 2040 and 2050 portends a horrific world with 150 million people dying of air pollution and heat, 200 million climate refugees and many trillions of dollars in mitigation efforts. Given that horrific assessment, Sognaes, et al (2021) reported that using seven diverse integrated assessment models the most optimistic scenario is still insufficient to limit global warming to 2 °C.

We need a plan that is capable of halting global warming in a few years rather than decades. What we have outlined here is just such a plan.

EW utilizes what are called ultramafic rocks. These are rocks rich in magnesium and iron oxides and silicates. They are very common, and deposits are present in virtually all countries. When crushed to a powder they take up CO₂ and convert it to carbonates which store carbon on geologic time scales. When placed in the ocean they bind up H⁺, add cations such as Mg⁺⁺ and Ca⁺⁺, increase alkalinity and decrease the acidity of the seawater. These NETs require no new technology and with suitable international effort, they are doable in the short term. If of all countries pledged to both reduce emissions AND use these technically straight-forward methods to sequester the amount of CO₂ they currently emit, the rapidly advancing and devastating global warming could soon be halted and then reversed. This would also be uniquely fair, since the amount of CO₂ each country would be asked to sequester would be directly proportionate to the amount they emit.

EW and OAE have Economic Advantages Instead of Disadvantages.

For 30 years the countries of the world have pledged to decrease emissions and yet the level of CO₂ in the atmosphere continues to rise. Why? Because until massive renewable energy and electric cars are in place it is economically and politically costly to significantly reduce emissions.

By contrast, one of the over whelming advantages of the EW and OAE NETs is that they come with an economic advantage rather than a penalty. When you ask a country to cut emissions toward zero that is equivalent to asking them to significantly cut down on their energy supply - something that is both economically and politically disastrous leading to resistance. In contrast, when you ask a country to start using EW and OAE it comes with economic advantages such as improved crop yields, reduction in soil acidity, reduction in soil erosion, expanded land suitable for agriculture, protection of fisheries and corals by combating ocean acidification AND combating global warming by sequestering CO₂ and decreasing N₂O production on land and in the sea. In addition, the mining industries of that country would become very profitable and if the country could produce more ultramafic rocks than they needed internally, they would enjoy an economic boon by selling the excess to other countries. This could be “the new oil.” This plan would also open up new jobs, worldwide.

We conclude that:

- by eliciting the cooperation of all countries to mine, grind, stockpile and use their ultramafic rocks for EW on croplands, non-croplands and the ocean to sequester at least the amount of CO₂ they currently emit,
- by continuing to sequester CO₂ at those initial levels, as the reduction in emissions kick in, increasing amounts of CO₂ will be removed from the atmosphere,
- by emphasizing the economic advantages of EW and OAE,
- by grinding the rocks to a particle size of 1 um or less,
- by using concurrent grinding (grinding + heat) if necessary,
- by using carbon free sources of energy for grinding,
- by using commercial waste sources of silicates (tailings),
- by recovering nickel from olivine,
- by factoring in the beneficial increases in crop yield,
- by factoring in the beneficial increase in pH of the soil,
- by factoring in the improvement of poor soils (oxisols and ultisols),
- by decreasing CO₂ emissions from soils and the ocean,
- by decreasing N₂O emissions from soils and the ocean,
- by increasing ocean alkalization,
- by decreasing ocean acidification,
- by decreasing ocean warming,
- by decreasing ocean deoxygenation,
- by emphasizing the use of EW at weathering “hot spots”,
- by using special ships for OAE designed to be carbon negative,
- by using ships for OAE that utilize efficient electrolysis techniques,
- by focusing OAE efforts on areas of CO₂ outgassing and threatened coral,
- by emphasizing the economic advantages to the miners of this “new oil,”
- by emphasizing the new jobs created world-wide,
- by partnering with New Caledonia to open up their vast reserves of ultramafic rocks for both *in situ* and *ex situ* sequestration,
- by urging the U.S. Military and Army Engineering Corp, in conjunction with existing mining companies, to start a project to mine, process and stockpile ultramafic rocks at the Twin Sisters site in WA and other sites in the US,
- by devoting these rocks entirely to EW and OAE,
- by partnering with other government agencies such as the Department of Energy, Department of Defense, Army Corp of Engineering’s Climate Preparedness and Resilience Program, US Navy, Department of Agriculture, Department of Commerce, CIA, Secretary of State, U.S. Geological Service, Department of the Interior, NOAA, EPA, the Biden Climate Group, and others...

...The use of enhanced weathering of croplands, non-croplands and oceans needs to be initiated world-wide such that each country sequesters the amount of CO₂ it currently produces. This would quickly stop the increases

in global temperature and get the world on a path of removing and safely storing gigatons of atmospheric CO₂.

Proposed Programs

We have outlined the following areas where we feel we can help.

1. A 3-Site Field Research Program comparing EW on croplands at three different sites – a wet tropical weathering “hot spot” such as in South or Central America, a wet temperate site such as in a southern coast state, and a dryer temperate site such as in the Midwest. This research will allow many different important variables to be tested. However, enough research has already been done to initiate EW and OAE in virtually all countries of the world.

2. Provide the funds to design and then build a Carbon Neutral Research Ship for OAE. This ship will run entirely on renewable energy to provide the electricity for driving the ship, final grinding and performing electrolysis on ultramafic rocks. It will initially focus its efforts on regions of ocean CO₂ upwelling (spilling of CO₂ into the atmosphere) and dying corals, then the rest of the ocean. These plans can be used by other countries to build additional ships.

3. Encourage the U.S. Military and Army Corps of Engineers to start a project, in cooperation with existing companies, to mine, grind and stockpile ultramafic rocks at the Twin Sisters site in WA and elsewhere.

4. Encourage the US to initiate an effort involving virtually all countries to begin the mining, grinding and stockpiling of ultramafics in their own country and using them for worldwide efforts at EW and OAE.

5. Encourage the U.S. to set up a Department of Enhanced Weathering/OAE with an Advisory Panel consisting of many of the experts cited in this review.

An international effort at mining ultramafic rocks is necessary because the use of EW and OAE to combat climate change worldwide cannot get started without an adequate supply of ultramafic rocks devoted solely to this purpose. It is impossible to extract and sequester huge amounts of CO₂ from the atmosphere without an equally huge stockpile of processed ultramafic rocks. This will clearly require an international effort.

To help to appreciate the magnitude of the problem, we show a picture of 12.5 gigatons of charcoal representing part of the amount of carbon humans put into the atmosphere each year. The pile is over a mile high and 4 miles wide.



A 12.5 gigatons of rock

It would require a pile about 1.2 times as large as this to remove 10 gigatons of CO₂ and twice this size to remove 20 gigatons of CO₂ each year. However, the pile for each country would be much, much smaller when divided by the 190 countries of the world.

The major energy cost of EW is that involved in the grinding of the rocks. A source of renewable, carbon free electricity for grinding may require solar or wind farms, or the utilization of modular Molten Salt Nuclear Reactors or the U.S. Military's Deployment of Microreactors. The U.S. Military and the Army Corp of Engineering are uniquely suited to carrying out this project and working with these sources of energy.

Another Economic Advantage of EW and OAE

An additional significant advantage of the EW – OAE approach is that it would not cost the U.S. many billions of dollars and worldwide would save trillions of dollars in mitigation costs. If the CO₂ sequestration was spread among all countries of the world (#4 above) the US would only need to sequester the amount of CO₂ equal to its own emissions. Goff and Lackner (1998) pointed out we have more than enough ultramafic rocks in the U.S. to do that. Although we suggested that the Military set up a project to mine ultramafic rocks at Twin Sisters, WA, this could be done in tandem with a private company, Unimin Corporation, which is currently mining at Twin Sisters. Funds from the government to significantly accelerate their mining and make it all available for EW and OAE would utilize a skill that is already in place.

One More Advantage of EW and OAE

There have been a number of Direct Air Capture (DAC) initiatives and the Biden Infrastructure Bill has included several billion dollars toward four of these projects. However, not all is rosy with this approach. For example, Summit Carbon Solutions, a 4.5 \$billion enterprise, plans to capture 12 million tons of CO₂ annually in a program to make ethanol a carbon negative fuel. The CO₂ is then transported by long pipelines from Iowa and Nebraska to South Dakota where it is to be pumped a mile underground under geologic formations, presumably basalt. This sounds great but a number of environmental

groups are opposed. "CO₂ pipelines are a questionable attempt to prop up fossil fuels by taking advantage of government subsidies while providing a pretense that they are environmentally friendly," stated Ken Winston of the Nebraska Sierra Club. There have been a number of other objecting voices. Some additional problems with CCS and DAC are the high degree of salinity under many basalt domes and the loss of CO₂ injected into old oil wells by conversion to methane and being dissolved in ground water. These are not a problem with EW and OAE and we believe that these two NETs will generate far fewer objections because of the many advantages inherent in the process (see above) and the absence of potentially dangerous long pipelines, absence of under basalt storage and without the use of old oil wells.

If 70 nations of the world were eager to spend 28 billion dollars to fund the ITER, a fusion machine that was unlikely to pay off for 50 years, the world should be jumping at the bit to pay a fraction of that to begin the process of mining and grinding their own ultramafic rocks, and immediately begin removing CO₂ from the atmosphere and safely storing it for thousands of years. This could be the "new oil" and could immediately begin to be a valuable resource. What is necessary is for the U.S. and or the UN to take the lead, set up the meetings and provide guidance. Some of the billions of dollars that are currently committed for mitigation in the Green Climate Fund, could be used to jump start these operations.

In the past decades 1,800 lawsuits have been filed, mostly by our youth, against companies and governments for failing to adequately address climate change. Initially ridiculed, these cases have recently gotten some traction. World-wide cooperation on development of mining of ultramafic rocks and their use for EW and OAE would not only show that the world is finally getting serious about combating the dangerous effects of climate change, but it would actually begin to reduce atmospheric levels of CO₂ and save our planet.

Rapidly Stopping Global Warming

The finding, mining, grinding and spreading of ultramafic rocks on croplands, non-croplands (EW) and oceans (OAE) is not technically difficult and virtually every country in the world has ultramafic deposits (see Appendix C) and many have access to the ocean. The approach could be called MINE, GRIND, SPREAD and SEQUESTER.

In addition to having all nations commit to stringent progressive reductions in emissions, there should also be a requirement that each nation commit to extracting from the atmosphere an amount of CO₂ equal to or greater than its current yearly output of CO₂. This would rapidly halt the increases in global temperature.

Since just sequestering the amount of CO₂ produced each year would halt but would not lower the amount of CO₂ in the atmosphere, it would be better to sequester the amount of CO₂ emitted each year + 30%. Then, as this continued each year the level of CO₂ in the atmosphere would decrease. Since the amount of CO₂ a country needs to sequester would be pegged to the level of their emissions, for if a country wished to free themselves of this task, this would provide a powerful incentive to further reduce emissions

We emphasize that this plan is not an excuse to stop reducing emissions. Continued reduction in emissions is critical to the success of the plan. Thus, for each country, as the level of emissions decreases and the yearly amount of CO₂ sequestered remains the same, as the years progress there would be more and more efficient removal of CO₂ from the

atmosphere. We believe this could result in the atmospheric level of CO₂ returning to pre-industrial levels by the middle of the century - and mankind's struggle with global warming would be over. Fairness is an additional advantage in that each countries' contribution would be directly proportional to its level of emissions. In addition, the total cost would be distributed among all countries, proportionate to the level of their emissions. Since it is likely that emissions will never totally reach zero, the continuation of EW and OAE, at a scaled back level, would ensure that the level of atmospheric CO₂ would never again be a problem.

But we need to get started

Since just sequestering the amount of CO₂ produced each year would not lower the amount of CO₂ in the atmosphere, it would be better to sequester the amount of CO₂ emitted each year + 30%. Then, as this continued each year the level of CO₂ in the atmosphere would decrease.

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The final conclusion is that we urge the United States, and/or the UN to convene a new COP27, or involve each country individually rapidly getting all countries of the world to commit to a MINE, GRIND and SPREAD program to sequester 100 + 30% of their yearly CO₂ emissions. If they have to purchase the necessary rocks from other countries but cannot afford it, the billions of dollars in the Green Fund for mitigation of climate change could be used. The important issue is that

We must start now.

The Comings Foundation

Enhanced Weathering: The Best Method of Removing CO₂ from the Atmosphere

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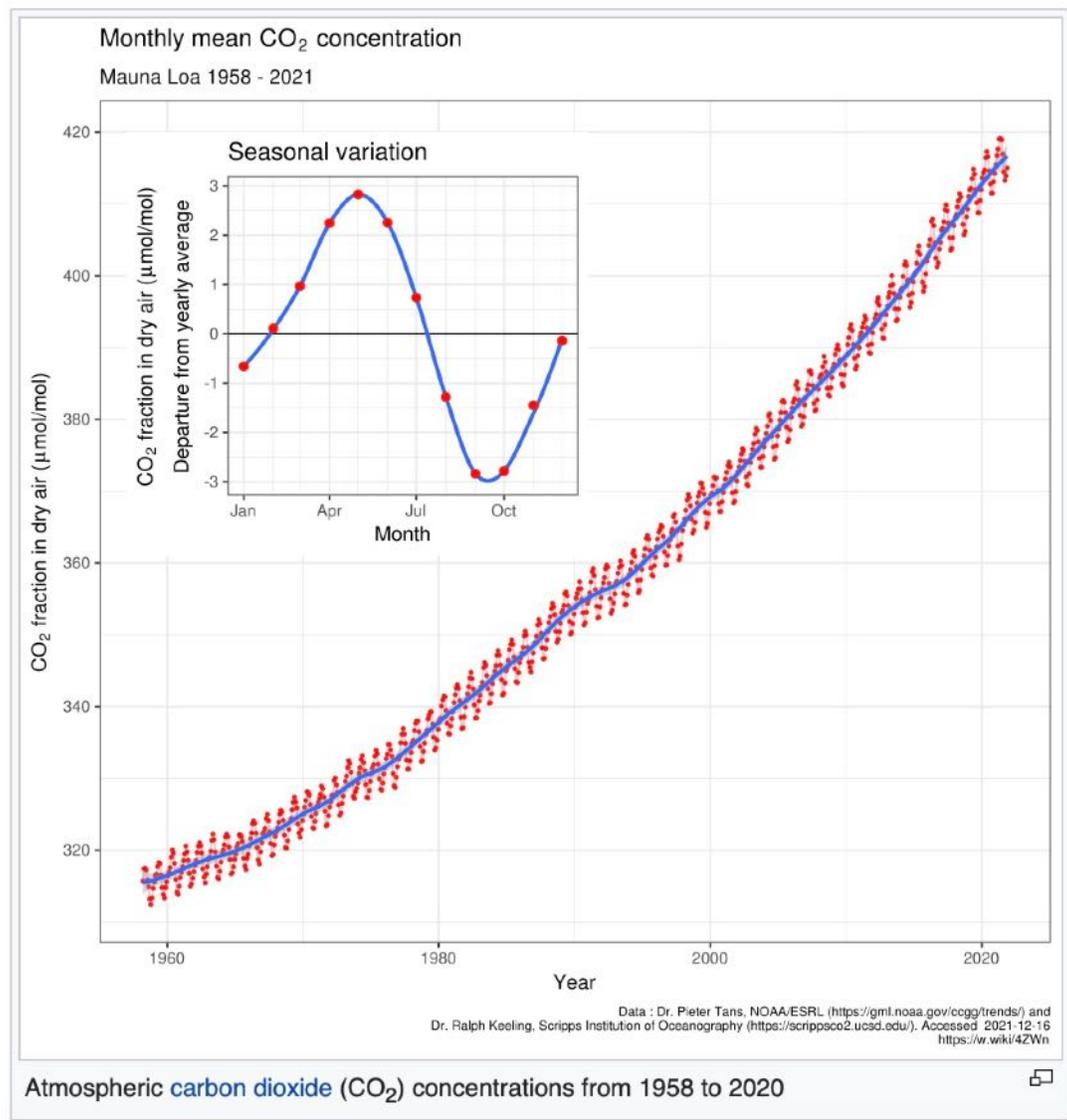
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Enhanced Weathering: The Best Method of Removing CO₂ from the Atmosphere

Keeling, Mauna Loa Observatory, and COPs

To date the primary method of combating global warming is through a series of Conference of Principals (COP) meetings at which the countries of the world commit to reducing their CO₂ emissions. The last of the series was COP26 in 2021 in Glasgow. So how is this working? In 1958 David Keeling set up the Mauna Loa Observatory in Hawaii, at 11,140 feet above sea level, to monitor atmospheric CO₂ levels. The results of these readings is shown below.



Results from the Keeling Mauna Loa CO₂ Observatory Wikipedia

The seasonal variations reflect the inhalation and exhalation of the Earth as plants grow, absorbing carbon in the summer and spring, and decay, releasing carbon in the fall and winter. The first major COP was COP3 in Kyoto, Japan in 1997. At that time the level was approximately 358 parts per million or ppm or umol/mol. Multiple meetings up to COP26 followed. The current level is 419 ppm. In fact, ever since 1997 the rate of accumulation of CO₂ in the atmosphere is actually increasing, not decreasing. Something else needs to be added.

Based on these and other findings, 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 **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). The **2021 UN Report on Climate Change is even more scary.**

CDR is not meant to minimize the need to cut emissions. Both approaches are critically 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 come in. We propose to support the research, development and implementation of both of these technologies – **Enhanced Weathering on Croplands and Ocean Alkalinity Enhancement.**

CCS, CCUS. One of the most common NET proposals is **Carbon Capture and Storage (CCS).** This involves the capture of CO₂ **emitted by power plants burning fossil fuels.** This capture is followed by the sequestration of the CO₂ into various underground storage sites. A modification of this approach is **CCUS (Carbon Capture Use and Storage)** where the captured CO₂ is put to a variety of uses and the excess sequestered. For an extensive review of the many potential uses of CO₂ see Mikkelsen, et al (2010). 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, the CCS process has considerable energy requirements and financial costs (Siefert and Litster, 2013).

Third, there are serious concerns about the permanence and safety of the sequestered CO₂ due to earthquakes (Yu et al, 2008; Gough, 2008) and leakage (Damen, et al, 2006). There are also potential problems with corrosion and leakage of CO₂ pipelines (Mazzoldi et al, 2008).

Fourth, 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 1,200 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.

Fifth, in a Nature Climate Change article entitled, "Uncertain storage prospects create a conundrum for carbon capture and storage ambitions," Lane et al (2021) suggest,

“..the essence of our abatement challenge is not the volume of storage available, it's the rate at which CO₂ can be safely injected and permanently contained that counts.”

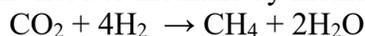
Sixth, regarding CCUS MacDowell et al (2017) point out that it is highly improbable the chemical conversion of CO₂ will account for more than 1% of the mitigation challenge. They further stated that CCUS may prove to be a costly distraction, financially and politically, from the real task of mitigation.

As pointed out by Mann (2021) 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. 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 are the **large salt reservoirs underneath basalt domes**, and here one 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.

Conversion of CO₂ to methane in with storage of CO₂ in depleted oil wells

An additional complication of CCS is the observation that 13 to 19% of the CO₂ injected to depleted oil wells is converted to methane by methanogenic bacteria as follows:



The problem with this is that methane is less soluble and more mobile than CO₂ and therefore there is an enhanced risk of escaping gas. In addition, up to 74% of injected CO₂ is dissolved in ground water, a further source of loss (Tyne, et al, 2021). Thus, of the two major proposed sites of storage in carbon capture and storage, the basalt domes have problems with high levels of salinity and the depleted oil wells have problems with CO₂ loss by conversion to methane and solubility in ground water.

Thus, CCS and CCUS NETs are complex and carry a potentially huge price tag. The EW and OAE NETs described in this proposal do not have these problems.

DCCS, DAC A second major approach is **Direct Carbon Capture and Storage (DCCS) or Direct Air Capture (DAC)**. 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 disadvantages, depending upon how the CO₂ is stored. If it is stored **under basalt domes**, it has the **same disadvantages as above with CCS and CCUS**, namely concerns about the safety, permanence and cost of the CO₂ storage. If it uses the technique of *in situ* sequestration consisting of chemically reacting the CO₂ with mafic and ultramafic rocks, the storage can be permanent and safe.

A few projects using DAC with chemical storage in basalt (a mafic rock), have started in Iceland and elsewhere, these involve the sequestration of thousands to millions of tons of CO₂. We need to sequester 1,000 to 10,000 times this amount, i.e., billions or gigatons of CO₂.

***In situ* Sequestration** by the injection of CO₂ directly into mafic and ultramafic rocks (see *in situ* sequestration below) is the safest form of storage for DAC. A review of different aspects of this technique is presented below. Also see Ballerat-Busserolles, et. al. (2018).

Department of Energy sponsored DAC At the COP26 Secretary Granholm announced the DOE Carbon Negative Shot initiative, part of President Biden's broader climate plan. This goal will span carbon removal solutions, from direct air capture (DAC) to soil carbon sequestration. The initiative aims to lower the cost of removal to \$100 per ton or less (for capture and storage), prioritizing high-quality lifecycle accounting, equity and justice, and durable storage for at least 100 years. Ultimately, the goal is to catalyze gigatons of carbon removal.

The bipartisan infrastructure bill provided \$3.5 billion for DOE to build out four regional direct air capture hubs. The DOE renamed the Office of Fossil Energy to include Carbon Management (now known as FECM). The FECM leadership includes Dr. Jennifer Wilcox, Dr. Emily Grubert, and Dr. Shuchi Talati some of the best people Carbon 180 could imagine leading this program. The Carbon Negative Shot can play a central role in starting to get to gigaton-scale removal and net-negative emissions.

The Comings Foundation applauds this initiative. We will interact with the DOE to determine if they have plans to support EW and OAE that we think is an even better approach, as part of this program.

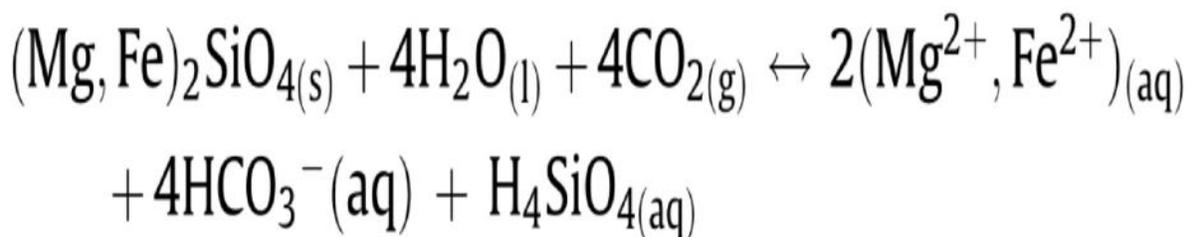
Both **CCS, CCUS, DCCS and DAC** have the disadvantage that they do not address two other serious problems with climate change and greenhouse gases - ocean acidification and atmospheric N₂O. Two additional alternatives termed ***ex situ* sequestration** do not have these problems.

1. **CCSM (Carbon Capture and Storage by Mineralization)** Here CO₂ is removed from flu gas and other outputs of power plants and sequestered using ground up mafic and ultramafic rocks. This has the advantage that storage is safe and permanent, but the disadvantage that it only mitigates the CO₂ produced by power plants and does not remove CO₂ from the atmosphere. However, CCSM can be used with DAC.

2. **Enhanced Weathering (EW) using Croplands, Non-croplands, and Oceans (OAE).** These are close to being the ideal NETs (see below) and avoid the issues noted above.

The Equation that Saved Planet Earth – And with Help Can Do It Again.

The atmosphere of Venus is 96.5% carbon dioxide resulting in a deadly temperature of 872 °F. By comparison, the atmosphere of the earth contains 0.04% CO₂ or 413 ppm and a temperature compatible with life. Schuiling (2013) pointed out that the difference between the two planets was the presence of **water on earth** which allows the CO₂ to be permanently mineralized based on the following equation, where the left-hand compound is **olivine, a ultramafic rock**.



This reaction, sequestering CO₂, could only occur in the presence of water. The complete fate of the different parts of this equation are shown below.

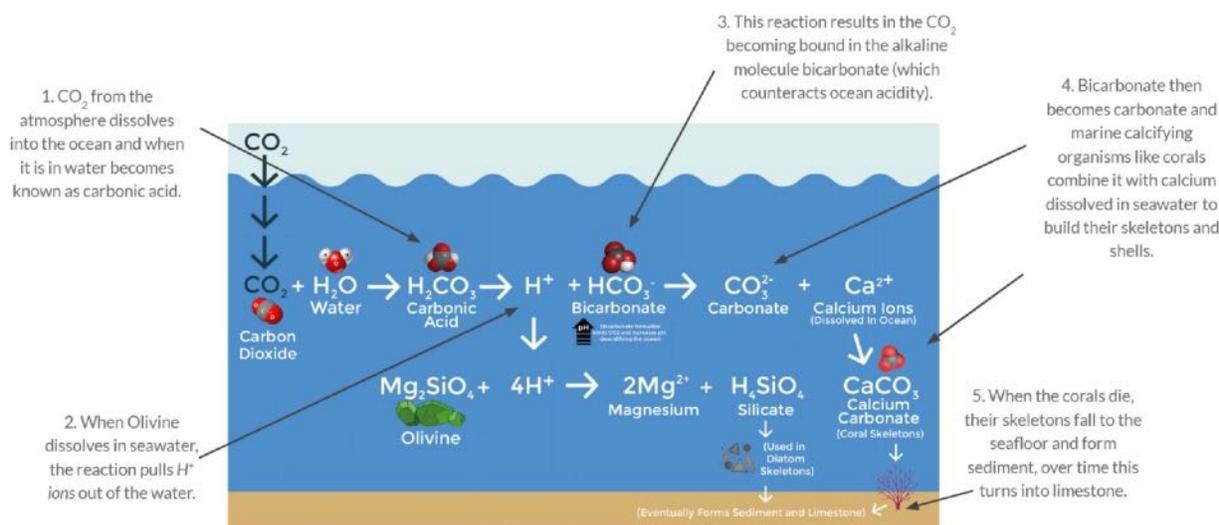


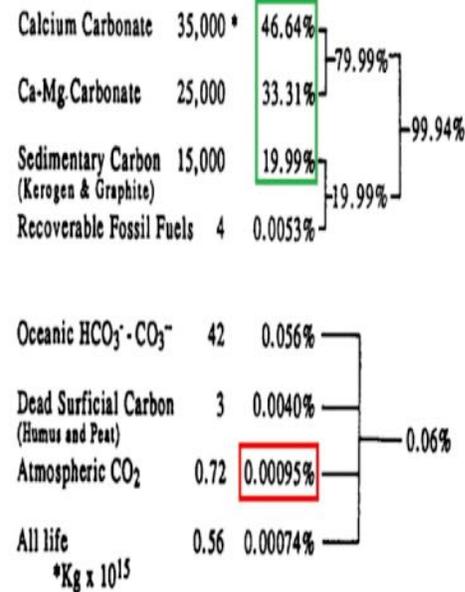
Figure from Project Vista

CO₂ from the atmosphere dissolves in water producing carbonic acid, H₂CO₃ which produces acidic H⁺ and HCO₃⁻. Ultramafic minerals such as olivine, Mg₂SiO₄ combine with the H⁺ to produce silicates H₄SiO₄ which are taken up by diatoms which die and fall to the ocean floor. The carbonic acid also produces carbonates CO₃²⁺ which combine with calcium Ca²⁺ to produce calcium carbonate CaCO₃ which is used by corals and shells of other marine organisms. Combined, these reactions permanently store in mineral form 99.94% of all the CO₂ ever produced on earth and make the earth a livable planet.

What do we mean when we say, “And with help can do it again?” The above reaction in nature took thousands of years. However, if the ultramafic rocks are ground to a fine power (the finer the better) and spread on croplands, non-croplands and the ocean, the rate of the reaction of dissolution can be dramatically accelerated. Much of the research cited below was devoted to identifying methods of accelerating this reaction.



Estimates of the relative distribution of carbon on Earth, in kg and % (after Berner and Lasaga, 1989).



The White Cliffs of Dover are an example of where 99.9% of carbon on Earth is sequestered. This mineral storage is massively greater than that of all the trees and plants on earth.

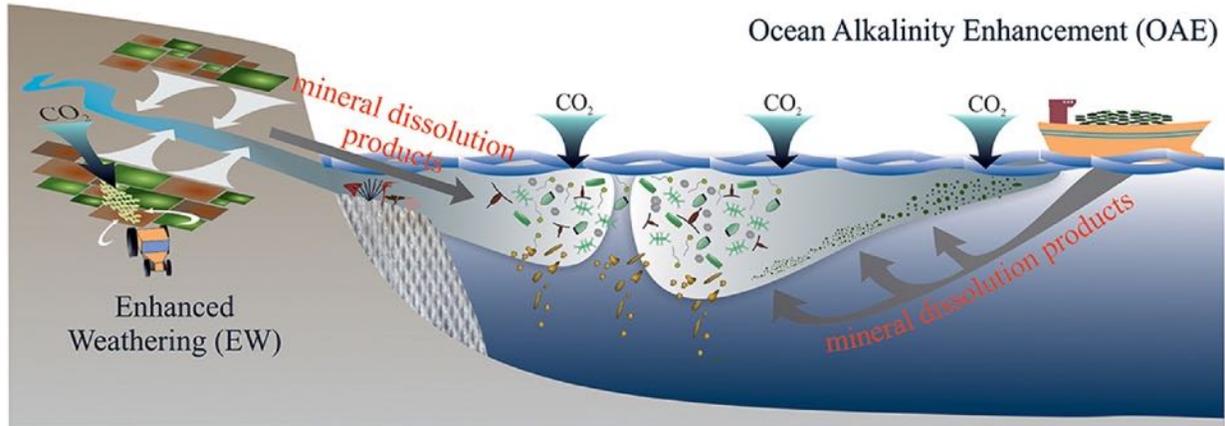
What the ideal CO₂ removal technique should accomplish.

The following are the characteristics of an ideal method of removing CO₂ from the atmosphere.

- Provide for a **permanent and safe long-term storage of gigatons of CO₂ for thousands or millions of years.**
- Directly remove CO₂ from the atmosphere.
- Decrease ocean acidification.
- Decrease in ocean warming,
- Decrease in ocean deoxygenation,
- Decrease marine production of N₂O.
- Decrease the soil production of N₂O.
- Do not compete with regular croplands, but actually, improve existing croplands.
- Largely avoid the restrictions of regulatory groups as compared to ocean iron fertilization and SRM (solar radiation management).

Enhanced Weathering utilizing croplands and non-croplands and oceans meet all of these requirements.

Acceleration of weathering (mineralization) without underground storage can 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).



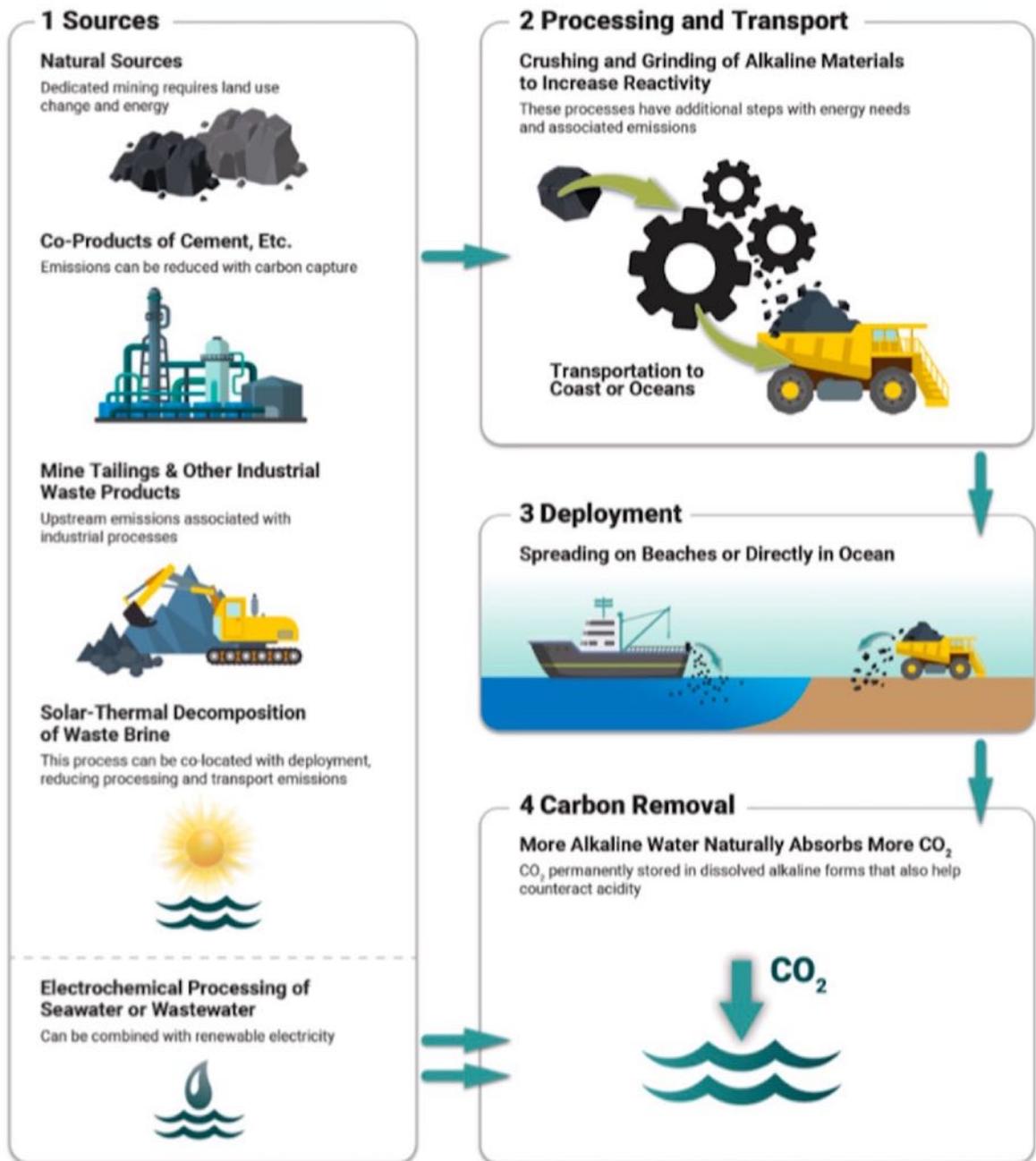
During EW, mineral dissolution products enter the ocean mostly via rivers so that perturbations first occur in estuarine and coastal regions. In the case of OAE, ships could transport the minerals to coastal regions or further offshore.

Not only do we believe that EW, both *in situ* and *ex situ*, and OAE, are the best NETs, we believe there needs to be an international effort in which most nations participate (see below).

Ocean Alkalinity Enhancement (OAE)

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

Ocean Alkalinity Enhancement Approaches and RD&D Needs



Background Information

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

A. Alkalinity

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

“Total alkalinity (TA) refers to the charge balance of weak ions in **seawater** and 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 form as follows:

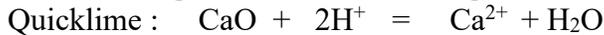
$$(1) \text{ TA} = [\text{HCO}_3^-] + 2 [\text{CO}_3^{2-}] + [\text{B}(\text{OH})_4^-] + [\text{OH}^-] + [\text{HPO}_4^{2-}] + 2 [\text{PO}_4^{3-}] \\ + [\text{H}_3\text{SiO}_4^-] + [\text{NH}_3] + [\text{HS}^-] - [\text{H}^+] - [\text{HSO}_4^-] - [\text{HF}] - [\text{H}_3\text{PO}_4]$$

H^+ is removed by OAE \rightarrow increased TA

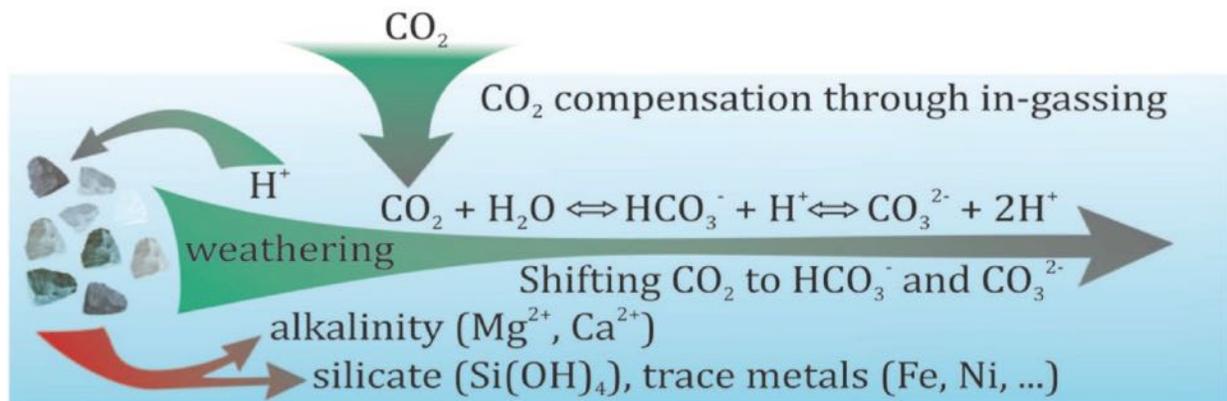
The dissolution of CO_2 in seawater and the subsequent reaction with H_2O have no effect on TA because the formation of proton donors and acceptors is balanced.



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 a 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 well covered by EFI (2019) *Clearing the Air* and 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 CO_2 emissions.¹⁷ As CO_2 dissolves in the ocean, it reacts with water to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). Most of the hydrogen reacts with existing carbonate ions (CO_3^{2-}) 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 ($CaCO_3$) 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

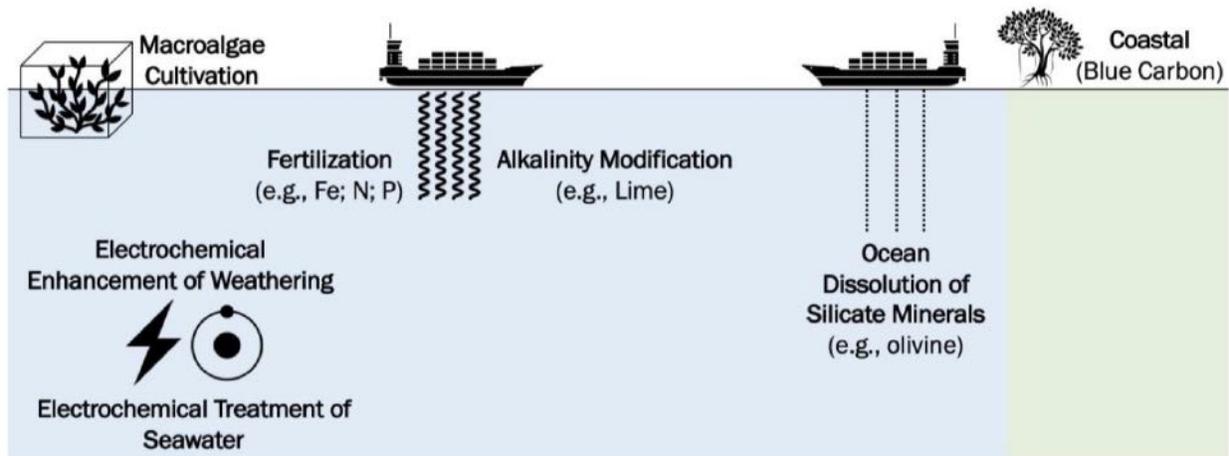
The relationship between CO_2 and ocean acidification may make it seem counterintuitive to actively store CO_2 in the oceans as a CDR technique. However, proposed CDR techniques such as ocean alkalinity modification (OAM) focus on storing carbon in the form of bicarbonate, chemically balanced by sources 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.

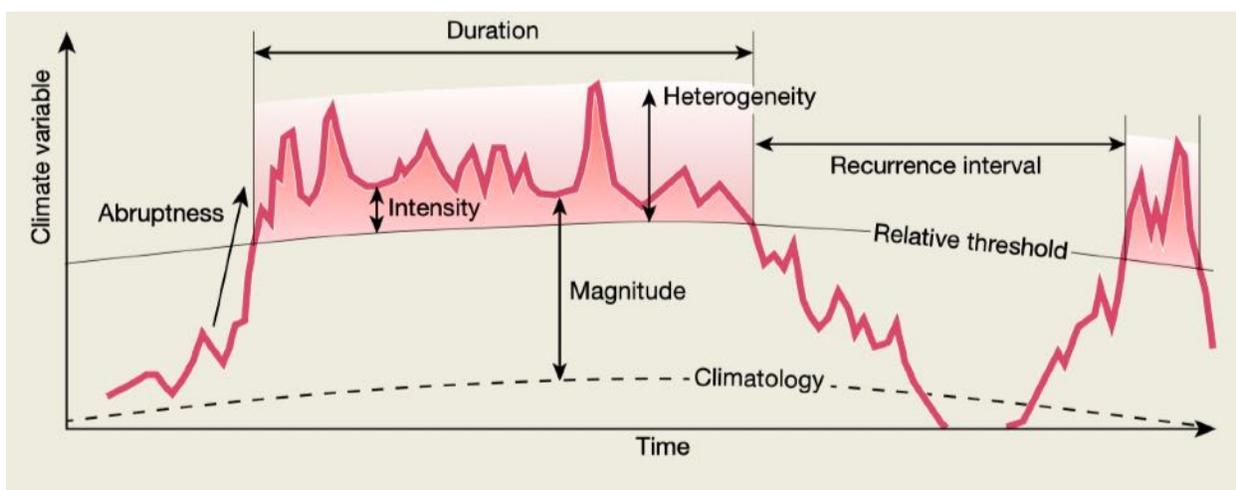
Some of these approaches are covered later.

C. Trio of acidification, warming and deoxygenation

In addition to acidification two other phenomena contribute to the negative effects that increased levels of atmospheric CO₂ have on the ocean – warming and low oxygen concentration. The deoxygenation is the result of the decreases solubility of oxygen in warmer oceans. This trio of acidification, warming and deoxygenation leads to **extreme events** with dramatic consequences. “For example, between 1982 and 2016, the number of days with marine heatwaves—defined here as days on which the sea-surface temperature (SST) exceeds its local

99th percentile—has doubled, even though human-driven global warming caused the ocean surface to warm by ‘only’ around 0.4 °C, over this period. One of the most prominent heatwaves was the ‘Blob’ in the northeast Pacific that occurred between 2013 and 2015 with SST anomalies of up to 6 °C relative to 2002–2012. This event had severe consequences for marine life, ranging from **massive die-offs of marine birds, higher mortality of sea lions, reduced stocks of many commercially valuable fish, to pronounced shifts in zooplankton community structure**. The trend towards more frequent marine heatwaves is projected to continue under global warming, with the ocean encountering 16 times more marine heatwave days compared with preindustrial conditions” (Gruber et al, 2021).

The following figure shows the characteristics of these extreme events.



Metrics associated with an extreme event includes the intensity, magnitude, duration, heterogeneity, abruptness and recurrence (Gruber et al, 2021).

D. DIC (Dissolved Inorganic Carbon)

The dissolved CO₂ can take several forms, including dissolved gaseous CO₂, carbonic acid (H₂CO₃), bicarbonate ions (HCO₃⁻) 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 below). At normal seawater pH values, most DIC is in the form of bicarbonate ions **HCO₃⁻**.

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 (HCO₃⁻ 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 HCO₃⁻. Meanwhile, the CO₃²⁻ content decreases, since the net effect of adding CO₂ is a reaction with CO₃²⁻ to form HCO₃⁻ (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 [HCO₃⁻] + 2 × [CO₃²⁻]).

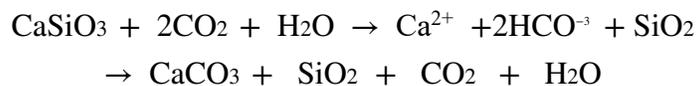
An important feature of DIC is that it is larger in the deep oceans than on the surface because of several “pumps,” including upwelling/circulation (the “**solubility pump**”), phytoplankton photosynthesis (the “**soft-tissue pump**”), and the formation of hard shells (the “**carbonate pump**”). **These 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.

E. The Urey Equation

In 1952, Dr. Harold Urey (Urey, 1952) of iridium/dinosaur killing meteor fame, provided the first successful attempt to explain the origin of the massive storage of carbon in the continental crust in the form of calcium carbonates in limestones and marble. “As carbon dioxide was formed it reacted with silicates to form limestones.”



The silicates may have been a variety of minerals, and the presence of atmospheric CO₂ was kept at a low level by this or similar reactions. The carbonation takes place when carbon dioxide (carbonic acid) in acid rain dissolves calcium silicate (wollastonite) sediments to give calcium, bicarbonate, and silica. The resulting calcium and bicarbonate ions flow in rivers to the oceans where either organic or inorganic precipitation produces the calcium carbonate. When water is included in the reaction (Blättler and Higgins, 2017) the formula becomes:



One of the most famous massive accumulations of CaCO₃ is the **White Cliffs of Dover**. They 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 (CaCO₃) 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 (Bernier 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 to 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.

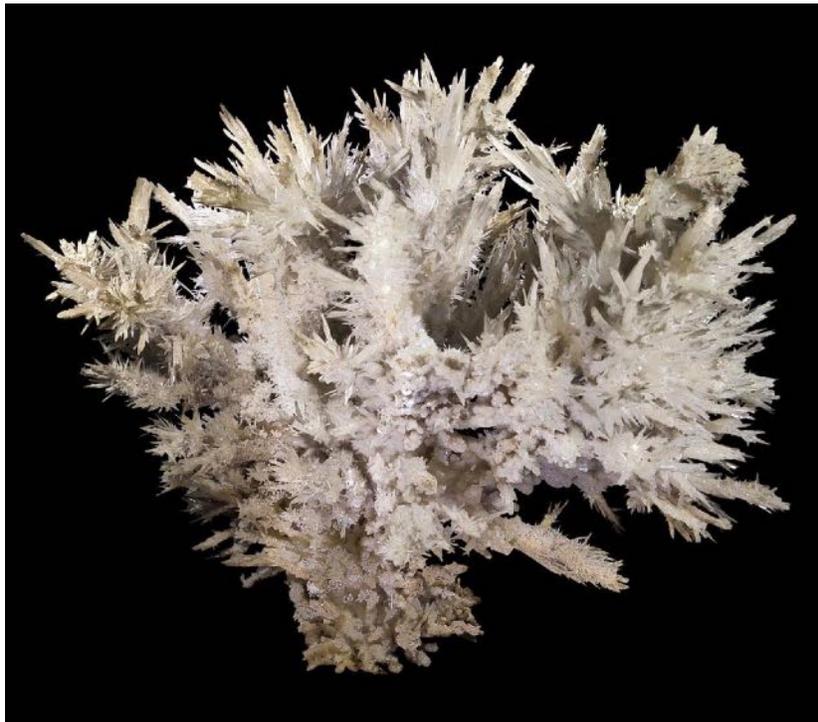
Between 55 and 200 million years ago there were 9 OAEs (Percival et al, 2016). Sequestration of CO₂ in organic-rich black shales and by reaction with silicate rocks exposed on continents would ultimately restore climatic equilibrium but at the expense of significant chemical change in the oceans and 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 2,000 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 413 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 olivine, serpentine and basalt.**

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

Alkalinity required a special explanatory section because it is an important concept in understanding the use of OAE. 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

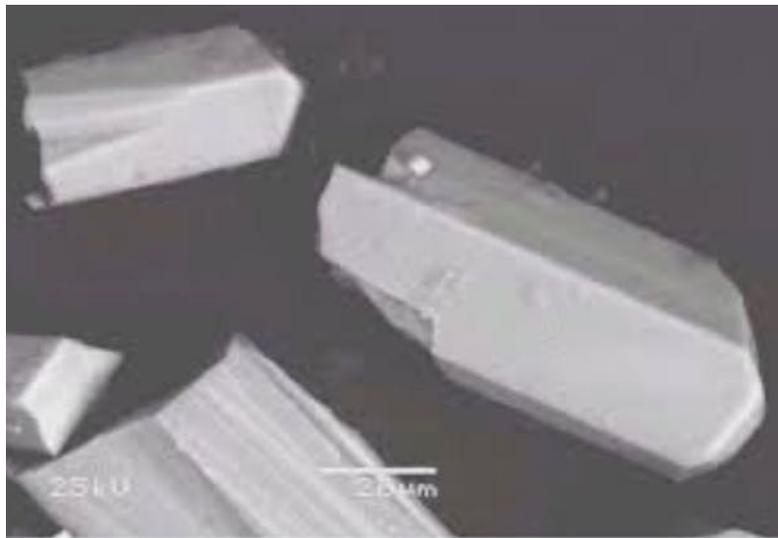
Aragonite is considered essential for the replication of reef conditions. It provides the materials necessary for much sea life and also keeps the pH of the water close to its natural level to prevent the dissolution of biogenic calcium carbonate.

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



Calcite Wikipedia

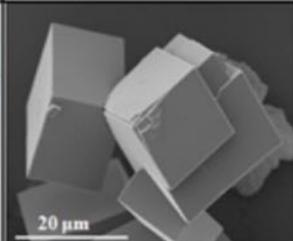
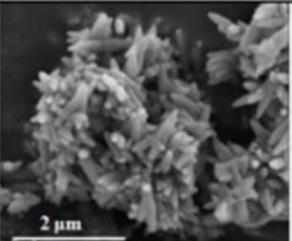
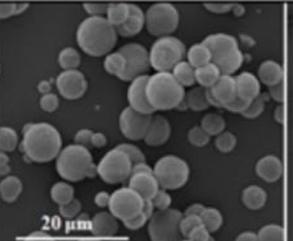
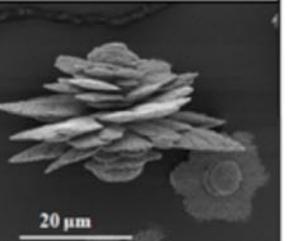
Vaterite was named after the German mineralogist Heinrich Vater. It is also known as mu-calcium carbonate ($\mu\text{-CaCO}_3$) and belongs to the hexagonal crystal system.



Vaterite Wikipedia

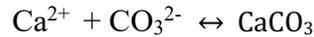
Recently, vaterite was found to have a huge potential for use as drug delivery carriers.

The following figure shows the different crystalline forms of CaCO₃.

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

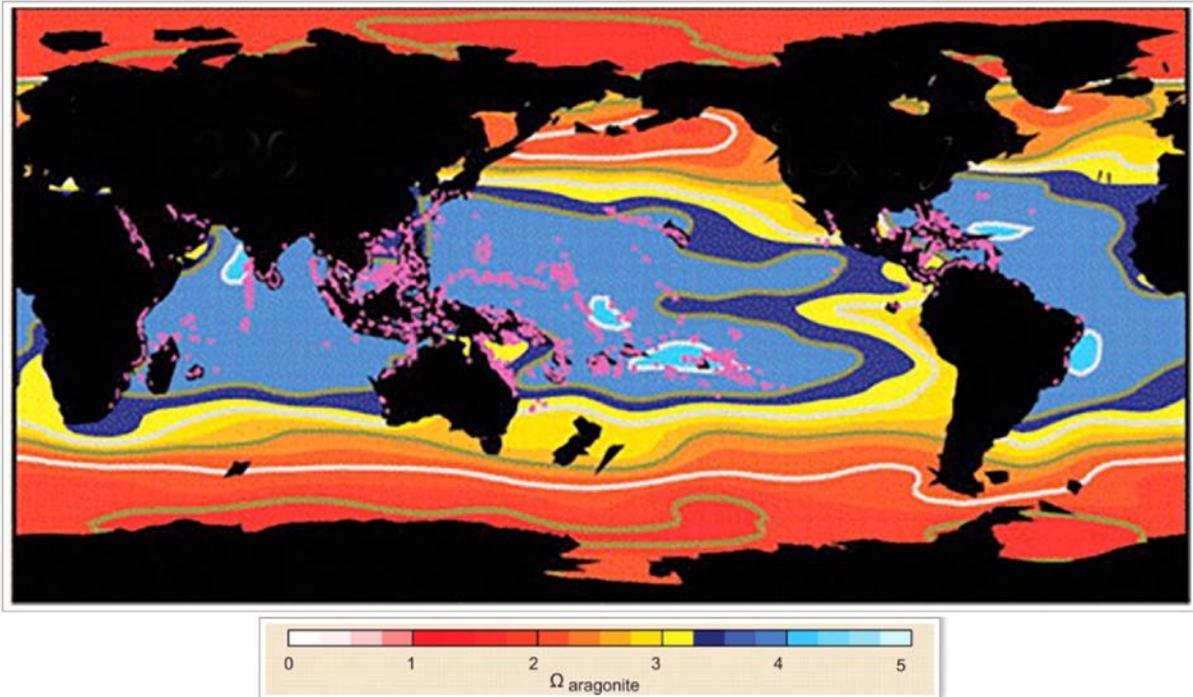


Figure adapted from Hoegh-Guldberg et al., (2007)
Coral reef locations are indicated by pink dots.

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.

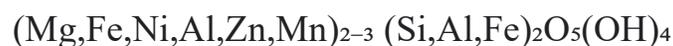
Conditions for coral reef growth are:

- $\Omega > 4.0$: 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 CO_2 emissions, contributing to the loss of coral reefs.

G. Serpentine and Serpentinization

Since the subject of serpentine and serpentinization is mentioned so often it is necessary to review what they are and mean. Serpentinization occurs when ultramafic rocks are exposed to circulating aqueous fluids at temperatures lower than 400°C , leading to the formation of serpentine phases. The combined formula for serpentines is:



Serpentine is a soft ductile mineral and its presence in the mantle wedge lubricates subduction of the oceanic plate. Production of serpentine in the oceanic crust produces hydrothermal fluids and releases gaseous methane and hydrogen, as observed along mid-ocean

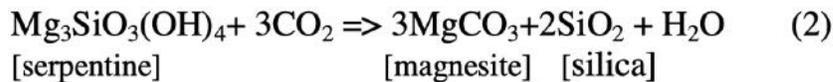
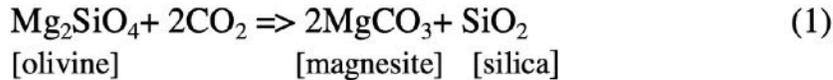
ridges. The pH of the hydrothermal fluids is generally low but under some conditions, notably at low temperature, may be high enough to be favorable to life.

The following formula shows the serpentinization for a single mineral outcome.

Serpentinization is essentially a hydration process.



The following formulas show how serpentine and olivine interact with CO₂.



A disadvantage of serpentine is that **serpentine dissolution kinetics are significantly slower than those of olivine** (Blondes et al, 2019; Daval et al, 2013). **Increased heat and decreased pH increase dissolution rates.** Serpentine and serpentinites are much more mineralogically variable than olivine and peridotites. Serpentinization is thermodynamically favored in near surface environments and its products are stable on a geological time scale. Thus, **both olivine and serpentized olivine are effective in the sequestration of CO₂.**

H. 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	quadrillion
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
pico	p	10 ⁻¹²	trillionth

In general use of the term pico refers to trillionth (10⁻¹²) and the use of the term giga refers to billions (10⁹). The variable use of grams versus tons can also be confusing. One metric ton = one million 10⁶ 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 (10¹⁵)? 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 10¹⁵ g equals a billion (giga) (10⁹) metric tons)” Finally, an author 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 $44/12 = 3.67$ tons of carbon dioxide.

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

I. 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.

J. A Short Course in Mineralogy see **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* sequestration**

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

***Ex situ* storage**

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

4. CO₂ Mineralization: Spreading **pulverized mafic rocks onto croplands and non-croplands.**

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. An extensive review of *in situ* sequestration is provided by Kelemen et al, (2019).

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 Hellisheidi 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 Lackner (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, New Caledonia, 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).

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. As a result, it has been estimated that **it is 10 times cheaper than ex-situ sequestration with ultramafic rocks** (NAS, 2019).

- **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.
- 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.

Given the huge potential of *in situ* sequestration, these disadvantages do not appear serious.

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.

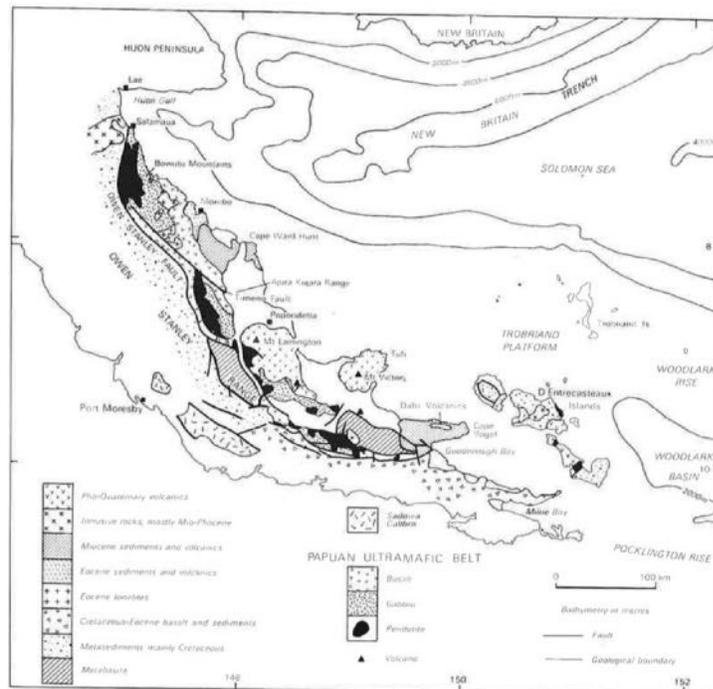
Since one or more private companies are already involved in *in situ* sequestration, the Comings Foundation will emphasize *ex situ* enhanced weathering.

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

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.

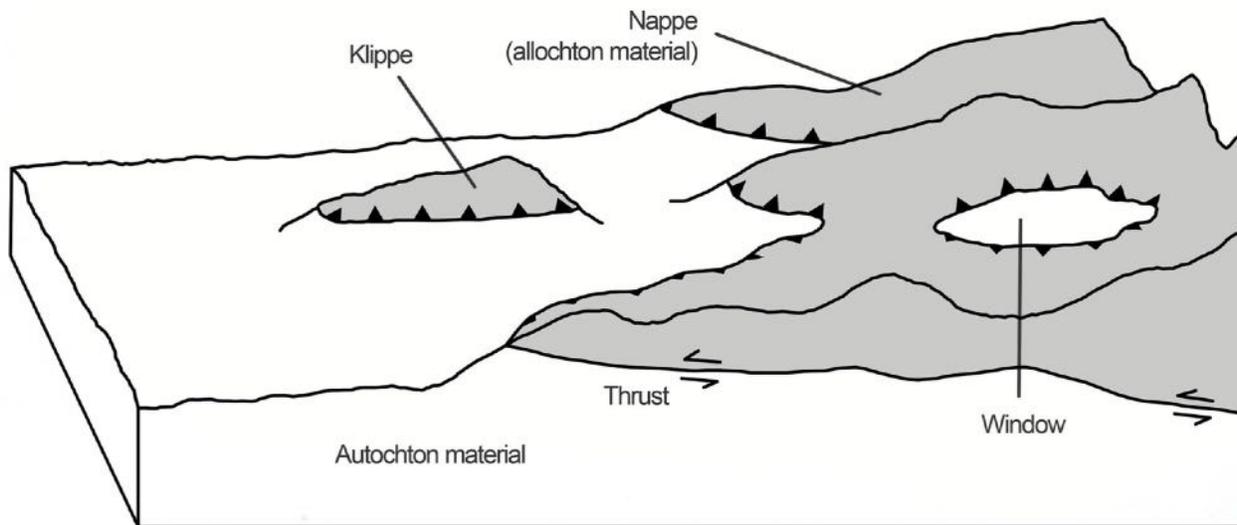
The following map shows the location of the **Papuan Ultramafic Belt** and Milne Terrain.



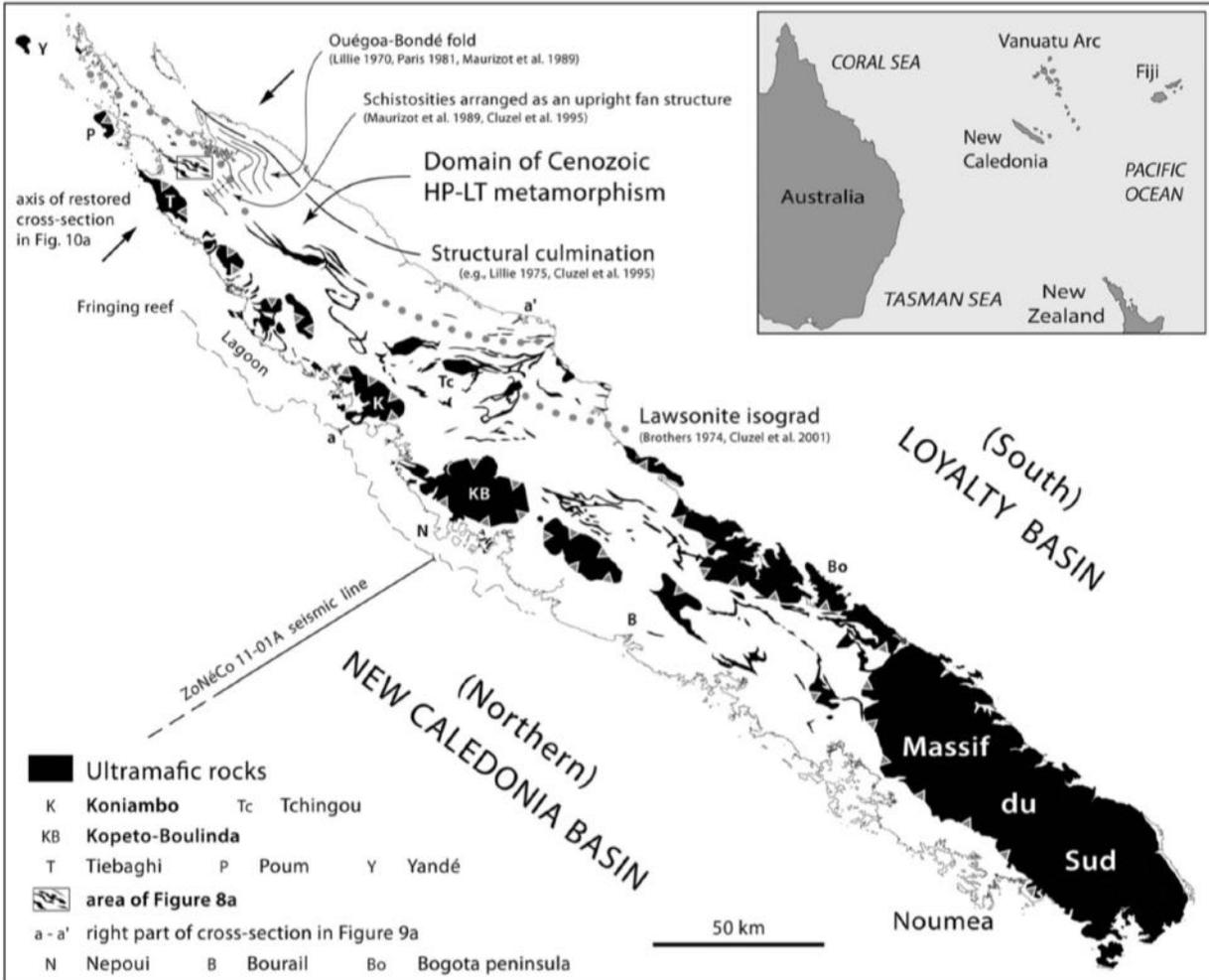
Papuan Ultramafic Belt (Davies and Jaques, 1984)

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 and for *in situ* sequestration.

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 **serpentinization** 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 klippe 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.

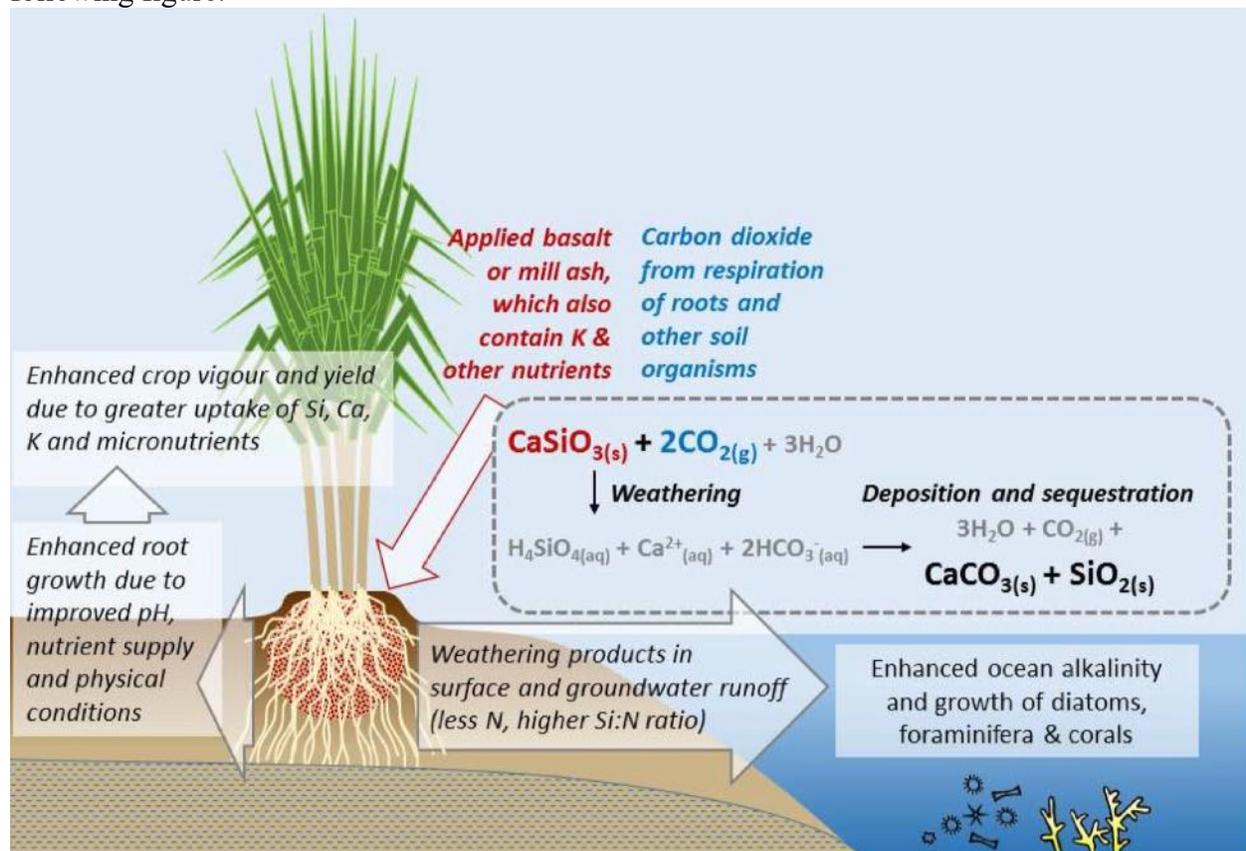
New Caledonia is an archipelago located in the Pacific Ocean to the south of the Equator. It is located in the southwest Pacific Ocean, 1,300 km east of Australia. The **climate is tropical**, influenced by the trade winds, with a **hot and rainy season**, a cool and drier season, and two intermediate 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, as well as for *in situ* sequestration of CO₂. 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.

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 also 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 (Fosterite)	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) ₄	Mg ₃ Si ₂ O ₅ (OH) ₄ + 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
Larnite	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 ₈	CaAl ₂ Si ₂ O ₈ + H ₂ CO ₃ + H ₂ O → CaCO ₃ + Al ₂ Si ₂ O ₅ (OH) ₄	16
Jennite	Ca ₈ Si ₆ O ₁₆ (OH) ₂ ·6H ₂ O	Ca ₈ Si ₆ O ₁₆ (OH) ₂ ·6H ₂ O + 1.67H ₂ CO ₃ → 1.67CaCO ₃ + H ₄ SiO ₄ + 1.77H ₂ O	47
Rankinite	Ca ₃ Si ₂ O ₇	Ca ₃ 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 + H ₄ SiO ₄	38
Tobermorite	Ca ₅ Si ₆ O ₁₆ (OH) ₂ ·4H ₂ O	Ca ₅ Si ₆ O ₁₆ (OH) ₂ ·4H ₂ O + 0.83H ₂ CO ₃ → 0.83CaCO ₃ + H ₄ SiO ₄ + 0.13H ₂ O	39
Pyroxene (Diopside)	CaMgSi ₂ O ₆	CaMgSi ₂ O ₆ + 2H ₂ CO ₃ + 2H ₂ O → CaCO ₃ + MgCO ₃ + 2H ₄ SiO ₄	41
Tremolite	Ca ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂	Ca ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂ + 7H ₂ CO ₃ + 8H ₂ O → 2CaCO ₃ + 5MgCO ₃ + 8H ₄ SiO ₄	38
Enstatite	MgSiO ₃	MgSiO ₃ + H ₂ CO ₃ + H ₂ O → MgCO ₃ + H ₄ SiO ₄	44
Laumonite	CaAl ₂ Si ₄ O ₁₂ ·4H ₂ O	CaAl ₂ Si ₄ O ₁₂ ·4H ₂ O + H ₂ CO ₃ + H ₂ O → CaCO ₃ + Al ₂ Si ₂ O ₅ (OH) ₄ + 2H ₄ SiO ₄	9

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

Olivine

The most common ultramafic rocks are **olivine**, **dunite**, **peridotite**, 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 crystalize. 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**.

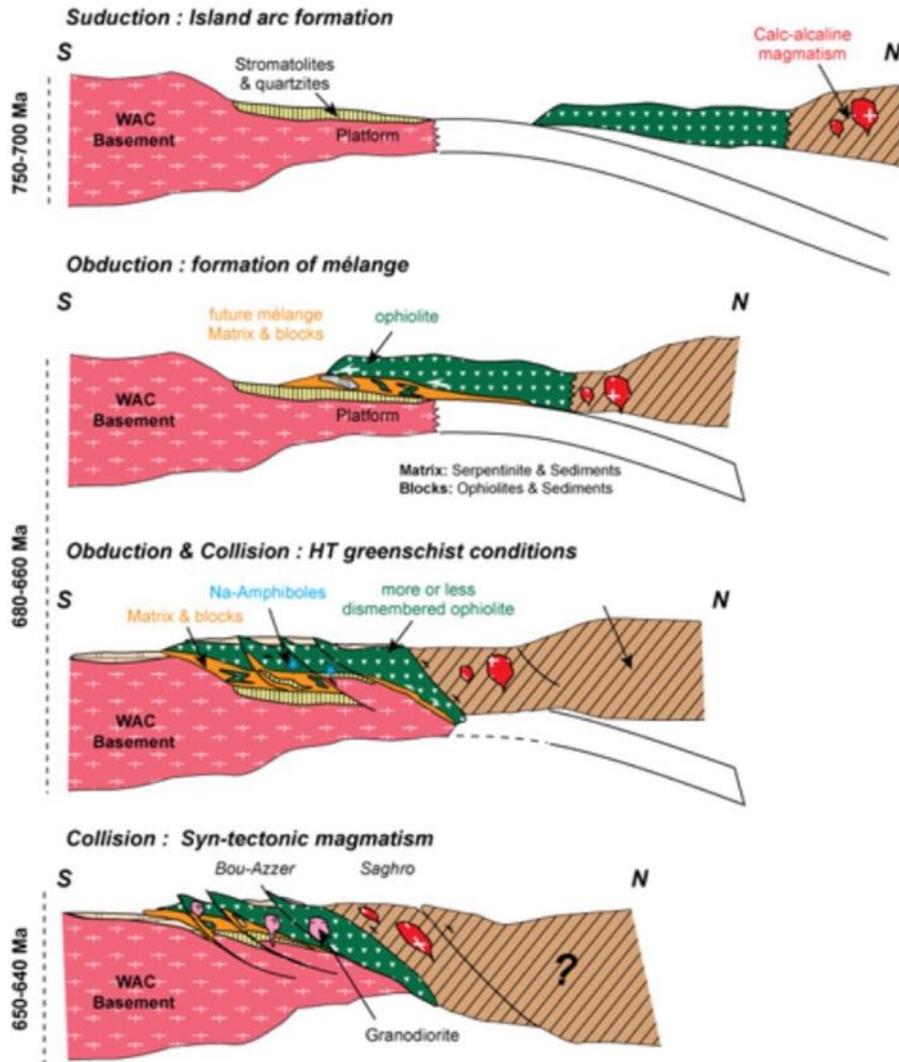
The following is a photo of my personal olivine-basalt that I purchased from a rock shop in Southern California.



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

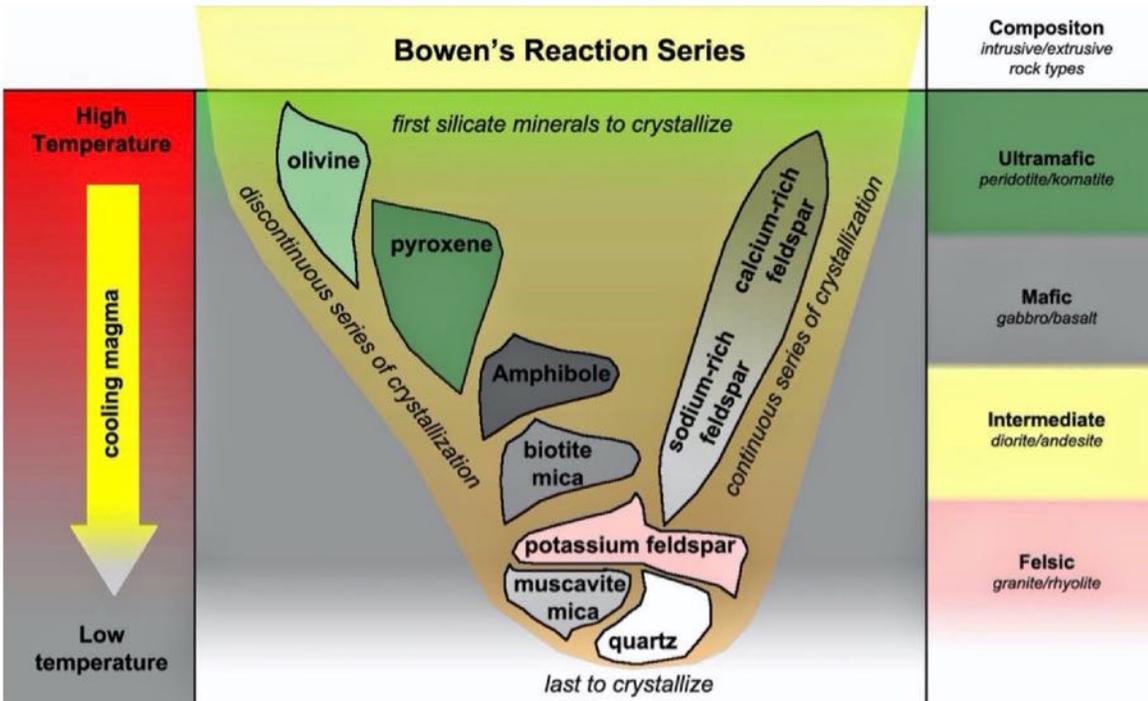
For those doing research on olivine reserves, if one searches for olivine, they will typically find only limited results. What to look for instead are the **ophiolites**. Ophiolites have an entire layer of olivine as the 90% pure form, dunite. And to further make it complicated to find olivine reserves, 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**.



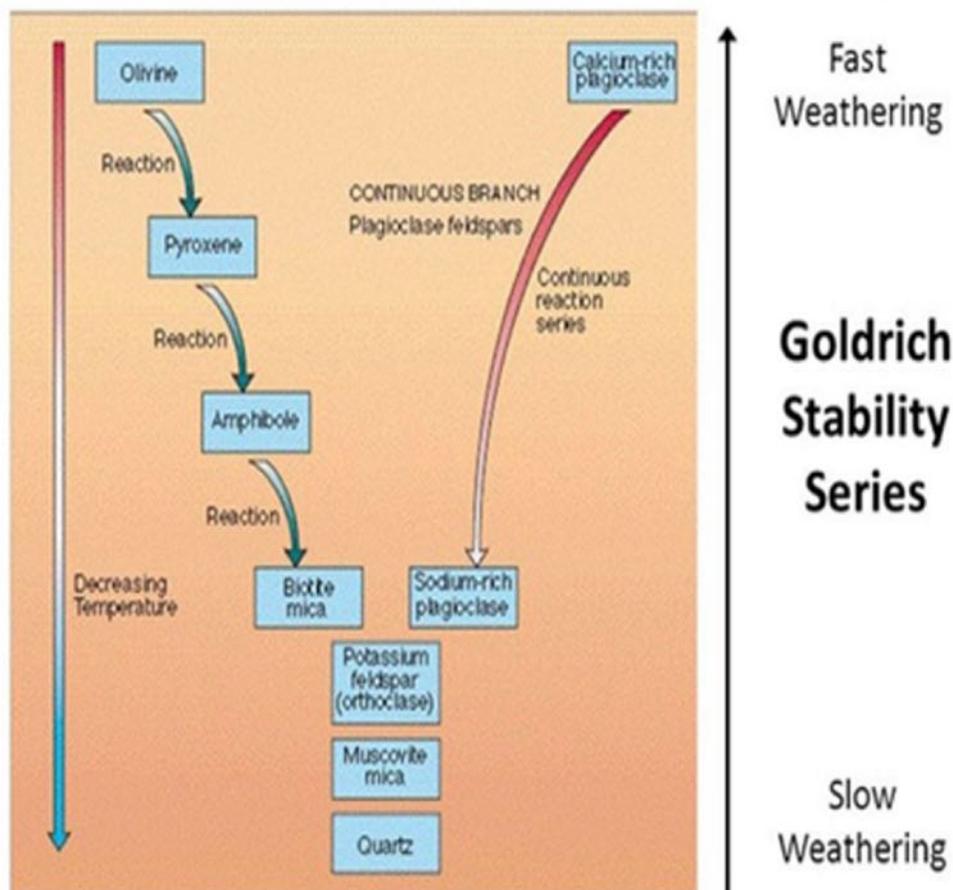
Model for the emplacement of the Bou-Azzer ophiolitic suite.

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).

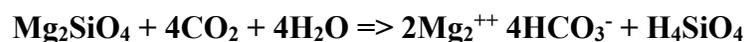


Olivine is the first to form from when magma cools, and the fastest to breakdown from weathering forces.

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).



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



Thus, one mole of olivine can sequester 4 moles of CO₂ in the presence of water.

Schuling (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 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 (~1,000 years, on average).

Effect of pH on Olivine Weathering

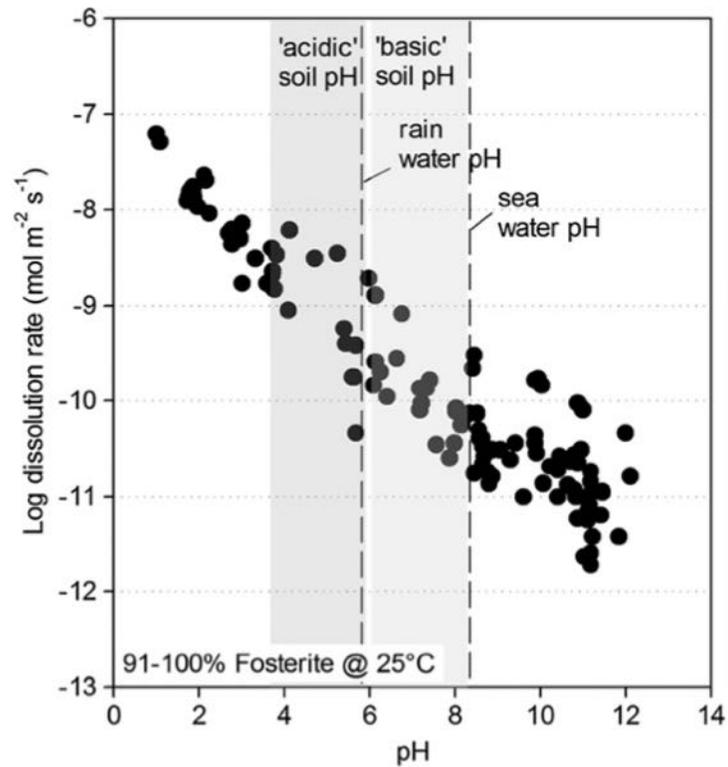
The following table shows the relative rate of weathering of olivine versus three other silicate minerals (basalt not included) at different pHs. Clearly olivine at pH 4 weathers very rapidly.

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.

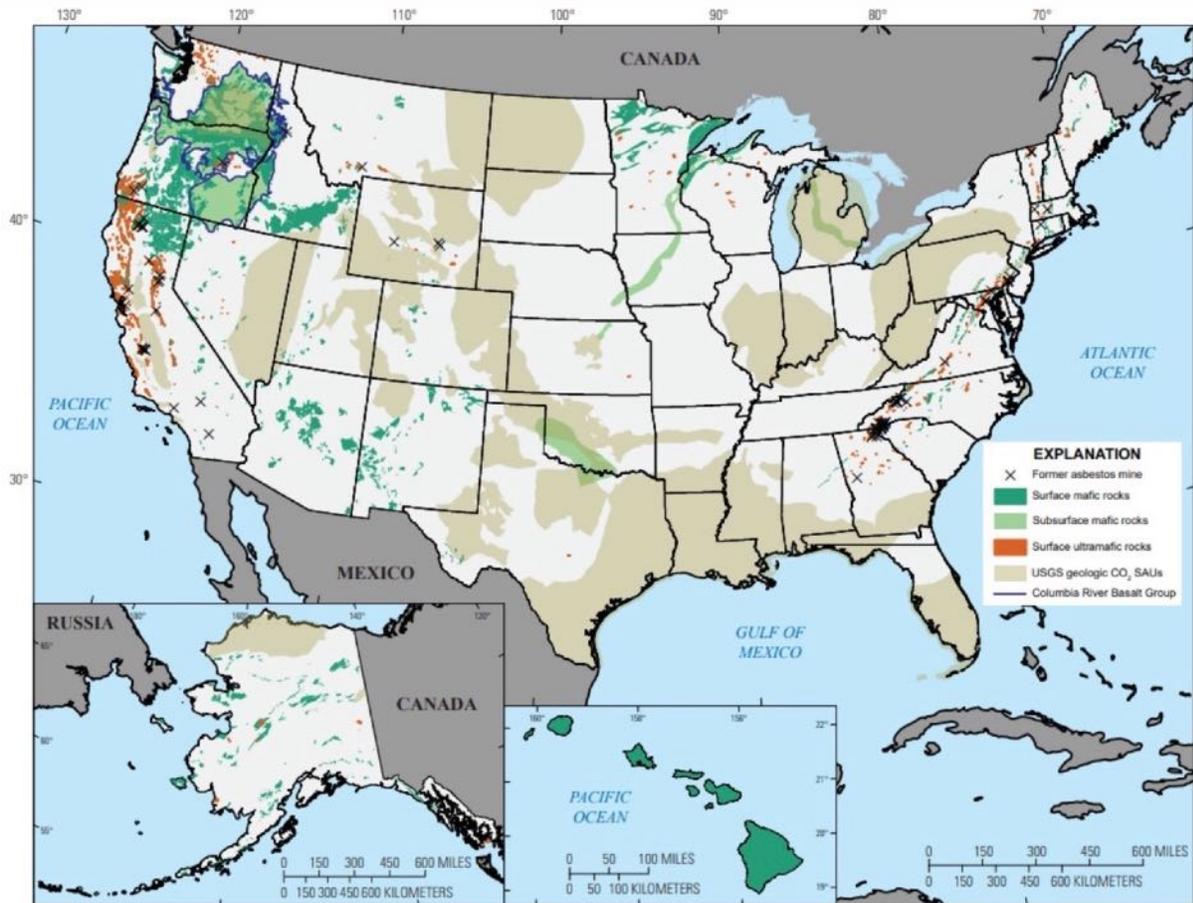


Dependence of olivine (Fosterite) dissolution on pH
 Figure from Hartman et al (2013)

The current average pH of ocean water is 8.1 while that of soil is 4 to 6. As can be seen, **olivine dissociates over ten 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 and Eastern US region. 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.

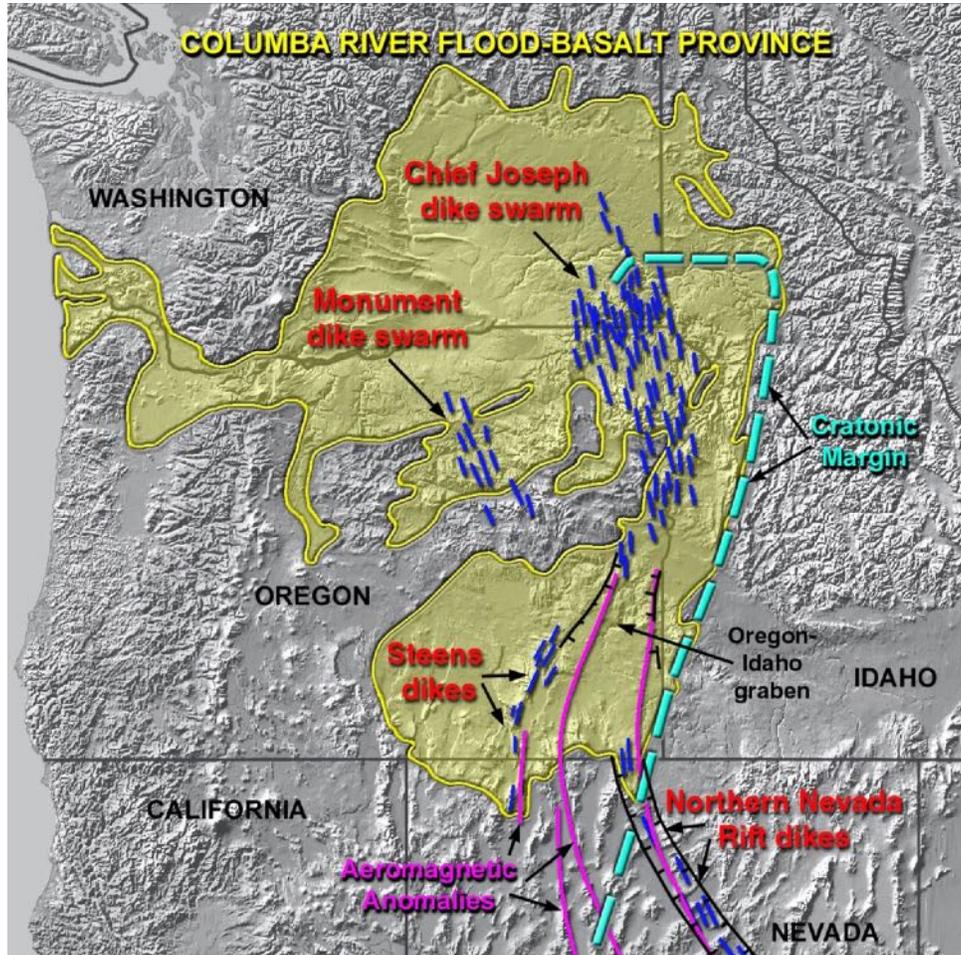


Ultramafic rock deposits in the U.S. The names of these sites are shown below.



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.



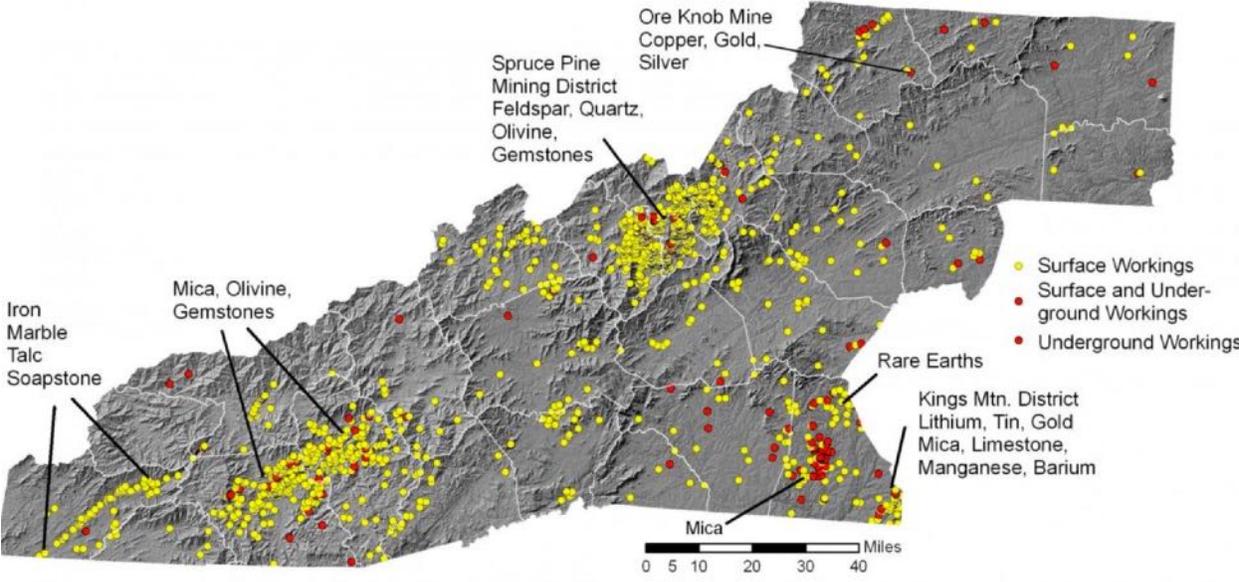
Columbia River Flood Basin

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



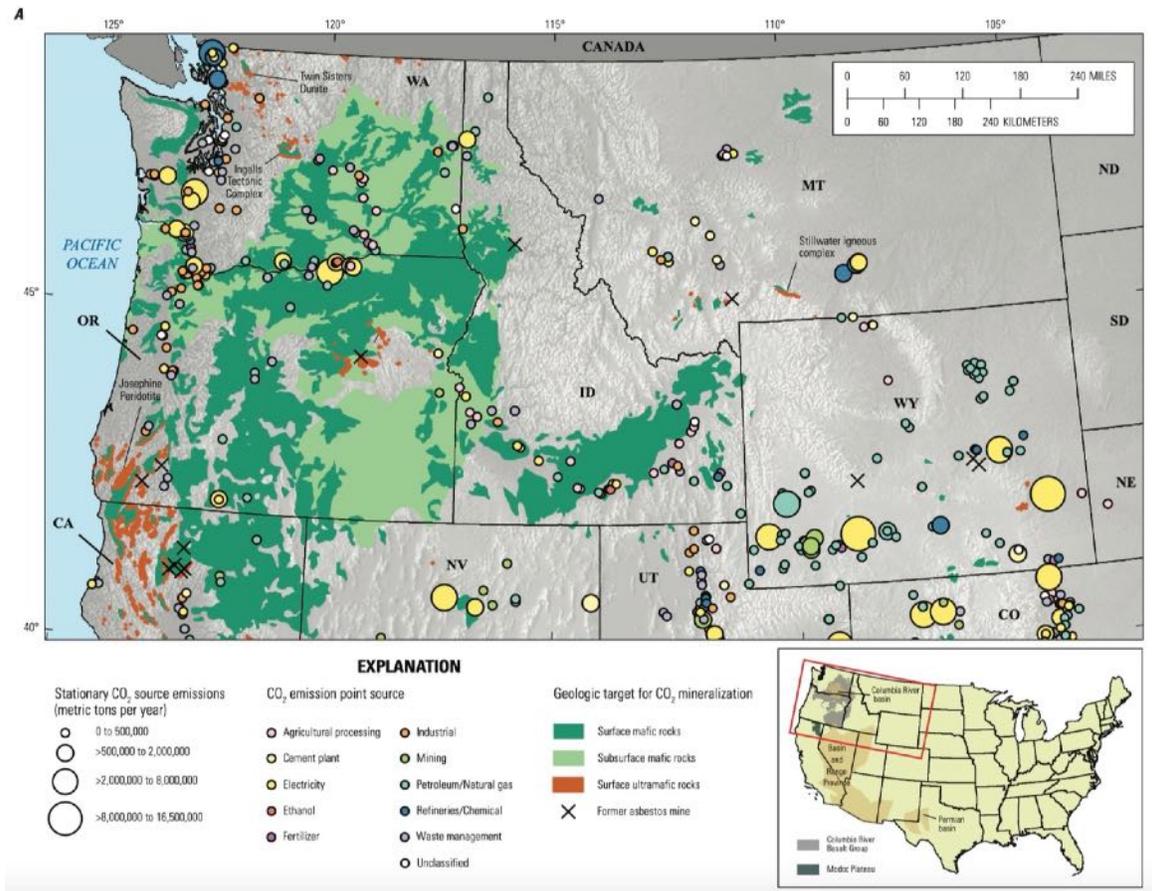
Credit: US Department of Energy/National Academies of Sciences, Engineering, and Medicine. Map of basalt formations (red) at and near the surface of the US that would be suitable for CO₂ sequestration.

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 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) **and Twin Sisters, WA**.

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.

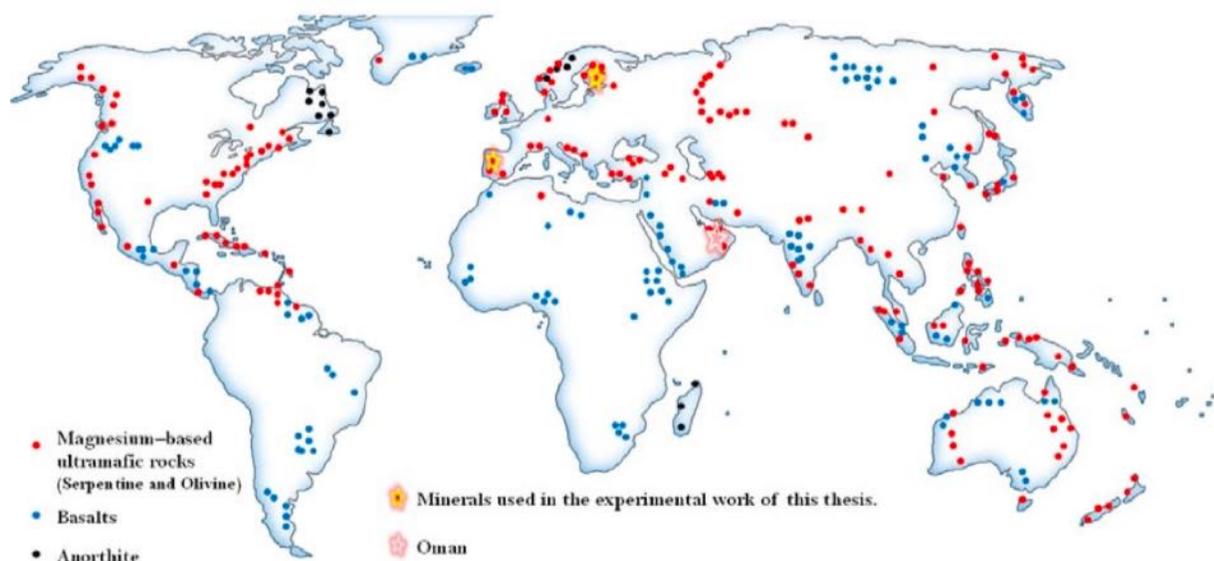
The table above (Kramer, 2020) showed that Norway is by far the greatest commercial producer of olivine at 6,300 thousand metric tons per year versus 90 thousand metric tons for the US.



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.

Where are the Olivine Deposits Worldwide?

The following map shows the location of ultramafic rocks, olivine and serpentines, throughout the world (Romanov, 2015)



A detailed list of worldwide location of ophiolites is present in **Appendix C. Worldwide Ultramafic Mining Sites and Companies** and shows many additional sites.

Weathering by Type of Land

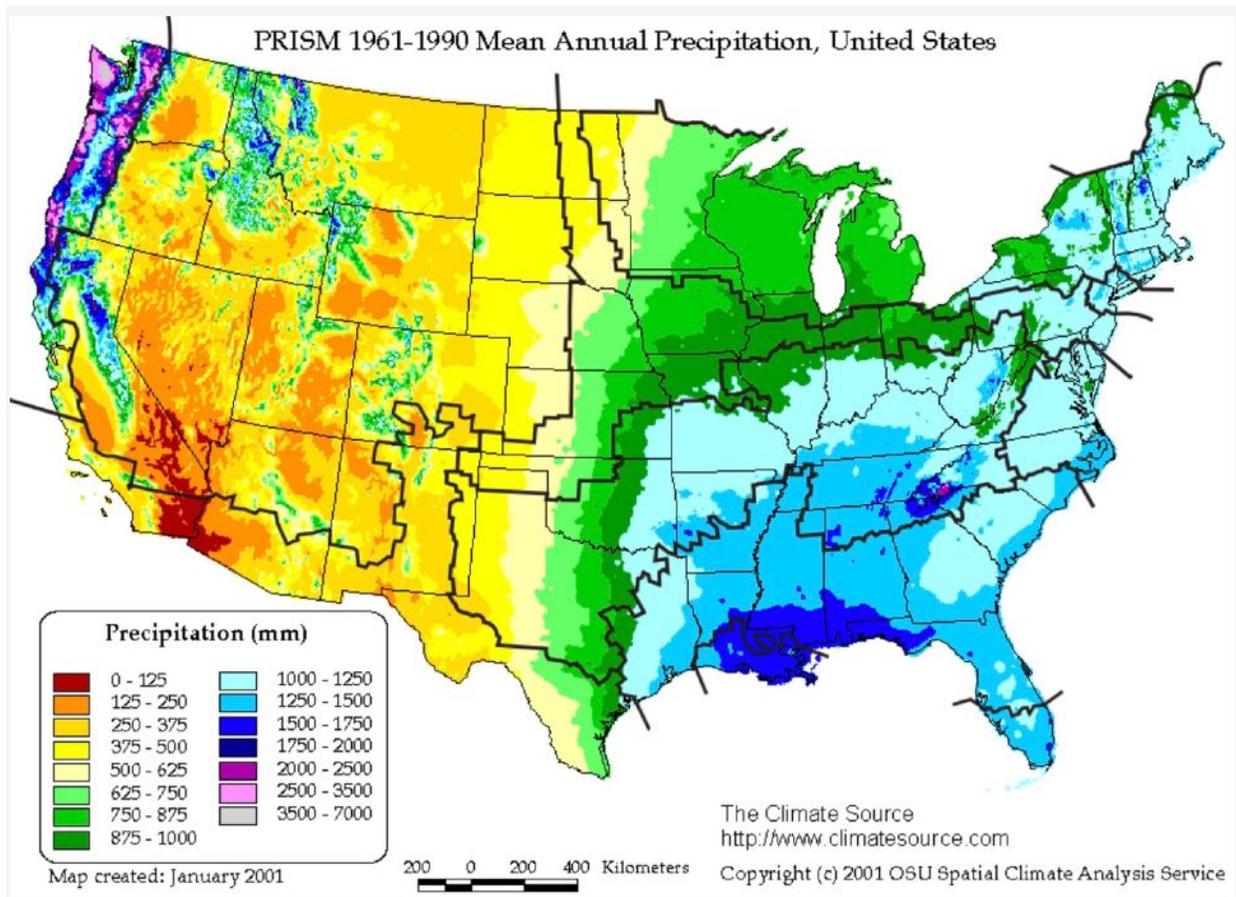
Weathering takes place faster in tropical and sub-tropical regions. But by how much? The following Table 3 is taken from Hartman and Kempe (2008) based on studies by Ludwig (1998).

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

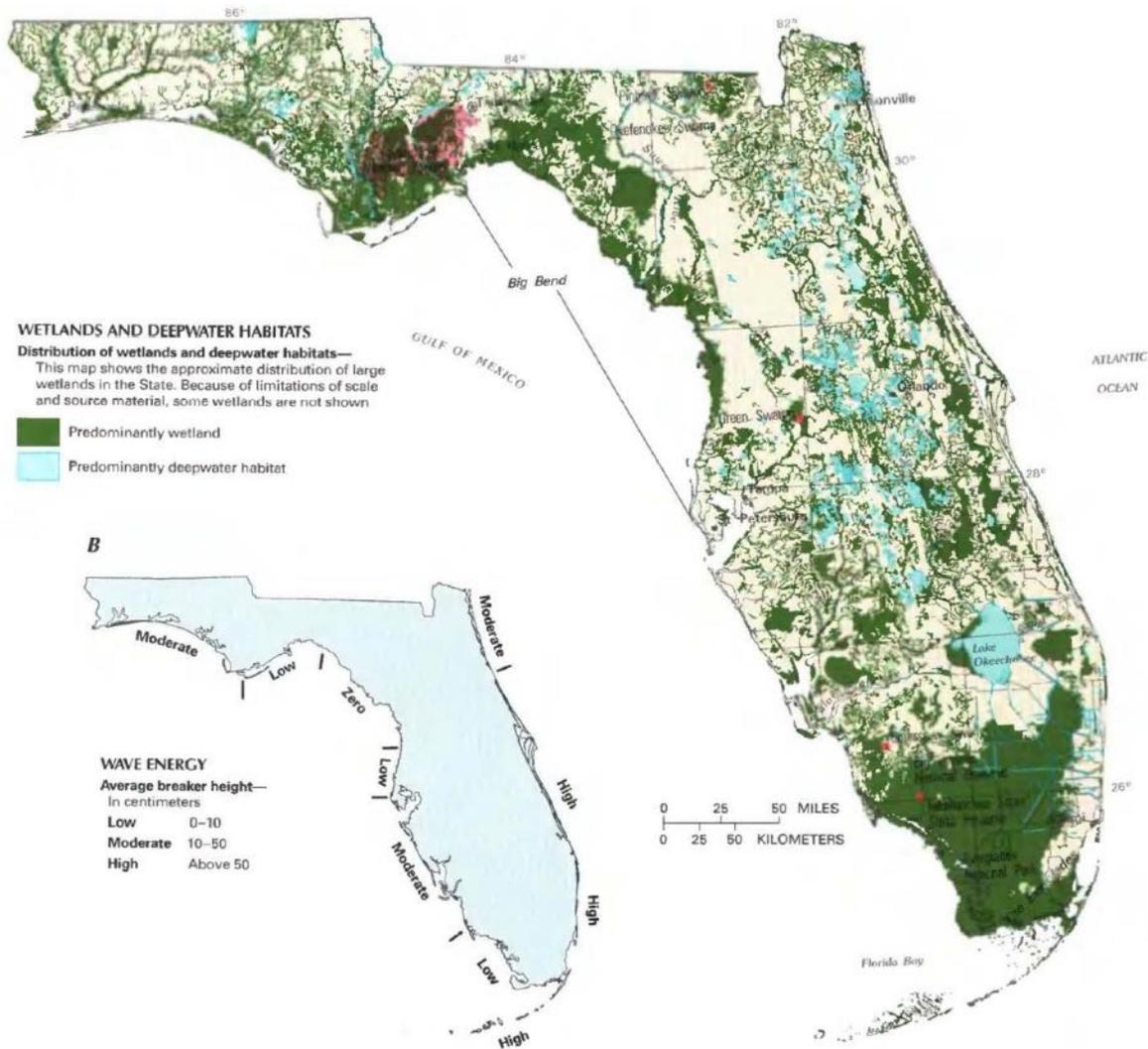
	Area 10 ³ km ²	CO ₂ consumed 10 ⁶ t C a ⁻¹	CO ₂ consumed t C km ⁻² a ⁻¹
Polar (without ice)	3,892	3.4	0.9
Tundra and Taiga	23,232	33.5	1.4
Temperate dry	9,635	4.4	0.5
Temperate wet	16,918	48.4	2.9
Tropical dry	21,790	15.1	0.7
Tropical wet	24,919	128.1	5.1
Desert	5,940	0.4	0.1

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 try 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 be 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 Humprey 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 and rainfall**, 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 $0.58\text{--}2.54 \times 10^6$ mol/km²/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 $1.3\text{--}3.4 \times 10^6$ mol/km²/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 (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, calls for innovation in the industrial sector, such as grinding and milling technology **powered by renewable energy sources (solar, wind, microreactors or small nuclear molten salt reactors (MSRs)**, 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 and agencies 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.TheComingsFoundaton.org -> 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 which 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.

c) **The DoD Microreactor Initiative** In 2018 the Department of Defense issued a *Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations*. The DoD manages 500 installations, and this uses 21% of the total Federal energy consumption. The Micro-reactors were designed with island-mode operations, black-start capabilities, an ability to protect against severe natural phenomena as well as man-made physical and cyber security threats, and to operate for several years without the need to shut down for refueling. Small modular reactors, defined as less than 300 MWe, offer the ability to contribute to DoD missions The deployment of the first micro-reactor was expected to take between 5 to 10 years. Thus, it could be ready by 2028 or sooner, a time frame that makes it suitable to provide the power for grinding at the Twin Sisters facility (see below).

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 dissolve 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 ground basalt, an abundant, weatherable Ca- and Mg-rich rock, is feasible at large scale with existing farm equipment.

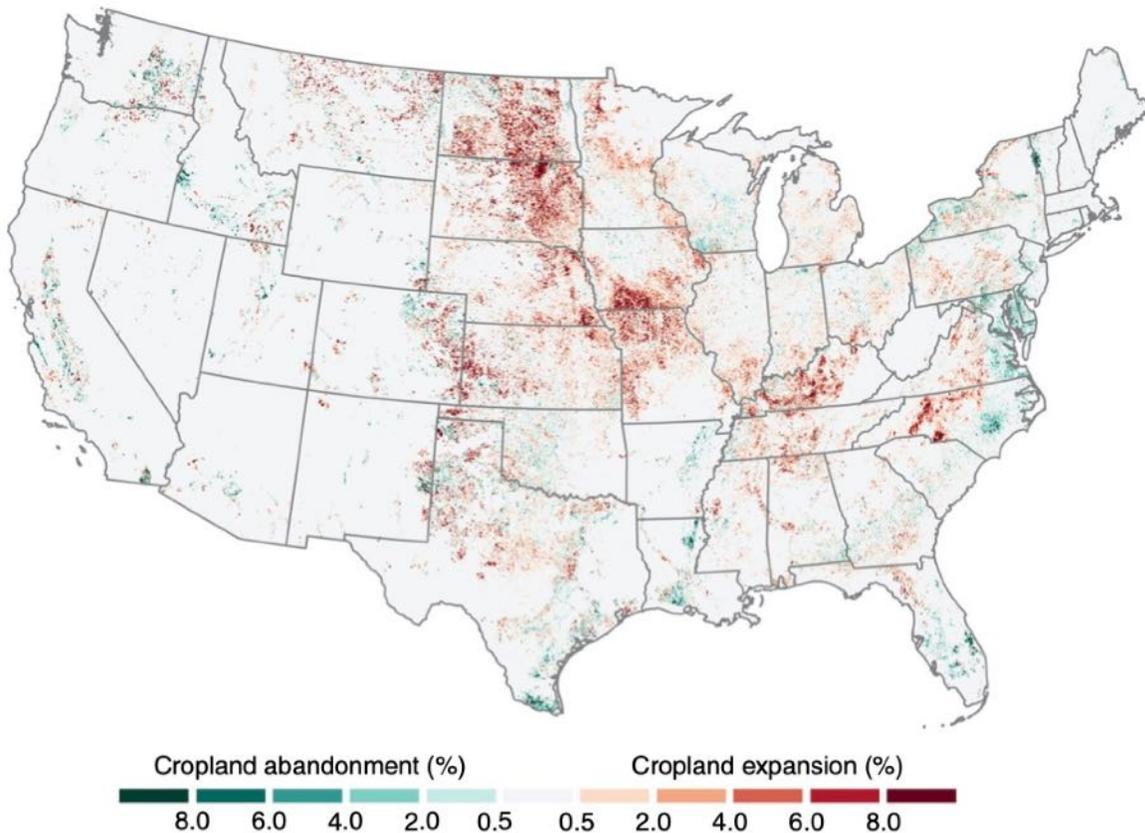
Silicon Enhancement of Soil Enhanced weathering strategies not only capture carbon but could also help restore soils and resupply impoverished reserves of trace elements important for human nutrition and crop production (Guntzer, et al 2012). The discovery of **silicon transporters** in several plants 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.

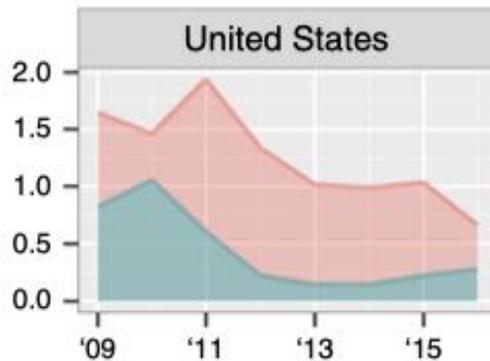
An example of the use of crushed basalt in improving crop yields came from sugarcane trials with crushed basalt applications in excess of 20 t/ha in combination with standard NPK fertilizer treatments **increased yields by up to 30%** over five successive crops on the highly weathered soils of Mauritius 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**. They observed that some of this 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.



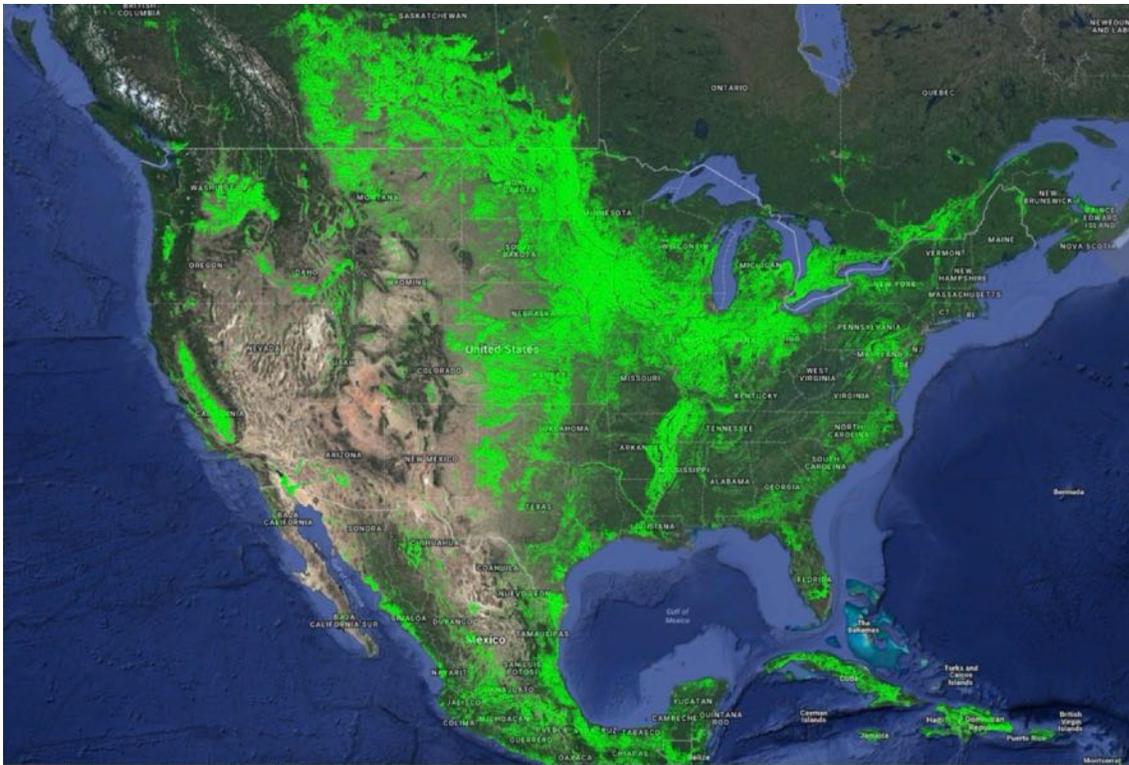
This figure summarizes the ratio of cropland abandonment (green) versus cropland expansion (red).

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. **If some of the newly converted areas, with the least disruption of wildlife, can be shown to have lower than average rates of crop production, they would be good candidates for EW.** 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 relevant would be the **spreading of ground olivine, serpentine, or basalt on the abandoned cropland simply to sequester CO₂ independent of improving cropland.**

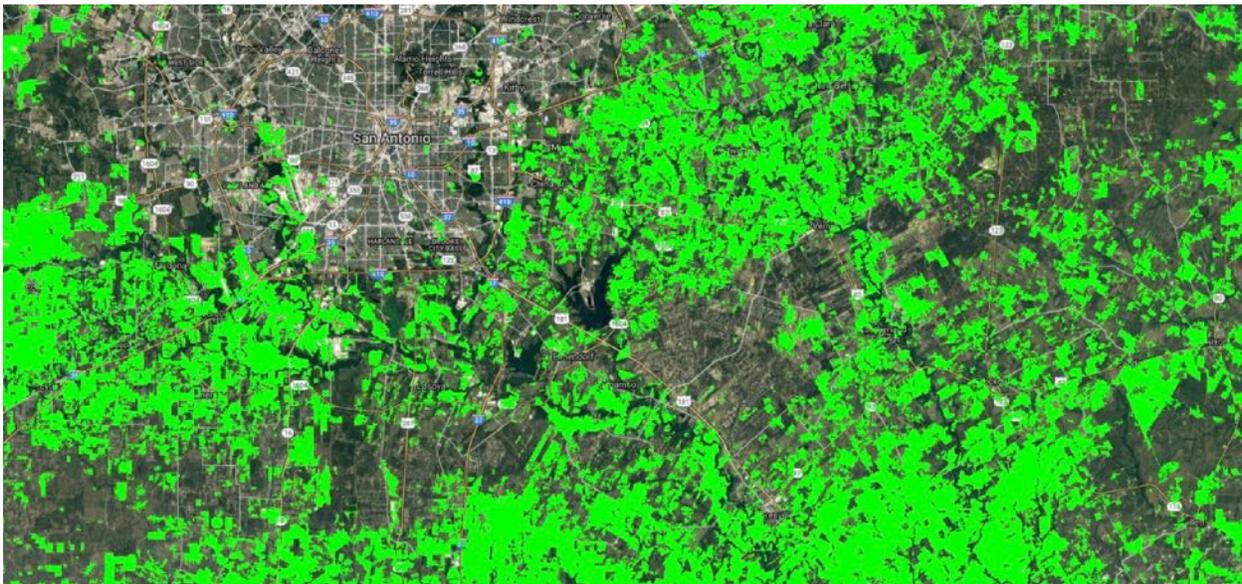
Non-cropland in the US The above showed the abandoned cropland in the US. The real issue is how much non-forest non-cropland is there in the US? The following map shows the cropland in the US. By default, also shows the non-cropland, which is extensive.

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; McQueen et al, 2020)

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 600°C to 900°C 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

Ex-situ Sequestration

During WWII there was considerable interest in using ultramafic rocks as a source of magnesium and much research was devoted to enhancing this process. Later, the same techniques were used to enhance the carbonation or CO₂ uptake of these rocks especially as it relates to removing CO₂ from flue gas for purposes of combating the release of CO₂ by industrial processes.

The most studied mineral for *ex-situ* carbon mineralization was **olivine**. It is abundant, has a high reaction rate, and exhibits little passivation (coating). While the optimum temperature for carbon mineralization of olivine is ~185 °C. (O'Connor 2005) **it can also be used without this pretreatment**. However, these *ex situ* approaches with their requirement for mining, grinding and transportation are more expensive than the projected cost of direct air capture of CO₂ and *in situ* storage, and more expensive than CO₂ storage in subsurface basalt domes. As a result, the cost of *ex situ* carbon mineralization is several fold higher than CO₂ injection and sequestration into subsurface reservoirs (NAS, 2019). A disadvantage is that sites suitable for *in situ* sequestration are somewhat limited or undeveloped (see section on *in situ* sequestration).

The added conclusion that that the dissolution rate of ultramafic rocks in native soil is several fold slower than for laboratory studies (see below) would seem to count against this technique. However, there are a number of unique advantages of *ex situ* sequestration that make up for these disadvantages. These include the **improvement of croplands production and combating ocean acidification**. In addition, because of the wide availability of olivine, basalt and serpentine deposits, *ex situ* sequestration and improvement of croplands can be done in many countries

Relative to cropland improvement, EW will become a valid alternative to supply phosphorus or potassium but also further nutrients, with potentially important local impact on food security. Because of limited supply of current fertilizers, alternative fertilizer for certain regions needs to be developed to enhance productivity. This is especially true for Africa.

The subject of *ex situ sequestration* can be broken down into 11 areas:

- I. **Olivine Dissolution: Laboratory Studies**
- II. **Olivine Dissolution: Field Studies on Cropland or Simulated Cropland**
- III. **Serpentine Dissolution: Laboratory Studies**
- IV. **Serpentine Dissolution: Field Studies on Cropland or Simulated Cropland**
- V. **Basalt Dissolution: Laboratory Studies**
- VI. **Basalt Dissolution: Field Studies on Cropland or Simulated Cropland**
- VII. **Wollastonite Dissolution: Field Studies on Cropland or Simulated Cropland**
- VIII. **Concurrent Grinding**
- IX. **Olivine: The Potential Role of Electrolysis**
- X. **Serpentine: The Potential Role of Electrolysis**
- XI. **The Koorneef et (2009) Study**
- XII. (XII is covered in the section below on Ocean Alkalinity Enhancement, OAE)

I. Olivine Dissolution: Laboratory Studies

Olivine is a nesosilicate, or orthosilicate, mineral with the general formula $(\text{Mg,Fe})_2\text{SiO}_4$. The olivine group consists of **forsterite** (Mg_2SiO_4) and **fayalite** (Fe_2SiO_4). **Olivine dissolves quickly in comparison to other silicate minerals.** At Earth surface temperatures, olivine dissolution usually occurs stoichiometrically. The general reaction for olivine, specifically **forsterite**, dissolution is



During WWII there was considerable interest in using ultramafic rocks as a source of magnesium and much research was devoted to enhancing this process. Later, the same techniques were used to enhance the carbonation or CO_2 uptake of these rocks especially as it relates to removing CO_2 from flue gas.

The following Table 1 from Azadi et al (2019) illustrates the many techniques used to increase the dissolution rate ultramafic rocks, especially serpentine. The references cited can be found in the Azadi article.

Table 1. Strategies and methods used to increase the speed and efficiency of the carbonation reaction.

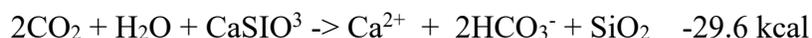
Strategy	Reference	Method	Benefit
Mechanical pretreatment of serpentine rock	[62–66]	High-energy crushing and grinding	Increases the overall specific surface area of the minerals, i.e., the surface per unit mass available for Mg/Ca-extraction
Thermal activation of the hydrated Mg-silicate serpentine	[67–73]	Heating the mineral to 630 °C or above	Destabilises the crystal lattice, thus increasing the reactivity of the mineral Heat activation also creates an even higher specific surface area [46]

Increasing reaction temperatures	[74,75]	Applying operating temperatures above 100 °C	Accelerate the kinetics of the reaction
Increasing reaction pressure	[76,77]	Applying operating CO ₂ pressure above 150 bar	Increases the activity of protons needed for metal extraction. Also counteracts the low solubility of CO ₂ at high temperature
Using organic and inorganic chemicals	[61,78–80]	Adding different substances as catalysts and additives to the reactants	Enhances the kinetics of the carbonation process and precipitation of magnesium carbonate
Applying New double-step and multistep process designs	[81]	The operating conditions are changed between the different stages	Allows to control and promote extraction and precipitation separately
Direct capture of CO ₂ from flue gas stream	[81,82]	Capturing CO ₂ directly from a flue gas stream by mineral carbonation	Provides a simple and straightforward process route

Some of these and other papers are reviewed below. The literature on the use of basalt on the soil is also relevant since although the rate of dissolution of basalt is also lower than that of olivine and yet there are number of studies on the use of basalt on croplands.

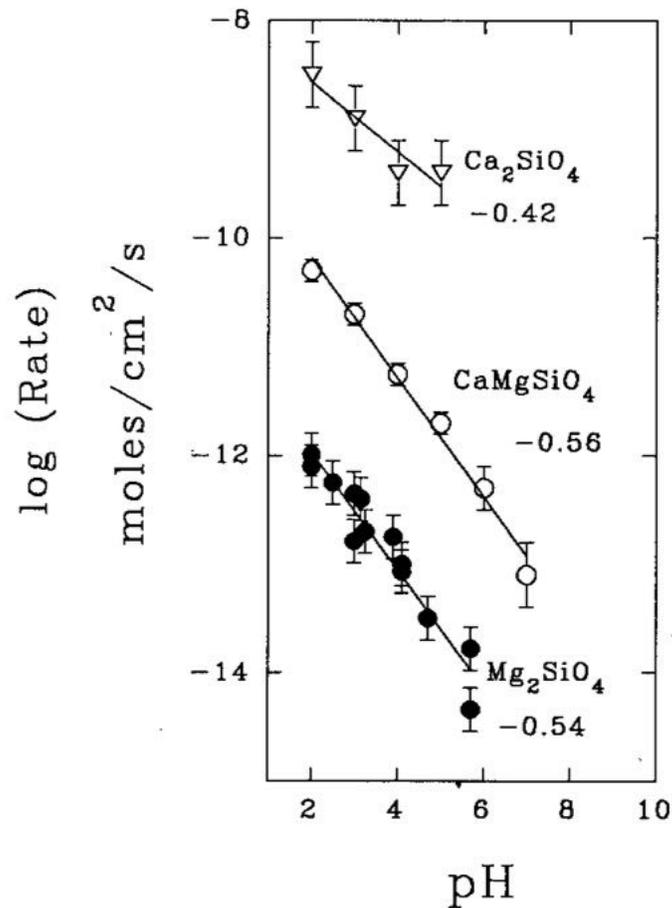
Bates and Morgan (1985) The rate of **chrysoile olivine** dissolution over five days was studied in constant-pH, batch suspensions at 25°C. After the first day, release of Mg occurred at a constant rate and exhibited a fractional dependence on pH, $[H^+]^{(0.24)}$. Interpreted in terms of a site-binding model for adsorption of protons on the surface. This fractional dependence implies that the rate is **limited by a chemical reaction involving less than one adsorbed proton per Mg released** into solution. The actual magnitude of the rate ($10^{-15.7}$ mol/cm²/s at pH 8) supports this interpretation. The inorganics NO₃⁻, Cl⁻, HCO₃⁻ and SO₄⁻² and the organics catechol and oxalate affected the rate of Mg release only during the initial 12 to 24 hours of each experiment. Silica release was linear from the outset of each experiment but showed no definite pH dependence.

Seifritz (1990) In a brief note in Nature, Seifritz noted that the combination of CO₂ with calcium silicate is slightly exothermic while most other reactions are endothermic. Thus,



He suggested that pressurized CO₂ could be pumped into a closed container containing a suspension of pulverized silicates in water. The resultant hard water and SiO₂ could be drained into the deep ocean and the process repeated. He felt that experimental work would be necessary to determine if this scheme was practical.

Westrich, et. al. (1993) examined the dissolution rates of three types of olivine varying by whether these silicates were complexed with Ca₂ or Mg₂ or intermediate CaMg. The dissolution rates by pH at 25°C are shown as follows.



Dissolution rate of Larnite olivine Ca_2SiO_4 ,
 Montecellite olivine MgCaSiO_4 and
 Fosterite olivine Mg_2SiO_4 by pH at 25°C.

Note the progressively more rapid dissolution rates progressing from Mg_2 to CaMg to Ca_2 silicates. The dissolution rate of Larnite olivine, Ca_2SiO_4 , was 4 orders of magnitude faster than Fosterite olivine. If this is a common mineral it could be ideal for CO_2 sequestration EW.

Kojima et al, (1997) Proposed the absorption and fixation of CO_2 using calcium and magnesium silicates. The amounts of pulverization energy of wollastonite (CaSiO_3) and olivine sand were evaluated using industrial data of their pulverization. It was concluded that the CO_2 absorption by rock weathering was one of the most promising measures for the CO_2 problem.

Jonckbloedt (1998) A kinetic model for the **dissolution of olivine in sulphuric acid** at elevated temperatures was presented. The effects of temperature, **grain size** fraction and olivine amount on the neutralization rate were quantified by carrying out a range of complete-neutralization experiments. Under natural weathering conditions the dissolution rate of olivine was controlled by rates of surface reactions. Under these conditions dissolution was kinetically controlled by surface reactions. For the interpretation of the experimental data, a measure of

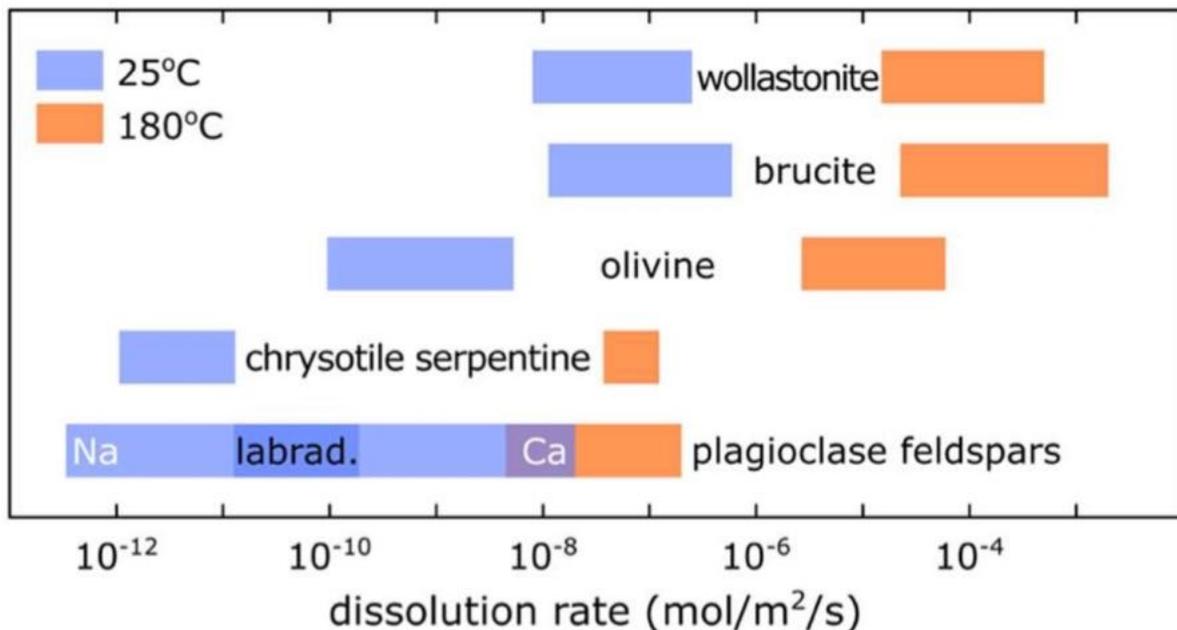
the hydrogen ion activity was required. The equation used was validated for the dissolution of Norwegian olivine, with **grain sizes from 63 to 300 μm**, in sulphuric acid at temperatures ranging from 60 to 90°C.

Chen, et al (2000) Dissolution experiments with **forsteritic olivine** were conducted in a batch reactor at a temperature of 65°C between pH 2 and 5. As temperature increased, the dissolution rate of forsteritic olivine becomes more pH-dependent, which is consistent with a surface protonation model for dissolution. The activation energy of dissolution, E_a has been estimated based on our results and literature data at 30 ± 4 kcal/mol.

Rosso and Rimstidt, (2000) The authors reviewed 10 studies of dissolution rates of olivine at up to 90 °C and a full range of pH. The **dissolution rates ranged from 1.3×10^{-11} to 7.6×10^{-13} mol/cm²/s**

Albany Research Center (ARC) (2000 to 2005). This pioneering work on CO₂ dissolution and mineralization of ultramafic rocks for the purpose of greenhouse gas emission control, included **over 700 kinetic tests** conducted at the **Albany Research Center (ARC)** in the US (now part of the National Energy Technology Laboratory) by O'Connor and coworkers. Much of this work was initially directed toward the extraction of Mg and improvement of *in situ* CO₂ storage, **not the improvement of using ultramafic rocks on cropland**. Nevertheless, these studies could have relevance to the latter.

The following diagram lets one get a feel for the values and units of different dissolution rates at two different temperatures.



Dissolution rates of magnesium- and calcium-rich minerals at 25 °C (blue) and 180 °C (orange). The plagioclase feldspars (NaAlSi₃O₈ to CaAl₂Si₂O₈) are a solid solution between a sodium-end-member (albite NaAlSi₃) and a calcium-end-member (anorthite CaAl₂Si₂O₈) indicated as **Na** and **Ca**. The most common plagioclase feldspar basalt is

labradorite (labrad.). Wollastonite = CaSiO₃. Brucite = Mg(OH)₂ Olivine = (Mg,Fe)₂SiO₄ Chrysotile serpentine = Mg₃Si₂O₅(OH)₄ (Figure from Kelemen et al, 2019) modified from National Academies of Sciences Engineering Medicine, NAS (2019).

Note the units are (**mol/m²/s**) and the significant increase in dissolution at 180°C.

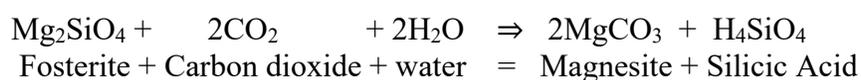
The conditions used of high temperature (185°C), high pCO₂ pressure (150 atm), and high salt concentrations play a role in the faster rates of dissolution compared to those quoted by other investigators.

O'Connor, W.K.O. et al (2000). The ARC (Albany Research Center) (in Albany Oregon) have focused tests on *ex situ* mineral carbonation in **an aqueous system**. The process developed at ARC utilizes a slurry of water mixed with a magnesium silicate mineral, **olivine** [forsterite end member (Mg₂SiO₄) or **serpentine** (Mg₃Si₂O₅(OH)₄).

Results of the baseline tests, conducted on ground products of the natural minerals, have been encouraging. Tests conducted at ambient temperature (22°C) and subcritical CO₂ pressures (below 73 atm) resulted in **very slow conversion to the carbonate**. However, when **elevated temperatures and pressures** are utilized, coupled with continuous stirring of the slurry and gas dispersion within the water column, significant reaction occurs within much shorter reaction times. Extent of reaction, as measured by the stoichiometric conversion of the silicate mineral (olivine) to the carbonate, is roughly 90% within 24 hours, using distilled water, and a reaction temperature of 185°C and a partial pressure of CO₂ (PCO₂) of 115 atm. Recent tests using a bicarbonate solution, under identical reaction conditions, have achieved roughly 83% conversion of heat treated serpentine and 84% conversion of olivine to the carbonate in 6 hours. The results from the current studies suggest that reaction kinetics can be improved by pretreatment of the mineral, catalysis of the reaction, or some combination of the two. Future tests are intended to examine a broader pressure/temperature regime, various pretreatment options, as well as other mineral groups.

The focus of these experiments was an aqueous process using hydrochloric acid (HCl) to leach serpentine and produce magnesium chloride (MgCl₂). This reaction was well developed by the Tennessee Valley Authority and U.S. Bureau of Mines during World War II as part of an alternative process for **the production of magnesium metal**. However, the complexity of this process led the ARC group to consider an alternative mineral carbonation process, the **direct carbonic acid route**, a new method for which DOE has filed a report of invention (O'Connor, et al., 1999).

In the **direct method** with carbonic acid, CO₂ is dissolved in a slurry of water and mineral reactant, such as **forsterite** (Mg₂ SiO₄). The CO₂ reacts with water to form carbonic acid (H₂CO₃), which dissociates to H⁺ and HCO₃⁻. Reaction of the carbonic acid with the mineral consumes most of the H⁺ and liberates equivalent amounts of cations (Mg²⁺) and bicarbonate (HCO₃⁻), which react to form the solid carbonate mineral magnesite (MgCO₃). Because this slurry is under high PCO₂, the carbonic acid is continuously regenerated as it is consumed, maintaining the reaction sequence until the mineral reactant is exhausted. The theorized reaction equation follows.



Several ultramafic complexes in North America contain sufficient quantity of magnesium silicate mineral to provide raw materials for the mineral carbonation of all annual CO₂ emissions for many years (Goff, et al., 1997).

Particle size was recognized as a major factor determining reaction rate and extent of reaction, because most mineral dissolution reactions are surface controlled. Initial carbonation tests conducted **on serpentine ground to -37 microns (37 um or less) resulted in much lower extent of reaction than identical tests conducted on olivine**. For example, when olivine was ground to -37, no pre-treatment, 185°C for 24 hours gave 91 percent conversion. When serpentine was treated the same way, it resulted in only 34 percent conversion.

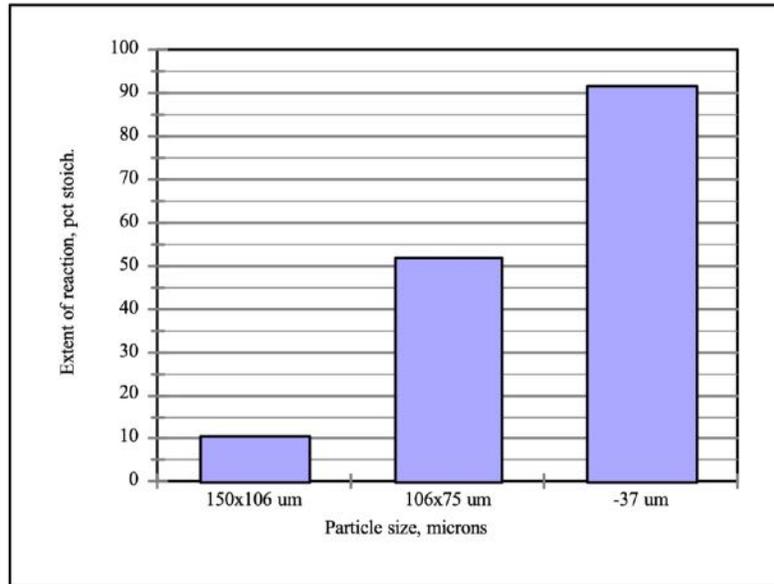


Figure 2.- Effect of particle size on the olivine carbonation reaction.
Test conditions: 24 h, T = 185°C, P_{CO₂} = 115 atm, in distilled water.

The hydrated state of the serpentine was expected to have a negative impact on the carbonation results, so thermal gravimetric analysis (TGA) and differential thermal analysis (DTA) were conducted on the serpentine head sample to determine the appropriate temperature for removal of all water. The endotherms on the plot signify three separate stages of water removal. **Desorption of adsorbed water was complete at 160°C**, while evolution of water of crystallization (dehydration) was accomplished at 374°C. However, de-hydroxylation (evolution of constitutional water, or hydroxyl groups) required a temperature of 614°C. Subsequent heat treatments were conducted for 2 hours at 650°C, resulting in a consistent weight loss of 11 wt pct.

It was recognized that oxidation of the magnetite in the serpentine during heat treatment could potentially form a **passive layer of hematite (Fe₂O₃)** on the mineral surface, inhibiting the carbonation reaction. Thus, heat treatments were conducted in oxidizing (air) and non-oxidizing (CO₂) atmospheres to investigate this possibility. Analyses of the heat-treated products confirm that oxidation to hematite did occur in heat treatments conducted in air, while oxidation was limited during heat treatments conducted in CO₂. XRD analysis also confirms that the **serpentine was transformed to forsterite as a result of the heat pretreatment**.

The effect of the heat treatment atmosphere on the **serpentine carbonation** reaction was minimal for the tests conducted in distilled water (see figure 5 below), although heat treatment in general improved the extent of reaction from 34% to over 57%. However, the effect of the heat treatment was significant for the carbonation tests conducted in the modified solution (0.5 M NaHCO₃, 1 M NaCl). Extent of reaction increased to over 83% for the **serpentine heat treated** in CO₂, compared to 41% extent of reaction for the serpentine heat treated in air; both of these results were achieved in just 6 hours. In fact, heat treatment of the serpentine in CO₂ resulted in an extent of reaction which virtually duplicated that achieved for olivine in the modified solution chemistry.

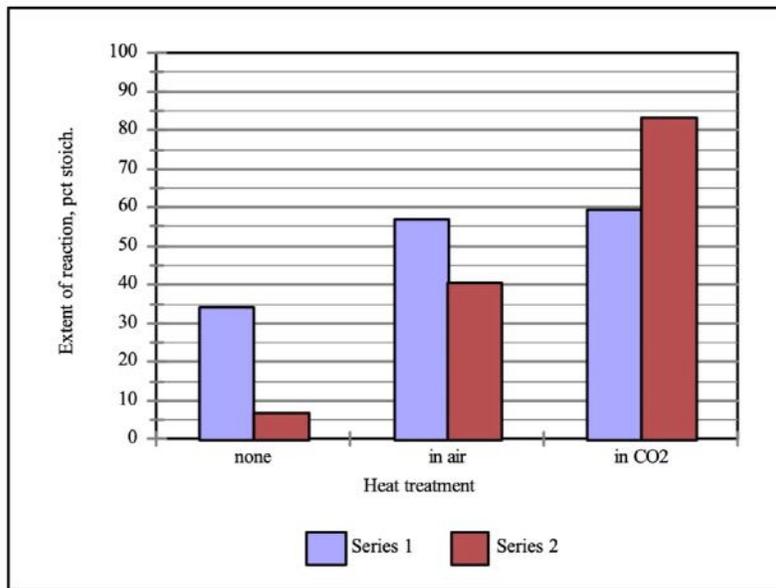
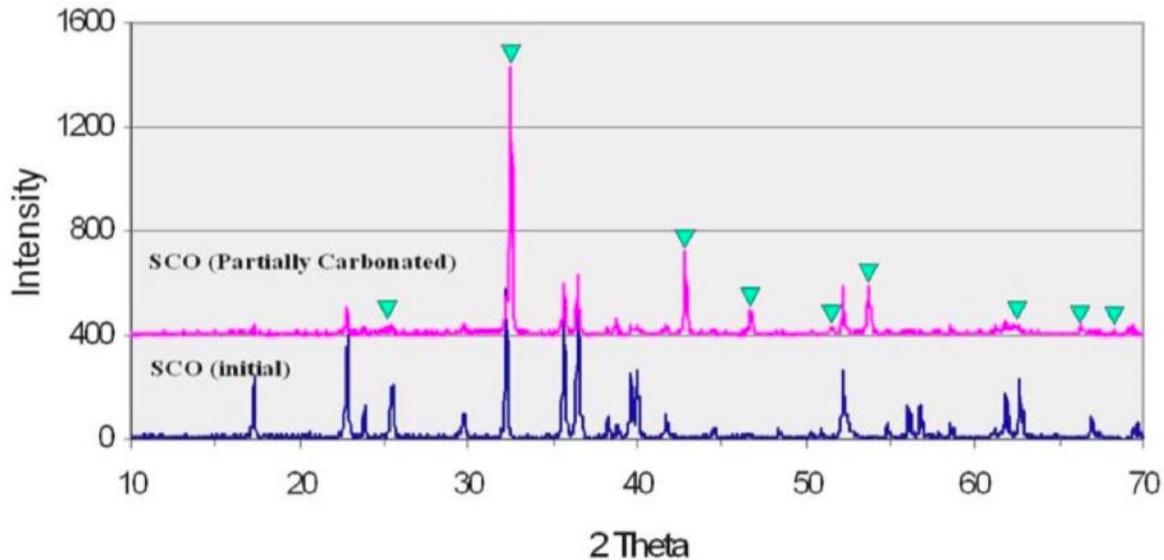
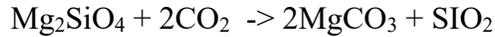


Figure 5.- Effect of heat treatment on the serpentine carbonation reaction, in two series: (1) 24 h, T = 185°C, P_{CO₂} = 115 atm, in distilled water; and (2) 6 h, T = 185°C, P_{CO₂} = 115 atm, in 0.5 M NaHCO₃, 1 M NaCl.

The results from these studies confirm that olivine and serpentine are equally amenable to the direct carbonation process, although **serpentine requires heat pretreatment**.

Béarat, H. e al (2003, 2006); McKelevy et al (2003) This study was from the Science and Engineering of Materials Graduate Program Arizona State University in Tempe. They pointed out that aqueous-solution olivine carbonation was a **complex process** associated with passivating silica layer formation and cracking, silica surface migration, olivine etch pit formation, transfer of the Mg and Fe in the olivine into the product carbonate, and the nucleation and growth of magnesite crystals on/in the silica/olivine reaction matrix. These phenomena occur in concert with the large solid volume changes that accompany the carbonation process, which can substantially impact carbonation reactivity.

The following X-ray powder diffraction analysis showed that the only crystalline product formed during mineral carbonation is magnesite, MgCO₃, resulting from the reaction of olivine with CO₂.



The major product magnesite peaks are identified by the green triangles.

This suggests that this type of analysis could be used to follow the dissolution of olivine in field studies.

The sequestration reaction conditions were 1 M NaCl + 0.64 M NaHCO₃ at T ≈ 185 °C and P CO₂ ≈ 135 bar. A large-scale atomic-level simulation of the reaction zone suggests that the silica-rich passivating layer possesses a “glassy” but highly defective SiO₂ structure that can permit diffusion of key reactants. **Mitigating passivating layer effectiveness is critical to enhancing carbonation and lowering sequestration process cost.**

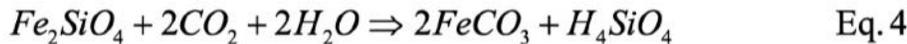
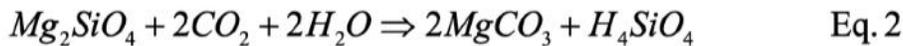
O’Connor, W.K.O. et al (2005). Aqueous mineral carbonation has been studied at the Albany Research Center as a potential option for CO₂ sequestration in collaboration with the Office of Fossil Energy - Mineral Carbonation Study Group of the DOE.

This research has included fundamental studies, resource evaluation, and process development. The studies have focused on the reaction of Ca, Fe, and Mg silicate minerals with gaseous CO₂ **to form geologically stable, naturally occurring solid carbonate minerals.** Process development has progressed in parallel with an economic evaluation, with an initial overall cost estimate of ~\$69/ton CO₂. Improved mineral pretreatment and reactor design indicate that costs could be reduced. However, the scale of ex-situ operations, requiring ~55 kt mineral/day to carbonate 100% of the CO₂ emissions from a 1 GW coal-fired power plant, may favor an in-situ methodology. Laboratory studies of *in situ* mineral carbonation showed promise.

The bench-scale grinding operations were conducted wet, to prevent dusting. Similar procedures would likely be necessary at the industrial scale.

This work has focused on the development of an *ex situ* aqueous process to convert magnesium silicate-rich ultramafic rocks and minerals, such as **olivine, serpentine and basalt** to magnesium carbonates by contact with gaseous CO₂ in an aqueous solution. The output was in the form of stable carbonate compounds, such as calcite (CaCO₃), siderite (FeCO₃), and

magnesite ($MgCO_3$). The carbonation reactions for the Mg^{2+} , Ca^{2+} , Fe^{2+} silicates are shown below.



A key theoretical yardstick for the value of a particular mineral reactant for mineral carbonation is its **carbonation potential**. The carbonation potential for a rock or mineral was described by Goff et al. (2000) regarding the hydrated magnesium silicate **serpentine** - $Mg_3Si_2O_5(OH)_4$. Goff used the molar concentration of Mg in a serpentine sample to calculate the theoretical number of moles of CO_2 that could be converted to magnesite, $MgCO_3$, by reaction with the serpentine. By this definition, **a low R_{CO_2} is preferable to a high R_{CO_2}** . The carbonation reactivity of a rock or mineral is dependent on numerous factors, including the mineral composition, pretreatment, and solubility at the specific carbonation conditions of time, temperature, and pressure.

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, Fe^{2+} and Mg in the feed, and is defined here as the **mass ratio of rock or mineral necessary to convert a unit mass of CO_2 to the solid carbonate**. By this definition, **a low R_{CO_2} is preferable**. The reactivity of the various materials was measured as the **extent of reaction, R_x** , or the **percent stoichiometric conversion** of the Ca, Fe and Mg silicates to their carbonate counterparts. **A high R_x is preferable**. ϵ_A = percent weight gain assuming 100% stoichiometric conversion of the available cations to the carbonates. The following Table 1 shows these variables for the different compounds.

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

Rock/mineral group	Mineral	Formula	Concentration, wt pct				$R_{CO_2}^2$	ϵ_A , %	R_x^3 , %
			Feed			Prod.			
			Ca	Fe^{2+}	Mg	CO_2			
Feldspar	Anorthite (An)	$CaAl_2Si_2O_8$	10.3	3.1	4.8	1.9	4.4	23	9
Serpentine	Antigorite (Ant)	$Mg_3Si_2O_5(OH)_4$	<0.1	2.4	24.6	24.2	2.1	47	92
Pyroxene	Augite (Aug)	$CaMgSi_2O_6 + (Fe, Al)$	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_2SiO_4	0.6	44.3	0.3	19.2	2.8	36	66
Olivine (Ol)	Forsterite (Fo)	Mg_2SiO_4	0.1	6.1	27.9	29.7	1.8	56	81
Serpentine	Lizardite (Liz)	$Mg_3Si_2O_5(OH)_4$	0.3	1.5	20.7	16.0	2.5	39	40
Oxide	Magnetite (Mt)	Fe_3O_4	0.6	21.9	0.3	1.5	5.5	18	08
Ultramafic	Talc	$Mg_3Si_4O_{10}(OH)_2$	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_{CO_2} =150 atm; 15% solids; 0.64 M $NaHCO_3$, 1 M $NaCl$.

² Mass ratio of ore necessary to carbonate unit mass of CO_2 .

³ Reaction efficiency, percent stoichiometric conversion of Ca, Fe^{2+} , and Mg cations in silicate feed to carbonate.

There is a great deal of important data in this table. Most of all, it answers the question of the relative value of **serpentines such as antigorite to olivines such as forsterite and fayalite**.

The lower the R_{CO2} and the higher the Rx, the greater that capacity to sequester CO₂. While the rate of dissolution of serpentines may be lower than olivines, the serpentine antigorite had the highest Rx 92, and the second lowest R_{CO2} 2.1 of all the compounds including the common Mg olivine forsterite which had a Rx of 81, and a R_{CO2} of 1.8 (the lowest). These studies indicate **that in addition to olivines, serpentines also qualify as excellent resources for EW.**

Second, these studies show the **wide range of ultramafic rocks that can be used for EW.**

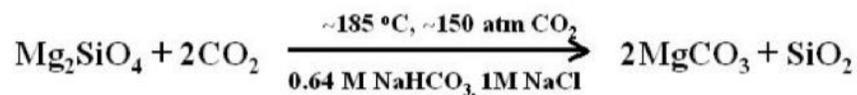
Third, they show that even though ground up **basalt** has frequently been used for EW studies on croplands, **it is actually among the least efficient in CO₂ sequestration of the ultramafic rocks listed.**

This showed that the minerals with the **lowest R_{CO2}** were **olivine as forsterite (1.8), olivine as fayalite (2.8).** It is also important to note that **serpentine** as antigorite (2.1) and serpentine as lizardite (2.5) talc (2.8) and Wollasonite (2.8) also had low levels of R_{CO2}. Of interest basalt had the second highest R_{CO2} (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.**

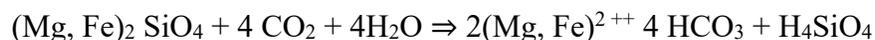
The ultramafic minerals investigated for mineral carbonation generally occur within large ophiolite complexes that are described as remnants of oceanic crust that have been compressed and folded along convergent continental margins. In North America, these ultramafic belts occur along both coasts, rather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

The conclusion of the ARC studies was that the following equation depicted the optimum conditions for carbonation of ultramafic rocks.



These are clearly not suitable conditions for EW on soils. Thus, further studies were required.

Schuling 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, he 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 and the expenses required.

The following two papers are reports of studies by the McKelvey/Chizmeshya group supported by DOE grants and referred to as the **Arizona State University (ASU) studies.**

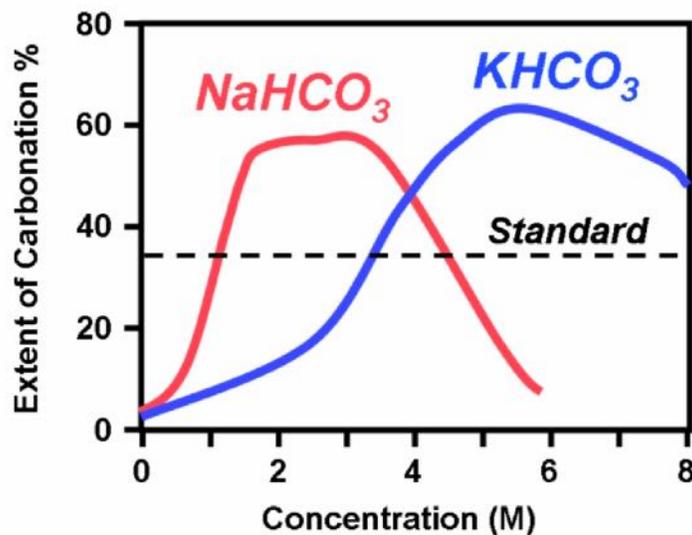
Chizmeshya, McKelvey, et al, (2004) Enhancing carbonation reactivity is key to economic viability of CO₂ sequestration. Recent studies at the U.S. DOE **Albany Research Center** have established that aqueous-solution carbonation using supercritical CO₂ is a promising process; even without olivine activation, 30-50% carbonation has been achieved in an hour. **Mechanical activation (e.g., attrition) has accelerated the carbonation process to an industrial timescale (i.e., near completion in less than an hour), at reduced pressure and temperature. However, this activation cost is too high to be economical and lower cost pretreatment options are needed.**

During the first project year they developed a new **sonication exfoliation** apparatus with a novel sealing system to carry out the sonication studies. They also initiated investigations to explore the potential that sonication may offer to enhance carbonation reactivity. During the second project year, they extended their investigations of the effects of sonication on the extent of carbonation as a function of the following parameters: particle size distribution, the mass of solid reactant, volume fraction of aqueous solution present, sonication power, time, temperature,

and CO₂ pressure. **To date, none of the conditions investigated have significantly enhanced carbonation**

By contrast, high concentration sodium, potassium, and sodium/potassium bicarbonate aqueous solutions have been found to be the most effective solutions for enhancing aqueous olivine carbonation to date. Thus far, they have succeeded in nearly doubling the extent of carbonation observed compared with the optimum procedure previously developed by the Albany Research Center.

The most promising solutions for enhancing carbonation to date have provided substantial increases in extent of carbonation, nearly doubling it. High concentrations of NaHCO₃ (2.5M) and KHCO₃ (5.5M) were found to be particularly effective at enhancing carbonation, with the extent of carbonation again exhibiting a strong dependence on the alkali cation species present. As shown below, the **NaHCO₃ was more effective at lower concentrations than KHCO₃.**



Extent of carbonation of San Carlos Olivine as a function of NaHCO₃ and KHCO₃ concentration after 1h at 185°C, 2200psi of CO₂ and stirring at 1,500 rpm. The dashed horizontal line represents the extend of carbonation using standard ARC conditions.

In their YEAR 2 studies they also demonstrated that the **addition of quartz particles** as an abrasive slurry component significantly enhanced carbonation, further substantiating the importance of particle-particle abrasion in enhancing passivating layer exfoliation and carbonation.

Their goal is to develop the understanding needed to engineer new low-cost carbonation processes that avoid the cost of pretreatment activation. The primary focus is on enhancing passivating layer exfoliation, which has the potential to substantially enhance carbonation without the need for pretreatment activation.

McKelvy, Chizmeshya et al (2006) Carbonation of the widely occurring mineral olivine (e.g., forsterite, Mg₂SiO₄) is a large-scale sequestration process candidate for regional

implementation, which converts CO₂ into the environmentally benign mineral **magnesite (MgCO₃)**. Mechanical activation (e.g., attrition, grinding) has accelerated the carbonation process to an industrial timescale (i.e., near completion in less than an hour), at reduced pressure and temperature. **However, the activation cost is too high to be economical and lower cost pretreatment options are needed.** Herein, they report their second year progress was exploring a **novel approach that offers the potential to substantially enhance carbonation reactivity while bypassing pretreatment activation.**

They discovered that **robust silica-rich passivating layers forms on the olivine surface during carbonation.** As carbonation proceeds, these passivating layers thicken, fracture and eventually exfoliate, exposing fresh olivine surfaces during rapidly-stirred/circulating carbonation. They tested incorporating select sonication to enhance exfoliation and carbonation. **They succeeded in nearly doubling the extent of carbonation observed compared with the optimum procedure previously developed by the Albany Research Center.**

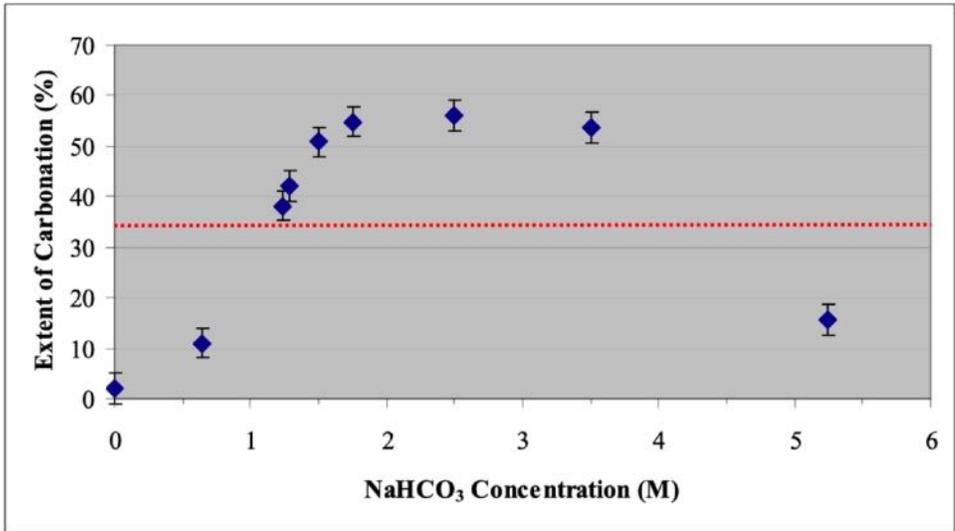
Aqueous carbonation reactivity was found to be a strong function of the ionic species present and their aqueous activities, as well as the slurry fluid flow conditions incorporated. High concentration sodium, potassium, and sodium/potassium bicarbonate aqueous solutions have been found to be the most effective solutions for enhancing aqueous olivine carbonation to date.

Slurry-flow modeling using Fluent indicates that the slurry-flow dynamics are a **strong function of particle size and mass**, suggesting that **controlling these parameters may offer substantial potential to enhance carbonation.**

They developed a **new sonication exfoliation system** with a novel sealing system to carry out the sonication studies. They also initiated investigations into the potential that sonication offers to enhance carbonation reactivity. During the second project year, they extended their investigations of the effects of sonication on the extent of carbonation as a function of the following parameters: particle size distribution, the mass of solid reactant, volume fraction of aqueous solution present, sonication power, time, temperature, and CO₂ pressure. Thus far, none of the conditions investigated have significantly enhanced carbonation.

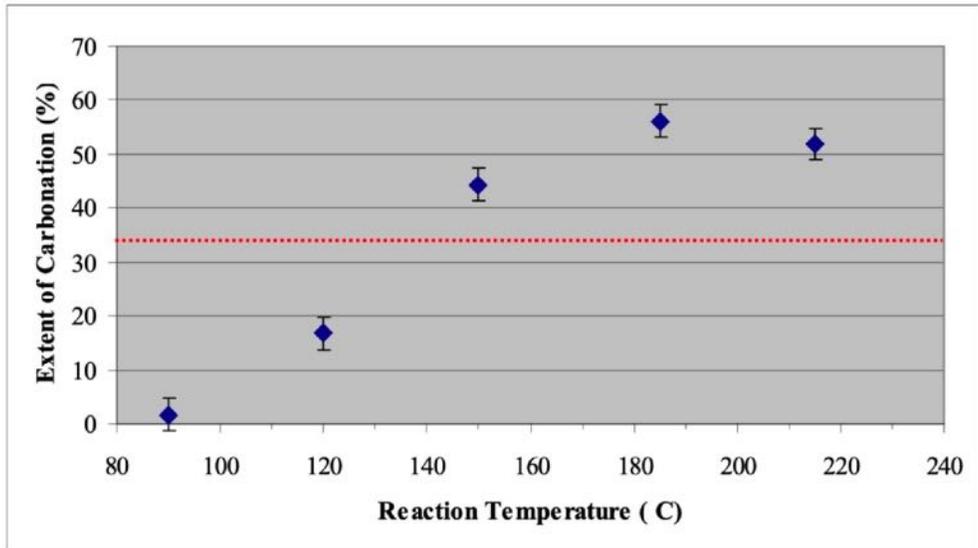
1,500 rpm stirring was used to replicate the ARC process in the studies at Arizona State University. These mineral carbonation reactions were performed using a 100 ml Autoclave Engineers EZE-Seal Hastelloy C-276 reactor, which is a smaller scale version of the 2,000 ml EZE-Seal Hastelloy C-276 reactor used at the Albany Research Center.

The results of the studies of the effect of NaHCO₃ are shown as follows.



Extent of carbonation of $< 38 \mu$ San Carlos Olivine as a function of NaHCO_3 concentration after 1h of carbonation at 185°C , under 2200psi of CO_2 , and with $\sim 1500\text{rpm}$ stirring. The dashed horizontal red line represents the extent of carbonation observed using the standard $0.64\text{M NaHCO}_3 + 1.00\text{M NaCl}$ aqueous solution under the same reaction conditions.

The effect of temperature is shown below,

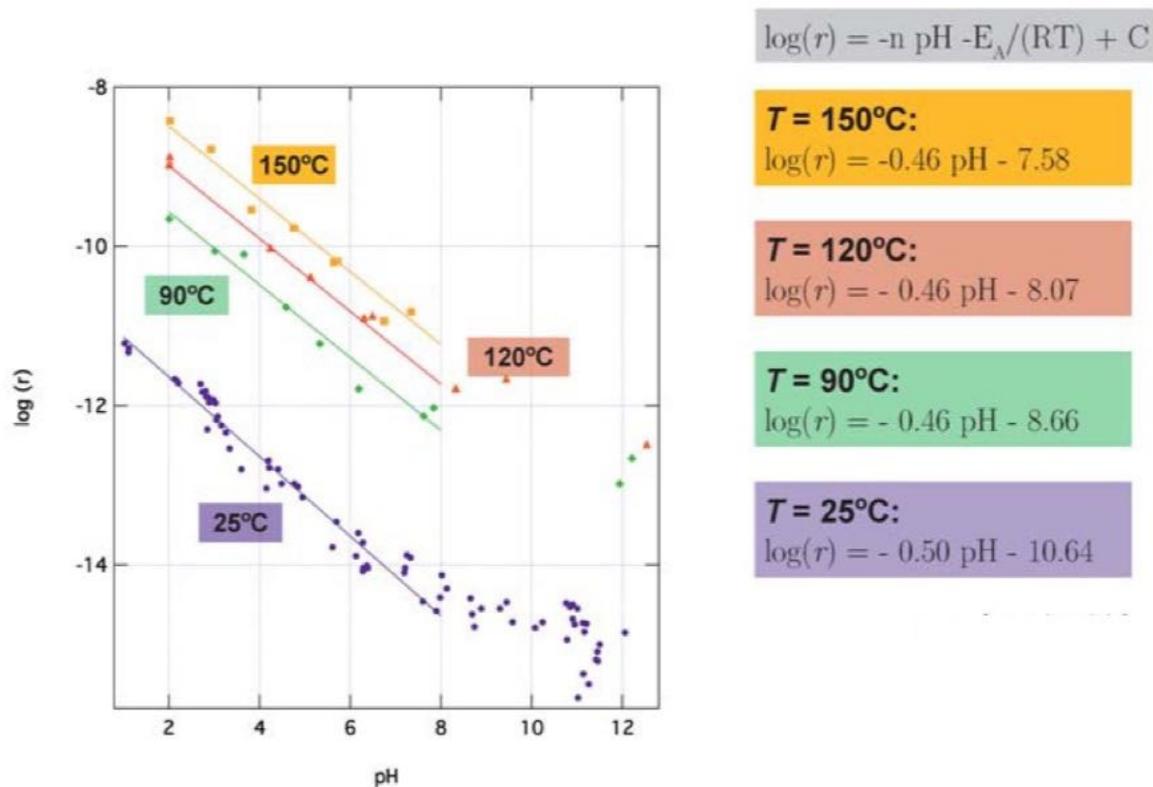


The effect of reaction temperature on the extent of carbonation of San Carlos olivine ($< 38\mu$). Reaction conditions: 1h, 2,200 psi CO_2 , 1500rpm stirring, and 2.5M NaHCO_3 . The dashed red line represents the average extent of carbonation observed using the standard aqueous solution ($0.64\text{M NaHCO}_3 + 1.00\text{M NaCl}$) at 185°C .

Studies during their no-cost extension period emphasized the impact that controlled aqueous speciation and activity and slurry-flow dynamics have on the mechanisms that control carbonation reactivity and **the potential they offer to substantially reduce olivine mineral sequestration process cost.**

Hänchen, M, et al (2006) examined the **dissolution of olivine** at temperature of 90 to 150°C in the presence of CO₂ at pressures of 15 to 180 bar. The presence of **citric acid, an organic ligand, significantly increased dissolution rates** in respect to the baseline HCl solution.

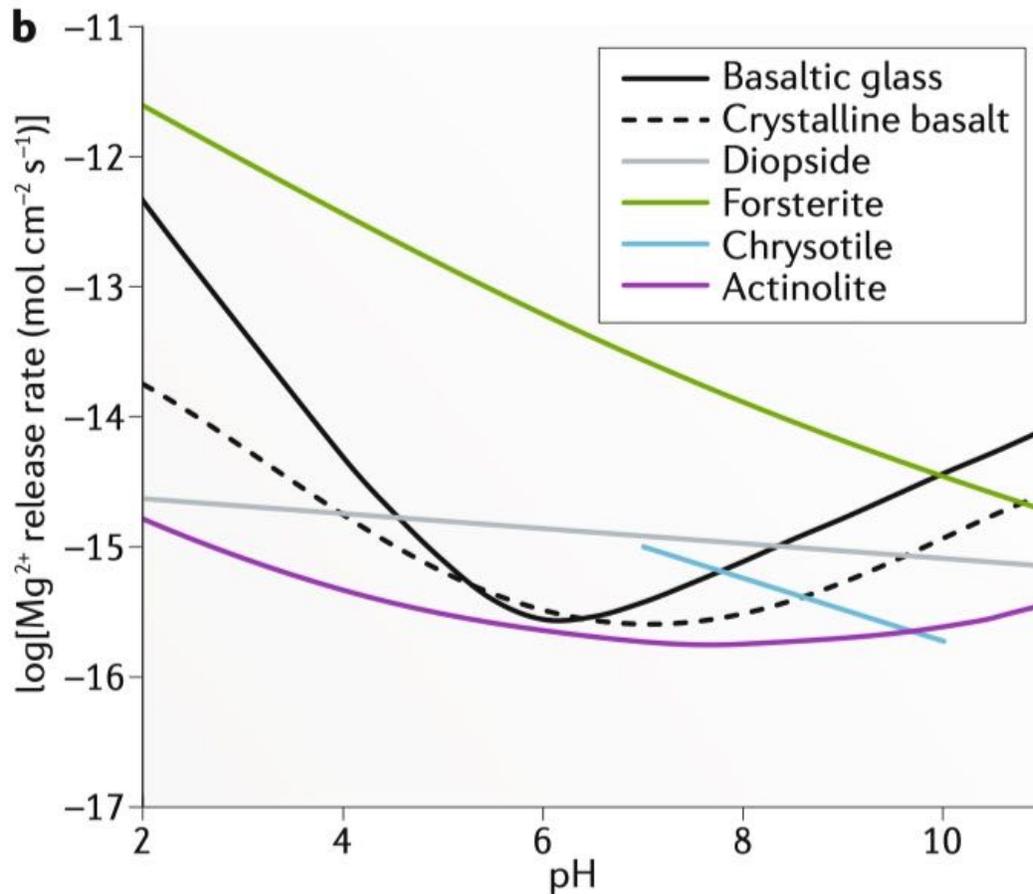
Prigobbe, V. et al (2009) and Pokrovsky and Schott (2000). Looking for optimal conditions to speed up **dissolution of olivine**, experiments were performed in a flow-through reactor at 90-120-150°C. The pH was adjusted by adding either acids (e.g., HCl, citric acid) or LiOH, and by changing PCO₂. The salinity was changed by adding NaCl and NaNO₃. Here **r is the specific dissolution rate (mol/cm²/s)**.



Logarithm of the specific dissolution rate r as a function of pH and at different temperatures. In **violet** is the literature data by Prokovsky and Schott (2000) for comparison.

Here it is possible to see the dissolution rate of fosterite olivine at ambient temperature (25°C) and neutral pH, similar to that of soil. **At neutral pH the dissolution rates are 10⁻¹⁴ mol/m²/s. Lower pH and higher temperatures significantly increased the dissolution rates.** While these studies were designed for capture of CO₂ from flu gas the data for neutral pH and ambient temperature have some relevance to the application of olivine to soil.

Snæbjörnsdóttir et al (2020) As a comparison with the above figures, this author compared the dissolution studies of different minerals by several authors.



Calcium and magnesium release rates from mafic rocks and minerals. Variation of Mg^{2+} release rates from common minerals at pH, 25 °C. chrysotile = $\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$; basaltic glass; diopside = $\text{MgCaSi}_2\text{O}_6$; crystalline basalt, forsterite = Mg_2SiO_4 actinolite = $\text{Ca}_2(\text{Mg}_{4.5-2.5}\text{Fe}^{2+}_{0.5-2.5})\text{Si}_8\text{O}_{22}(\text{OH})_2$. See paper for references.

Note that forsterite olivine dissolution has a steep linear relationship to pH while diopside have an almost flat relationship. The important lesson is that **some mafic and ultramafic rocks do not have a strong relationship to pH**. There was good agreement with the dissolution rate of forsterite vs pH between Prokovsky and Schott (2000) (above) and the Snæbjörnsdóttir et al (2020) data.

Renforth, (2012) The silicate resources in the UK are large and could theoretically capture **430 billion tons (Gt) of CO_2** . The majority of this resource is contained in basic rocks (with a carbon capture potential of $\sim 0.3 \text{ tCO}_2/\text{t rock}$). There are a limited number of ultrabasic formations ($0.8 \text{ tCO}_2/\text{t rock}$) with a total carbon capture potential of 25.4 GtCO_2 . It is shown that the energy costs of enhanced weathering may be $656\text{--}3501 \text{ kWh/tCO}_2$ for basic rocks and $224\text{--}748 \text{ kWh/tCO}_2$ 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 \$70–\$578/tCO₂ and \$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.

Turianicová, E. et al (2013) studied the influence of mechanical activation of olivine on the carbonation process at ambient temperature (25 ± 1 °C) and at significantly lower pressure than in previous work (60 bar), and no organic or inorganic additives were added to enhance the process. Structural, surface and morphological changes of mechanically activated olivine resulted in an increased reactivity. The process produced **amorphous magnesium carbonate in the form of hydromagnesite ((MgCO₃)₄ · Mg(OH)₂ · 4H₂O)** which is energetically favored over magnesite (MgCO₃). The authors proposed that **the mineral carbonation of mechanically activated olivine proceeds according to a reaction forming hydromagnesite.**

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.

Strawn, Bohn, & O'Connor (2015) are the editors of the 4th edition of *Soil Chemistry*. Chapter 6. Mineralogy and Weathering Process in Soils presents the following table (6.8) showing the types of crystalline structure for different mafic and ultramafic rocks.

Table 6.8 Structural classification of silicates. The Si:O ratio refers to the number of Si atoms divided by the number of O atoms that are ligands in the Si tetrahedra. In determining Si:O ratio, isomorphic substitution of Al^{3+} in the Si^{4+} positions (underlined Al in table) counts as a silicon atom.

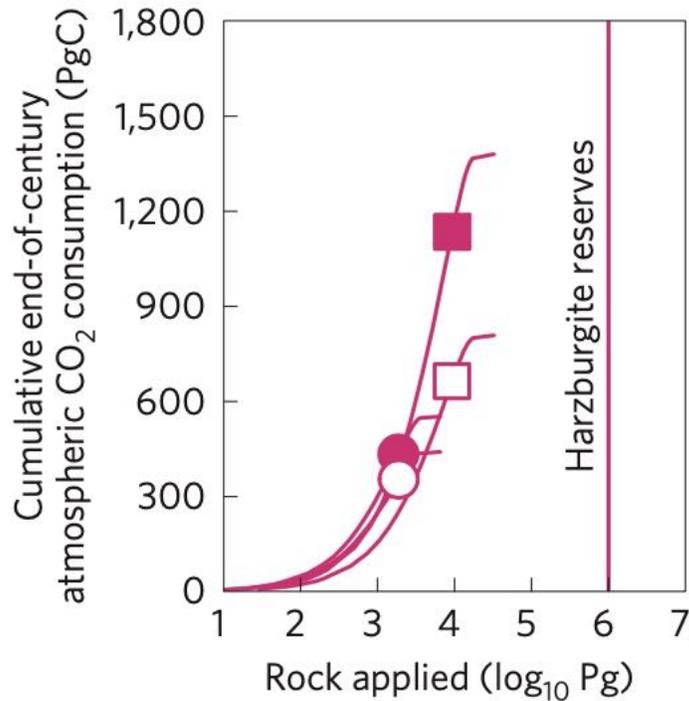
Classification (group)	Structural arrangement	Si/O ratio	Examples
Nesosilicates (island silicates)	Single tetrahedra	1/4	Olivine $((Mg,Fe)_2SiO_4)$, garnet
Inosilicates (single-chain silicates)	Continuous single chains of tetrahedra sharing two corners	1/3	Pyroxene $(MgSiO_3)$
Inosilicates (double-chain silicates)	Continuous double chains of tetrahedra sharing alternately two and three oxygens	4/11	Amphiboles $(Mg_{3.5}Si_4O_{11}(OH)_1)$
Phyllosilicates (sheet or layer silicates)	Continuous sheets of tetrahedra each sharing three oxygens	2/5	Micas, clay minerals (muscovite- $K_2Al_4Si_6\underline{Al}_2O_{20}(OH)_4$)
Tectosilicates (framework silicates)	Continuous framework of tetrahedra each sharing all four oxygens	1/2	Quartz, feldspars, zeolite (quartz- SiO_2 ; orthoclase- $K(Si_3\underline{Al}O_8)$)

Olivine is a Nesosilicate with a single tetrahedra while the pyroxenes are Inosilicates with chains of tetrahedra and serpentines are Phyllosilicates with continuous sheets of tetrahedra each sharing three oxygens. These structures can account for the different dissolution rates of these minerals. The 3-D structures of olivine and serpentine are shown on other pages.

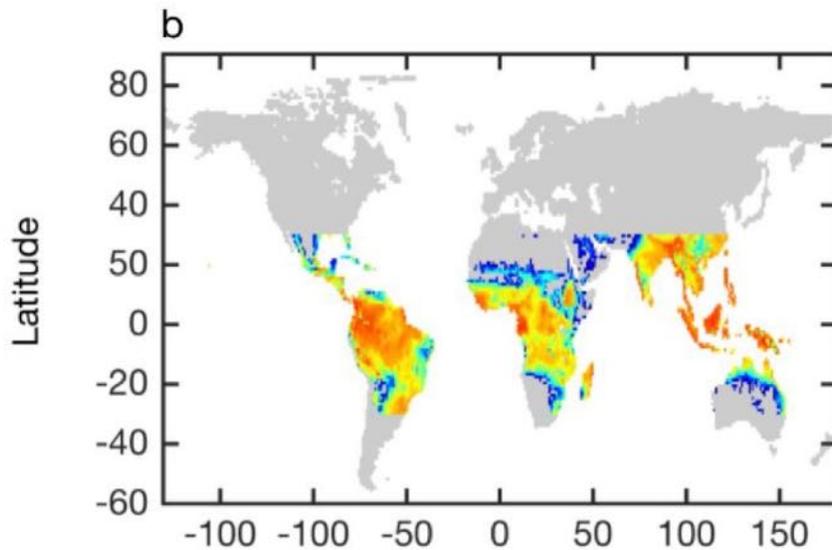
Kleiv et al, (2016) reported milling experiments on **olivine** combining **the two milling modes, dry and wet**. These were performed using a laboratory planetary mill. The specific surface area of the milled products was determined by N_2 -adsorption (BET), and their crystallinity was studied using X-ray diffraction (XRD). Combining dry mechanical activation with subsequent wet milling made it possible to produce specific surface area at rates that exceed those that can be obtained by wet milling alone. **A value of $26.28 \pm 1.28 \text{ m}^2/\text{g}$ was obtained after 30 min of wet milling. By contrast, 25 min of dry mechanical activation followed by 5 min of wet milling resulted in a specific surface area of $64.44 \pm 2.13 \text{ m}^2/\text{g}$.** The concept could represent significant energy savings. This may have relevance to grinding serpentines.

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 CO_2 and ameliorate ocean acidification by 2100. However, they emphasize the problems with cost, acceptance and potential unanticipated side effects.

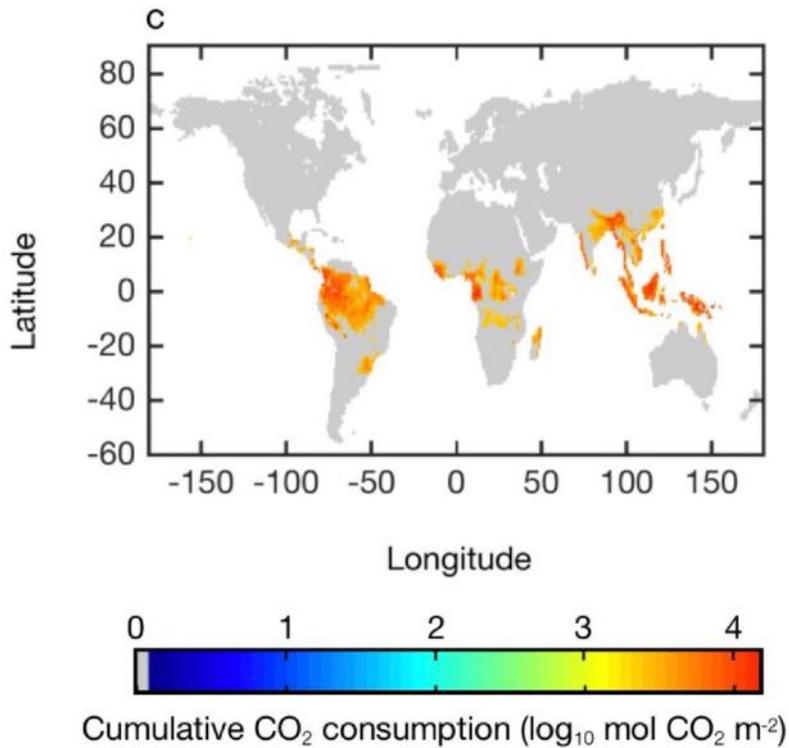
They examined the use of three minerals: **Dunite** (olivine – $(Mg-Fe)_2 SiO_4$, **Harzburgite** (olivine + low Ca^{++} pyroxene) and **Basalt**. The results for Harzburgite were as follows:



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.

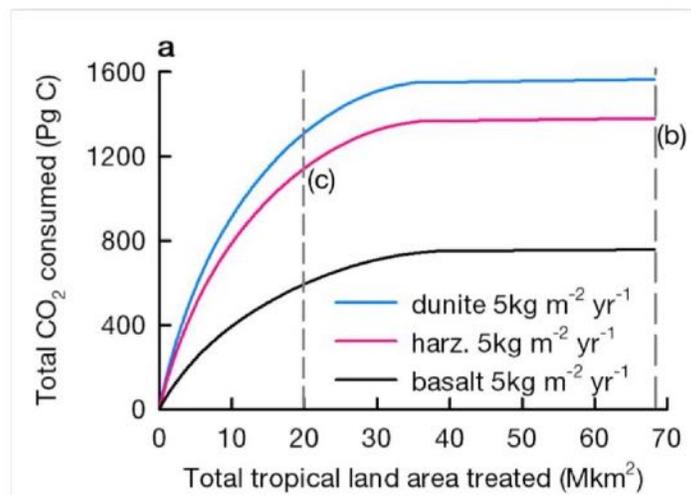


This is a map of the total tropical area 30° N to 30° S. It include both the tropical weathering hot spots and non-hot spots.



This is a map of the **Tropical Weathering Hot Spots** illustrates the meaning of this term, namely **areas where the cumulative CO₂ consumption is between 3 and 4 log₁₀ mol CO₂/meter.**

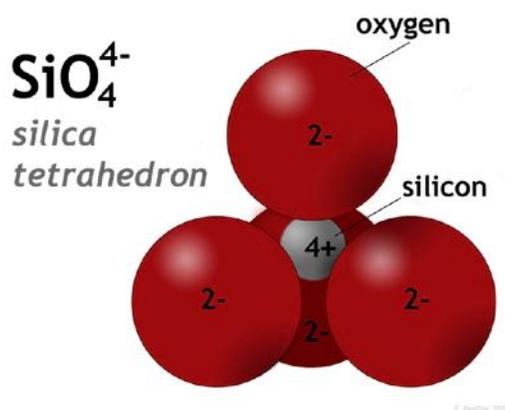
The next figure summarizes all of the above. This diagram shows the data for the hot spots only.



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

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 needs to be multiplied by 5, or **145 times to compare temperate dry regions to tropical hot spots**. The 3-site studies (see below) are needed to verify this.

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

Olivine dissolution can proceed by the breaking of just the ionic Mg-O bonds, liberating the SiO⁴⁻ 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.**

Turri et al (2019) described and compared the direct and indirect carbonation of olivine and proposed removing nickel from olivine using ion exchange techniques. The direct process consisted of performing the reaction at high temperature and CO₂ pressure as in the ARC studies.

This often had a higher cost because of incomplete carbonation. The indirect process consisted of acidic leaching (pH 0.55 to 1.0) followed by carbonation and separation stages. Several commercial resins were screened for the separation of Ni²⁺ in an acidic solution. They chose a Dowex M-4195 ® resin. The best results were obtained at pH's of 0.55 to 1.0. This degree of acidity and its removal would be difficult for placing high volumes of reactants on farmland.

II. Olivine Dissolution: Field Studies On Cropland or Simulated Field Studies

The one thing that became obvious is that there are very few actual field studies of EW.

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 1,630, 8,150, 40,700 and 204,000 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 appears fast enough to support the EW 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.

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 five 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.

Dietzen, C. et al (2018) Applying **finely ground silicate minerals to soils** could mitigate CO₂ emissions by enhancing the rate of carbon sequestration via silicate weathering. Using these minerals instead of agricultural lime to increase soil pH would also eliminate the dissolution of lime as a major source of agricultural CO₂ emissions. However, dissolution rates of silicate minerals in the soil environment are uncertain and the impacts of their application on the decomposition of soil organic matter have yet to be determined. A **3-month soil incubation** was performed to investigate the **effects of olivine**, a highly weatherable silicate mineral, **at two application rates, OLIVlow (0.008 g/g soil) and OLIVhigh (0.04 g/g soil).** There was no difference in cumulative net CO₂ flux between the olivine-amended soils and the control though **total flux from the limed soils was 221% higher than the control.** Heterotrophic respiration was also greatest in the lime-amended soils. The weathering rate of OLIV low (26.7%) was higher than of OLIV high (7.1%), but **both treatments increased soil pH to a level sufficient to overcome aluminum toxicity.** Our results suggest that **olivine amendments are an effective tool for carbon sequestration and a suitable replacement for lime.**

Amann, et al (2020) Instead of covering a large tract of cropland, Amann et al **Enhanced Weathering and related element fluxes – a cropland mesocosm approach,** chose to use very small plots of soil, thus the term a mesocosm approach. They stated that while there are some studies that propose and theoretically analyze the application of rock powder to agricultural land, **results from field experiments are still scarce.**

In order to evaluate the efficiency and side effects of Enhanced Weathering, a mesocosm experiment was set up and agricultural soil from Belgium was amended with **olivine-bearing dunite ground to two different grain sizes,** with and without crops.

Based on measurements of Mg, Si, pH, and DIC, **the additional weathering effect of olivine could be confirmed. Calculated weathering rates are up to 3 orders of magnitude lower than found in other mostly laboratory and theoretical studies.** The calculated CO₂ **consumption** by weathering based on the outlet water of the mesocosm systems was low with 2.3–4.9 tCO₂/km²/yr if compared with previous theoretical estimates. Suspected causes were the removal or dilution of Mg as a weathering product by processes like adsorption, mineralization, plant uptake, evapotranspiration, and/or preferential flow, not specifically addressed in previous EW experiments for CO₂ consumption. The observation that Mg concentrations in the upper soil layers were about 1 order of magnitude higher than in the outlet water indicates that a careful tracking of weathering indicators like Mg **in the field is essential for a precise estimate of the CO₂ consumption potential of EW,** specifically under global deployment scenarios with a high diversity of ecosystem settings. Porewater Mg/Si molar ratios suggest that dissolved Si is reprecipitating, forming a cation-depleted Si layer on the reactive mineral surface of freshly ground rocks.

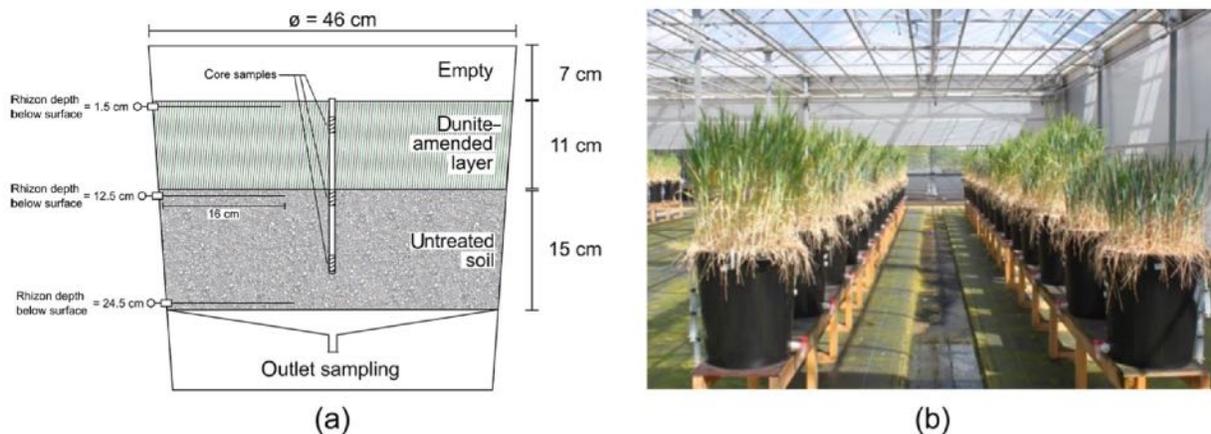
The release of potentially harmful trace elements is an acknowledged side effect of EW. Primarily Ni and Cr are elevated in the soil solution, while Ni concentrations exceed the limits of drinking water quality. The use of olivine, rich in Ni and Cr, is not recommended, and alternative rock sources are suggested for the application.

While the kinetics are relatively well understood at the laboratory scale, the dissolution rate of a rock powder mixture as soil amendment, with fresh surfaces, which have not been in contact with an aquatic phase before, **is nearly unknown**. Several points of the rock powder application on soils have to be considered. First, the upper parts of soils are not permanently saturated with water, which may lead to mineral dissolution–precipitation reactions. Second, it can be expected that mineral surfaces initially need to equilibrate with the new system and varying water content and that dissolution rates of minerals will be different from those in long-term equilibrium within the natural soil system. Third, trace elements from the applied rock material will eventually be released and migrate downwards, reprecipitated if oversaturation with a specific mineral phase occurs, or adsorbed to soil minerals or organic matter.

They studied the release of the major elements Mg and Si predominantly derived from Mg olivine, as indicators for the inorganic CO₂ sequestration potential, and assessed whether the release of elements into the soil solution occurs stoichiometrically, or whether a secondary layer covering the fresh surfaces of minerals will develop, potentially enriched in Si and depleted in Mg (Daval et al., 2013a; Hellmann et al., 2012; Pokrovsky and Schott, 2000), which could influence weathering and subsequently sequestration rates. In addition, the release of trace metals was used to understand how these behave in a near-natural environment to evaluate the impacts on the environment.

Methods. Rain barrels were used as miniature growing sites (mesocosms). They had a diameter of 46 cm and were filled with a natural loamy sandy soil from Belgium. Olivine-rich dunite was added to the top layer of the soils at a rate of 22 kg/m². Two different grain sizes were used – **course and fine**. It was applied to two crops, **wheat and barley**, and two different irrigation regimes, daily and weekly. Controls consisted of barrels without added dunite, and barrels without plants.

Soil material was obtained by extracting sediment cores (20 cm long and 28 mm in diameter) using a hammer auger with a removable plastic lining (Eijkelkamp 04.15.SA foil sampler, Giesbeek, the Netherlands). The following figures shows a summary of the methods.



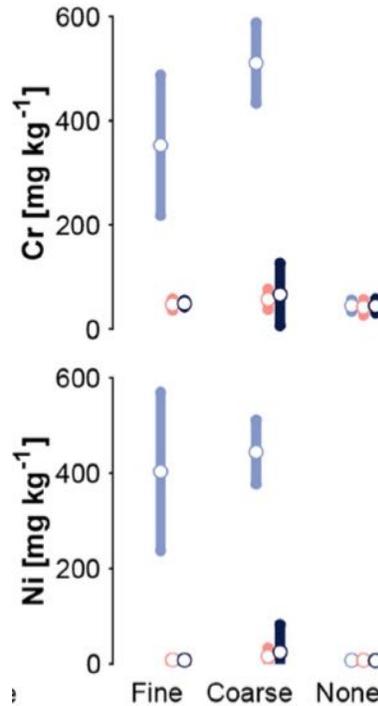
(a) Schematic mesocosm configuration; (b) status of the experiment in April 2014 (6 months in).

Von Strandman, 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 CO₂ 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.

How Much Rock is Required per Ton of CO₂ sequestered? The ability to sequester atmospheric CO₂ is material specific and depends on the Mg²⁺ that can be released during hydrolysis from the Mg-rich olivine. It is defined as the **carbon dioxide removal (RCO₂) in metric tons of CO₂ per metric ton of Mg olivine (estimated to be 1.1 for ultramafic (i.e., Mg rich) rocks;** Moosdorf et al., 2014). This assumption considers that impurities (like Fe abundance), in contrast to the ideal Mg olivine and equilibration effects, reduce the theoretical maximum **RCO₂ of 1.25 for forsterite**. Based on the average of Mg concentrations in the outlet water over the first year (340 d), the experiment leads to a **total annual CO₂ sequestration of 2.3–4.9 t /tCO₂/km²/yr** depending on the applied grain size. **These amounts are considerably higher than some earlier estimates.**

Ni and Cr Release The following diagram shown the amount of Chromium and Nickel released to different depths of soil.



Depths: blue: 2–4 cm; red: 10–12 cm; black: 18–20 cm below surface.

It is clear that these two metals were primarily released to the upper layers of soil.

III. Serpentine Dissolution: Laboratory Studies

While the dissolution of olivine on croplands has been emphasized, the problem is that **the majority of ultramafic rocks in the world are serpentinized and the rate of dissolution of serpentine is significantly slower than that of olivine** (Daval, 2013).

As to the question of whether serpentinized rock can be used for enhanced weathering on cropland, very few field studies have been undertaken about this. Thus, this will be examined in our proposed **3-Site Research** project (see below). We believe it will work since basalt on cropland has been shown to work and the dissolution rate of basalt is slower than for serpentine.

A number of things have been tried to accelerate the dissolution of serpentine. Much of that literature was aimed at the commercial extraction of magnesium, or use in extracting CO₂ from flu gas, while our goal is the relative rate of dissolution of serpentines in the soil. Most of the techniques proposed for the extraction of magnesium from serpentine would add significant costs to the use of serpentine on soils.

The serpentine group of minerals consists of the three polymorphs lizardite, antigorite, and chrysotile. The serpentine minerals are phyllosilicates, or sheet silicates, and share the general formula Mg₃Si₂O₅(OH)₄. As serpentine dissolves carbon dioxide is consumed by the reaction (Park and Fan, 2004)



General formula for the serpentines is $Mg,Fe,Ni,Al,Zn,Mn)_{2-3} (Si,Al,Fe)_2O_5(OH)_4$. The serpentine clay minerals are Lizardite, Atlantisite and Infinite, with the chemical composition of $Mg_3Si_2O_5(OH)_4$. They differ in color and where they are found. Lizardite is the most common and most often used in research studies.

Olivine is a nesosilicate mineral with the general formula $(Mg,Fe)_2SiO_4$. The olivine group consists of **forsterite (Mg_2SiO_4)** and **fayalite (Fe_2SiO_4)**. **Olivine dissolves quickly in comparison to other silicate minerals**. At Earth surface temperatures, olivine dissolution usually occurs stoichiometrically and few weathering products are formed. The general reaction for olivine, specifically forsterite, dissolution is



The studies of the dissolution of serpentines are reviewed below.

A major question is, **Does the application of serpentines to soil need any of the enhancements described in these papers?** We will attempt to answer this in the **3-Sites Research** proposal. Independent of this, what is the most effective method of enhancing the carbonation of serpentines?

Luce et al., (1972) Kinetic dissolution experiments on **serpentine, forsterite and enstatite** over a wide pH range at 25°C showed that there was an initial rapid exchange of surface magnesium ions with hydrogen ions followed by a longer period of hydrogen exchange and extraction of internal magnesium and silicon, with the amount extracted proportional to time. The **diffusion coefficients decrease in the order forsterite > serpentine > enstatite ($(Mg,Fe)SiO_3$)**.

Eventually the parabolic exchange rates decrease to the rate of dissolution of all material at the aqueous interface. Hence, over very long periods the amount of silicon and magnesium dissolved is proportional to time and dissolution is congruent. **In highly acid solutions dissolution rates are fast and this terminal condition is reached much sooner.**

Lin and Clemency (1981) Dissolution experiments were done on a series of layer-type Mg minerals (brucite, antigorite, talc, and phlogopite) of progressively more complex structure and chemical composition. **Brucite $Mg(OH)_2$, Anigorite $(Mg,Fe^{2+})_3Si_2O_5(OH)_4$, talc $Mg_3Si_4O_{10}(OH)_2$, Phlogopite $KMg_3AlSi_3O_{10}(F,OH)_2$.**

The advantages of this study were that dissolution was done in **water at room temperature and conditions**. A further almost unique advantage was that it examined very **small particle sizes** with 9 groups from < .5 μm to 37 μm . However, they were not studied individually but rather showed the range of particle sizes. For example, 35% of the anigoite sizes were less than 8 μm .

It appears that the solubility of these layer-type minerals was related to the relative number of octahedral to tetrahedral sheets present in the structure, i.e., the dissolution kinetics of layer-type silicate minerals is controlled by the rate of destruction of the tetrahedral silica sheets of the mineral.

Goff, F. and Lackner, K.S. (1998) **Serpentinites and dunites** comprise the best ores for CO_2 sequestration because they contain the most Mg by weight (35 to 49 wt-% MgO) and are

relatively reactive to hot acids such as HCl. Small ultramafic bodies (about 1 km³) can potentially sequester about 1 gigaton of CO₂ or 20% of annual U.S. emissions. A single large deposit of dunite (30 km³) could dispose of nearly 20 years of current U.S. CO₂ emissions.

The **carbonation of serpentinite** is broken up into several steps. The mineral ore is mined and **ground to a powder**. To improve the carbonation reaction kinetics, the magnesium is extracted from the ore and put in the form of magnesium hydroxide. The extraction is **accomplished with HCl**, which dissolves the mineral forming MgCl₂, and silica, which is readily precipitated. This process was described in the 1940s and 1950s when Mg shortages were driving research into alternative extraction technologies. This is a fairly complex process initially designed for the extraction of magnesium and involving piping CO₂ and Mg(OH)₂.

Drief and Nieto (1999) reported that **with prolonged grinding** the crystal structure of the **serpentine rock, antigorite**, was affected mainly along the c axis, causing a partial loss of crystallinity. **Vibration grinding modified mineral dehydration, accelerating the dehydroxylation process and transforming the structural OH to adsorbed water**. The **amorphous material product after 120 min** showed the same composition as the initial antigorite. Grinding led to a general decrease in particle size at the beginning of the experiment **followed by the agglomeration of ultrafine particles as grinding proceeded**. Grinding seems to be an important process for water extraction, including structural water, thus accelerating the dehydroxylation process.

Kim and Chung, (2002) A **serpentine mineral** was treated in a **planetary ball mill**, and the effect of grinding was studied on the crystalline structure, average size, and metal extraction rate by sulfuric acid leaching. The crystalline peaks of the serpentine were gradually reduced with increase of grinding time, and **after 120 min the serpentine turned into the amorphous phase**. It was found that the **extraction rate of the metals contained in the mineral by sulfuric acid was rapidly increased by the mechanochemical treatment**. For the mineral treated for 240 min, Mg and Fe metal elements were extracted at 100% within 5 min.

Park and Fan, (2004). The effect of the **physical activation on the dissolution of serpentine** was investigated and a pH swing scheme was developed to improve the overall conversion of the CO₂ mineral sequestration process. Various methods of the surface agitation such as **ultrasound and internal (in-situ) grinding** were examined for their effectiveness in removing the diffusion limiting SiO₂ layer in order to promote further dissolution of the inner MgO layer of serpentine. It was found that the fluidization of the serpentine slurry with 2 mm **glass beads** was most effective in refreshing the surface of the serpentine particles during the dissolution process. **Unlike the external attrition grinding, this method could be much less energy intensive**. It was also found that the mechanical agitation via the internal grinding alone did not enhance the dissolution of serpentine, while **the combination of the internal grinding and Mg leaching solvent resulted in rapid serpentine dissolution**. Using the proposed pH swing scheme, the overall conversion of the mineral carbonation radically improved. By controlling the pH of the system, three solid products were generated from the mineral carbonation process: SiO₂-rich solids, iron oxide and MgCO₃*3H₂O. Since the iron oxide and MgCO₃ produced were highly pure, these value-added products could eventually reduce the overall cost of the carbon sequestration process.

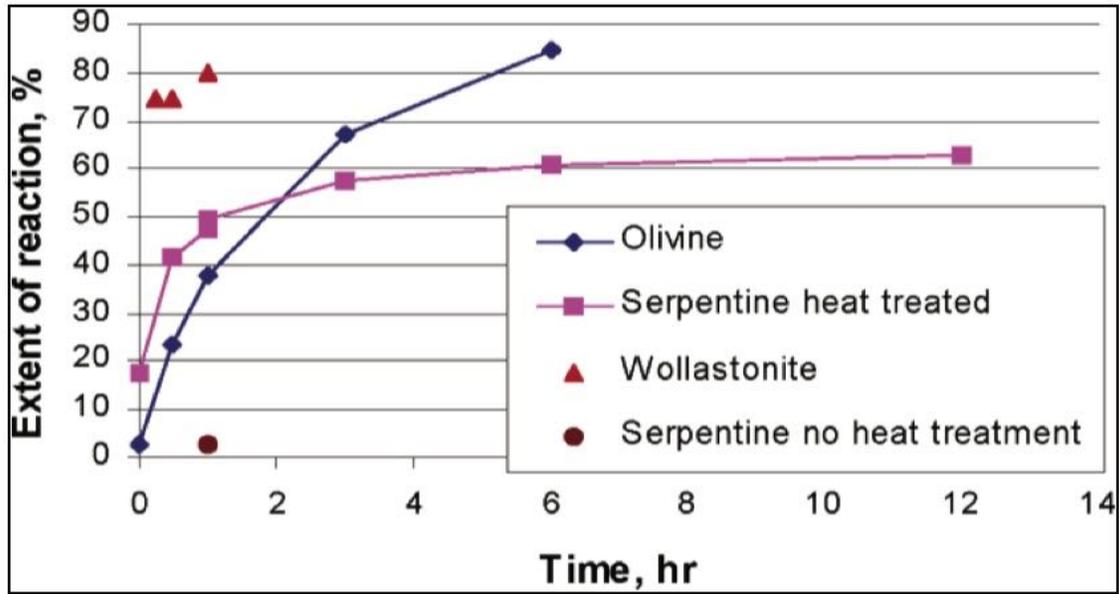
Gerdemann, et al, (2004, 2007) The U. S. Department of Energy's Albany Research Center is investigating mineral carbonation as a **method of sequestering CO₂ from coal-fired-power plants**. Magnesium-silicate minerals such as **serpentine** Mg₃Si₂O₅(OH)₄ and **olivine** (Mg₂SiO₄) **react with CO₂ to produce magnesite (MgCO₃)**, and the calcium-silicate mineral, **wollastonite (CaSiO₃)**, **reacts to form calcite (CaCO₃)**. It is possible to carry out these reactions either *ex situ* (above ground in a traditional chemical processing plant) or *in situ* (storage underground and subsequent reaction with the host rock to trap CO₂ as carbonate minerals). For *ex situ* mineral carbonation to be economically attractive, the reaction must proceed quickly to near completion. **The reaction rate is accelerated by raising the activity of CO₂ in solution, heat (but not too much), reducing the particle size, high-intensity grinding to disrupt the crystal structure, and, in the case of serpentine, heat-treatment to remove the chemically bound water.** All of these carry energy/economic penalties. An economic study illustrates the impact of mineral availability and process parameters on the cost of *ex situ* carbon sequestration.

The carbonation rates are very dependent upon the **type of serpentine**. Mineral carbonation of antigorite and lizardite is very different; with antigorite [(Mg,Fe²⁺)₃(Si₂O₅)(OH)₄] having a carbonation efficiency of 92% and lizardite [Mg₃(Si₂O₅)(OH)₄] of only 40% after thermo-activation

In situ carbonation offers economic advantages over *ex situ* processes, because no chemical plant is required. Knowledge gained from the *ex situ* work was applied to long-term experiments designed to simulate *in situ* CO₂ storage conditions. The Columbia River Basalt Group (CRBG), a multi-layered basaltic lava formation, has potentially favorable mineralogy (up to 25% combined concentration of Ca, Fe²⁺, and Mg cations) for storage of CO₂. However, more information about the interaction of CO₂ with aquifers and the host rock is needed.

The research included resource evaluation, kinetic studies, process development, and economic evaluation. An initial cost estimate of ~\$69/ton of CO₂ sequestered was improved with process improvements to ~\$54/ton. The scale of *ex situ* mineral carbonation operations, requiring ~55 000 tons of mineral to carbonate, the daily CO₂ emissions from a 1-GW, coal-fired power plant, may make such operations impractical.

The following diagram compares olivine to serpentine dissolution at 185°C and 150 atm CO₂ in NaCl NaHCO₃ solution.



Teir, S. et al (2007) In this study, the dissolution of natural serpentinite in respective solutions of acids, bases and ammonium salts has been investigated. Experiments performed at room temperature showed that H_2SO_4 was most efficient at extracting magnesium from serpentinite, followed by HCl, HNO_3 , HCOOH and CH_3COOH . Experiments for determining the dissolution kinetics was performed at temperatures of 30, 50 and 70 °C in 2 M solutions of H_2SO_4 , HCl and HNO_3 . At 70 °C temperatures all magnesium was extracted from serpentinite in each of the three acid solutions tested during 1–2 h. Also, a large part of iron in serpentinite was extracted, while very little silicon dissolved (<4%). The dissolution rate seemed to be limited by product layer diffusion for serpentinite particles with a size distribution of 74–125 μm . The apparent activation energies were 68 kJ/mol for dissolution in H_2SO_4 , 70 kJ/mol for dissolution in HCl, and 74 kJ/mol for dissolution in HNO_3 .

Although the experiments show that common mineral acids can extract magnesium from serpentinite in time frames relevant for industrial processes, a successful carbonation process must also manage to precipitate magnesium carbonate and recycle most of the additional chemicals used. Therefore, more research on process development is needed before serpentinites can be used for long-term storage of CO_2 .

Alexander, G. et al (2007) In this work, a statistical design of experiments was conducted to ascertain the effect of acid concentration, particle size and reaction time and temperature on the leaching of magnesium from serpentine using sulfuric acid. Results demonstrated that acid concentration provided primary control on the dissolution via the removal of water, which is closely correlated with the extraction of magnesium from serpentine. Particle comminution to a median size less than 163 μm remained an important consideration in increasing reactivity and liberating magnetite. Single variable experimentation demonstrated dissolution enhancements with increased reaction time and temperature. An increase in magnesium dissolution of 46% and 70%, over a baseline test, occurred for increased reaction time and temperature, respectively.

Brent, G.F. and Petrie, J.G. (2008) This study focused on using the techniques developed by ARC for the *ex situ* sequestering of CO₂ captured from coal fired power plants, instead of injecting it underground. This work focusses on serpentine as it is far more abundant and widespread in Australia than olivine and wollastonite.

The process uses aqueous buffer solutions of NaCl and NaHCO₃ slurred with **ground serpentine**. The role of the buffers is to simultaneously maximize serpentine dissolution and magnesium carbonation rates. Carbonation is achieved via contact with supercritical CO₂ at reaction conditions of 115 atm and 155°C. The final conclusion of the ARC team was that **serpentine required thermal or intense mechanical pre-treatment for activation (essentially a dehydroxylation step), and that this introduced prohibitive energy and cost penalties, effectively ruling out a viable serpentine process.** However, the ARC report did not consider pre-treatment via direct thermal activation in a fuel-fired furnace, nor **did it include any heat recovery from the exothermic carbonation reaction**, both of which offer significant reductions in net processing costs.

Other routes to process improvements have also been identified, including energy integration, improved carbonation reactor design, and more effective solids separation recycle technologies. These routes are under investigation in current research programs. Whilst not wanting to understate the technical challenges inherent in such new process development, **initial results are encouraging and indicate that a substantial reduction in the ARC-quoted energy penalty and costs may be achievable.**

The key to improving the overall viability of the ARC process is to consider means by which the net energy requirement for the process can be reduced. The process envisaged here focusses on sequestration of emissions from coal-fired power generation for regions where viable geosequestration or other options do not exist.

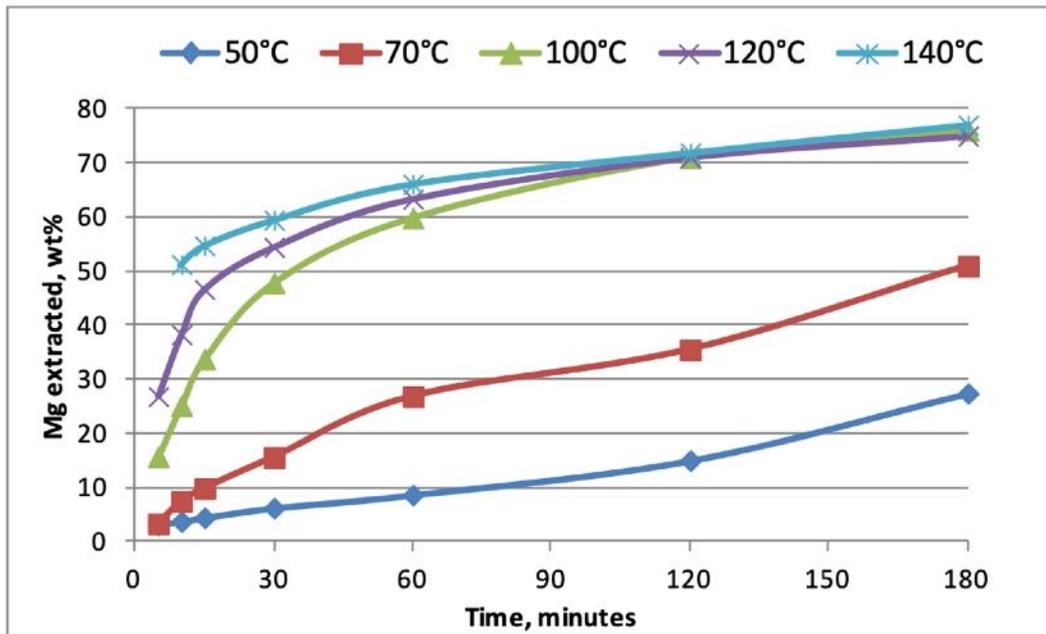
The amount of serpentine ore required would equate to less than half the amount of material currently mined in Hunter Valley open cut mines for each ton of coal processed. Fortunately, the largest occurrence of serpentine minerals in Australia lies in the so called **Great Serpentine Belt** (see for example McEvelly et al. 2004) of the Peel Fault system, stretching for well over 100 km from Tamworth.

The total current CO₂ emissions from NSW power stations are around 60 Mt pa. Four large facilities in the Hunter region make up over 70% of these emissions (Saddler et al., 2004). A future scenario can be envisaged where two to four new power generation plants, producing an equivalent 60 Mt CO₂ pa from about 25Mt coal pa, are centered on a serpentine mining industry still in reasonable proximity to the Hunter Valley or Gunnedah coalfields. **The magnitude of a serpentine mining industry required to sequester all these emissions would be about 180 Mt pa. This may require 10 medium scale open pit serpentine mines each producing 15 - 20 Mt pa.**

Krevor and Lackner, (2011) Neutral organic salts such as sodium oxalate, and **citrate** enhance dissolution kinetics of serpentine in the circum-neutral pH range appropriate for mineral carbonate precipitation and have potential for use in an enhanced carbonation process. Concentration and temperature dependencies for the dissolution of **antigorite serpentine in the presence of the citrate ion** are experimentally derived under weakly acidic conditions. **Rates are shown to be several orders of magnitude higher in the presence of citrate than in the weakly acidic solution alone.**

Orlando, et al (2011) In order to perform geological sequestration of CO₂, **serpentinite** should be dissolved by acids or by aqueous solutions. At atmospheric pressure serpentinite is efficaciously dissolved at 70 °C using **acid attacks**. At higher *P–T* conditions, significant carbonation occurs at 30 MPa (megapascal) and 300 °C using CO₂ saturated aqueous solutions.

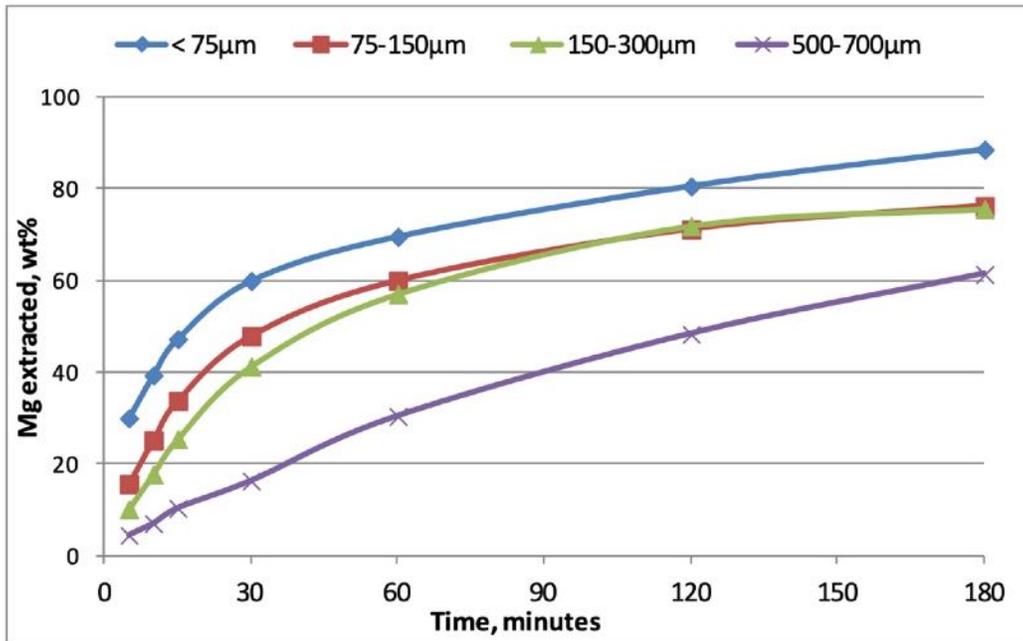
Sanna, A. et al (2013). The extraction of **Mg from lizardite serpentine** was studied as a function of temperature, particle size, of NH₄HSO₄ concentration and other variables. Some of these results are shown below.



2013

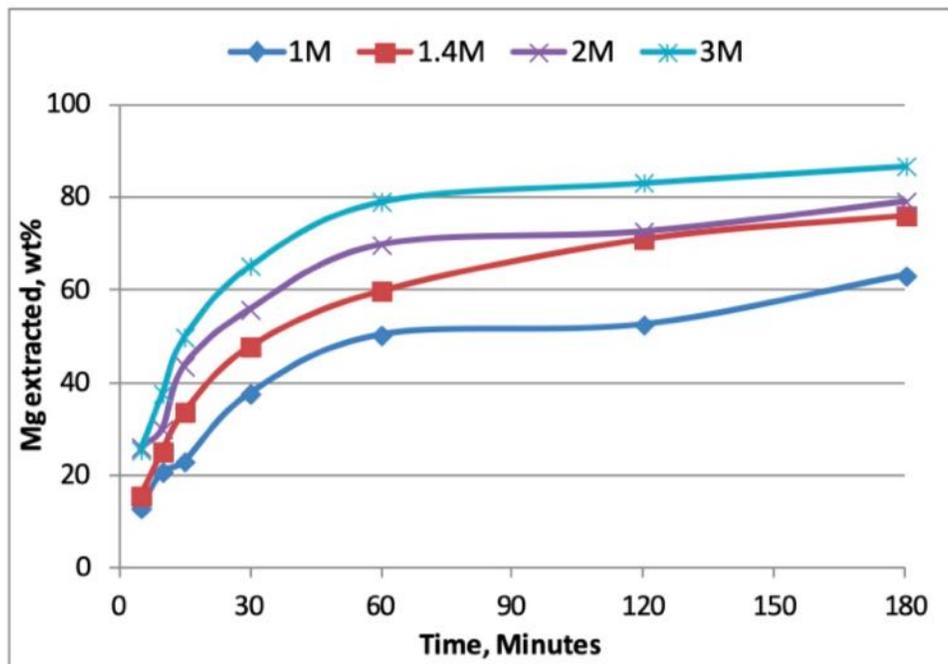
Effect of temperature and time on Mg extraction from serpentinized lizardite

The clustering shows that once the temperature of 100°C is reached, after 60 minutes, relatively less additional extraction of Mg was noted.



Effect of particle size and time on Mg extraction from serpentine (100°C, 50 g/l, 1.4 M NH₄HSO₄, 800 rpm).

As shown in many studies, the smaller the particle size the more efficient the dissolution. 75 µm is still a fairly large particle size. Although temperature and salts were also involved, these results **suggest that grinding to < 5 µm size may not be necessary for EW on soils.**



Effect of NH₄HSO₄ concentration and time on Mg extraction from serpentine.

Daval et al (2013a) reported that a critical factor in the **weathering of serpentine is the common formation of amorphous Si-rich surface layers (ASSLs)**, which may hinder contact between the fluid and the mineral surface. By considering ASSL as a separate phase that can control silicate dissolution rates, **extrapolated laboratory based rates at conditions relevant to the field can be lowered by up to several orders of magnitude**, thereby decreasing the large gap between laboratory and natural rates. This has important implications for more accurately modeling chemical weathering reactions, so important today for the C cycle and CO₂ sequestration. In their studies samples were in the size range of 300–500 μm.

Daval et al (2013b) examined the role of pH (2.5 to 6.7), temperature (27 to 90°C and pCO₂). For any single pH–T condition **lizardite dissolution rates were orders of magnitude lower than those of anhydrous basic silicates, such as olivine or pyroxenes**. The sluggishness of the dissolution reaction probably explains the slow carbonation rates that have been measured in previous studies. Lizardite, Mg₃Si₂O₅(OH)₄, volumetrically is the most common serpentine species.

Shikazono, N. et al. (2014) Dissolution experiments were performed **on serpentinite samples containing serpentine, brucite, olivine and pyroxene** from Mt. Iwanai, Hokkaido. From the results, we obtained dissolution rate constants for serpentine (Mg,Fe)(Si₂O₅)(OH)₄, brucite (Mg(OH)₂) and olivine (Mg,Fe)₂SiO₄) as functions of pH.

The results indicate that the amounts of primary minerals (brucite, olivine, and pyroxene) **decrease over time due to dissolution**. Artinite (Mg₂(CO₃)(OH)₂·3H₂O) forms as a product of this dissolution in the early stages and then its amount decreases as magnesite (MgCO₃) forms. 100% of the injected CO₂ will be fixed as magnesite in **22 years for sample A, a harzburgite serpentinite**, and in **3 years for sample B, a dunite serpentinite**. These periods are very short compared with other types of rocks like basalt, granite, and sedimentary rocks from Japan studied in our laboratory. This indicates that the **serpentinite rocks are potentially useful aquifer host rocks for underground sequestration of CO₂**.

Swanson, E. J. (2014) Accelerated weathering of ultramafic rocks is an environmentally benign route to a thermodynamically and kinetically stable form of carbon. However, the reactions are relatively slow and achieving the reaction rates necessary to justify incorporation into an energy conversion system is challenging. Comparing the freshly ground olivine cases with the literatures values, it is evident that the particle size, **particularly smaller than 20 μm**, is significantly involved in mineral dissolution and carbonation.

One conclusion was that **even without the pretreatments, some of the Mg-bearing minerals showed promising results for carbon storage**. However, the conversion of **magnesium serpentine** [Mg₅(CO₃)₄(OH)₂·4H₂O] to anhydrous magnesium carbonate [MgCO₃] is a challenging reaction to achieve reliably and reproducibly at reasonable process conditions. The persistence of metastable magnesium carbonate species reduces the overall efficiency of a carbon mineralization process due to the bulky nature and solubility limitations of the hydrated magnesium carbonates. In this study it was shown that **the presence of magnesite seeds avoided the formation of metastable species entirely**. It was also shown that it is **possible to grow magnesite crystals below 100 °C and with low CO₂ partial pressures, something that was previously thought far more difficult**.

Werner, M.S. (2014) The challenge of using **serpentine** to sequester CO₂ is tackled by carbonating the magnesium silicate serpentine, the world's most abundant mineralization precursor that can be **thermally activated for enhanced reactivity, in an aqueous medium at low CO₂ pressures**. Key to success for any aqueous mineralization process is to understand how to overcome the slow dissolution kinetics of the mineralization precursor.

The results suggested that the reaction progress was hindered by a **passivating layer of re-precipitated silica, quartz, or carbonates**, as well as by equilibrium limitations. Various strategies to improve the carbonation efficiency were tested. The logical next step in process development was to explore the carbonation potential of the activated serpentine at flue gas conditions.

The batches of Ca- and Mg-silicates used were subjected to mechanical pretreatment by **attrition grinding**, in order to maximize the specific surface of the minerals, i.e., the surface per unit mass available for Mg/Ca-extraction. Attrition grinding is a process in which the rock is ground over a sieve. Particles that are small enough to pass through the sieve are removed and only unground rocks remain. With time they are also ground up and pass through the sieve, i.e. by attrition.

The hydrated Mg-silicate serpentine was **thermally activated**, which creates an even higher specific surface area and destabilizes the crystal lattice, thus making the mineral more susceptible to dissolution.

Chemical additives were used to increase the ionic strength and the alkalinity of the solution. Obviously, any additive would have to be fully recoverable in a real process. While the single-step ARC process can be viewed as a benchmark, research has ever since striven after further improvements of the technology at affordable cost. Double-step and multi-step process designs were developed that allow for changing the operating conditions between the different stages, so as to promote extraction and precipitation separately.

To avoid the cost associated to a preliminary capture step, the most recently proposed routes aim at capturing the CO₂ from a **flue gas** at the same time while mineralizing it. Many of these studies relate to the utilization of flue gas. This is the gas that emanates from coal fired power plants.

The following table is an overview of the most important CO₂ mineralization techniques.

Processes		Suitable solid feed	Operating T [$^{\circ}\text{C}$]	Operating $p\text{CO}_2$ [bar]	Additives
Single step aqueous carbonation	ARC benchmark	wollastonite, silicious waste materials	>100	>15	optional (NaHCO_3 , NaCl)
		olivine, HT serpentine and mine tailings	>150	>80	optional (NaHCO_3 , NaCl)
		CaO-rich waste materials	<100	<3	none
Double step aqueous carbonation	pH-swing	any	various	various	strong base, strong acid
		any	<100	<1	NH_4SO_4
	pH-buffer	wollastonite, waste materials	various	$p\text{CO}_2$ -swing	pH buffer agents
	T - $p\text{CO}_2$ -swing	HT serpentine, waste materials, wollastonite	T -swing	$p\text{CO}_2$ -swing	none
Aqueous carbonation using ligands		olivine, serpentine	<120	various	chelating agents
ÅA process (3-step)	NH_3 -driven precipitation	serpentine	400, 20, 500	20	NH_4SO_4
Alkaline solution based	manufactured alkalinity	brines, red mud	low to moderate	low to moderate	alkalinity (NaOH)
Single step dry carbonation		CaO-rich waste materials (APC-residues, fresh concrete)	25–500	various	none

Du Breuil, et al (2019). Serpentine minerals ($\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$) have shown great potential for carbonation. **A way to improve yield is to thermally activate serpentine minerals prior to the carbonation reaction.** This step is of great importance as it **controls Mg^{2+} leaching, one of the carbonation reaction limiting factors.** Previous studies have focused on the optimization of the thermal activation by determining the ideal activation temperature. However, to date, none of these studies have considered the impacts of the thermal activation on the efficiency of the aqueous-phase mineral carbonation at ambient temperature and moderate pressure in **flue gas conditions.** Several residence times and temperatures of activation have been tested to evaluate their impact on serpentine dissolution in conditions similar to mineral carbonation. A novel approach in order to quantify the meta-serpentine formed during dehydroxylation is introduced. The most suitable mineral assemblage for carbonation is found to be a mixture of the different amorphous phases identified. This study highlights the importance of the mineralogical assemblage obtained during the dehydroxylation process and its impact on the magnesium availability during dissolution in the carbonation reaction.

Thermally produced amorphous phases enhance Mg^{2+} solubility during carbonation reaction. Furthermore, the formation of meta-serpentine, resulting in a complete dehydroxylation, significantly upgrades Mg^{2+} leaching yield.

Haque, F. et al. (2019) Candidate materials for enhanced weathering **olivine**, pyroxene and **serpentine**, given their reactivity with CO_2 and global availability. When these **finely crushed silicate rocks are applied to the soil, the alkaline earth metal cations released during mineral weathering** gradually react with carbonate anions and results in the formation of pedogenic carbonates which, over time, and under the right conditions, can accumulate in the soil. The CO_2 sequestration potential via alkaline mineral soil amendment is quantified and shows that it has the potential to serve as a climate change stabilization wedge. **The important aspect of this report is the conclusion that the only pretreatment required is finely grinding the respective rocks.**

Tebbiche, I. et al (2021) In this paper, **heat integration was coupled with serpentine preheating temperature** optimization. This was the first time applied to a mineral carbonation process. For this, a process was selected with **the aim to minimize its heat demand.** Aspen® Energy Analyzer software was used for heat integration with pinch analysis. The mineral carbonation plant considered here **processes 100 tons of serpentine per hour**, with Mg content of 237 kg per ton of rock, corresponding to 0.88 million tons per year to treat 0.5 million tons of CO_2 emitted from a cement plant. In the base case considered for heat integration, 50% of the serpentine magnesium content was converted to hydromagnesite using 30% of the flue gas CO_2 which means that **5.85 tons of rocks were required to capture 1 ton of CO_2 .**

The serpentine **preheating temperature** was optimized as 400 °C. Application of heat integration at this solid preheat temperature reduced the process heat demand by 25% compared to our previous study, as 5.0 GJ per ton of CO_2 captured or 9.5 GJ per ton of CO_2 avoided. This corresponds to 0.86 GJ per ton of ore as the process heat demand was only attributed to the mineral activation. Furthermore, the uncertainty behind unknown parameters such as activated serpentine heat capacity and solid heat transfer coefficient was evaluated to validate the study.

IV. Serpentine Dissolution: Field Studies on Cropland or Simulated Field Studies

Baumeister (2012) The author's studies were for a master's thesis and was entitled **Chemical Weathering of the Mafic Minerals Serpentine and Olivine in Natural Environments**. This covers the information relevant to what we are seeking, i.e., **what is the natural weathering rate of serpentine compared to olivine**.

Significant amounts of carbon dioxide are consumed during the natural weathering process, or dissolution, of the mafic minerals, olivine and serpentine. There have been many studies of the rate of olivine in the laboratory (see references in the thesis). **By contrast, serpentine dissolution studies performed at temperatures and pH ranges relevant to the natural environment are very limited.**

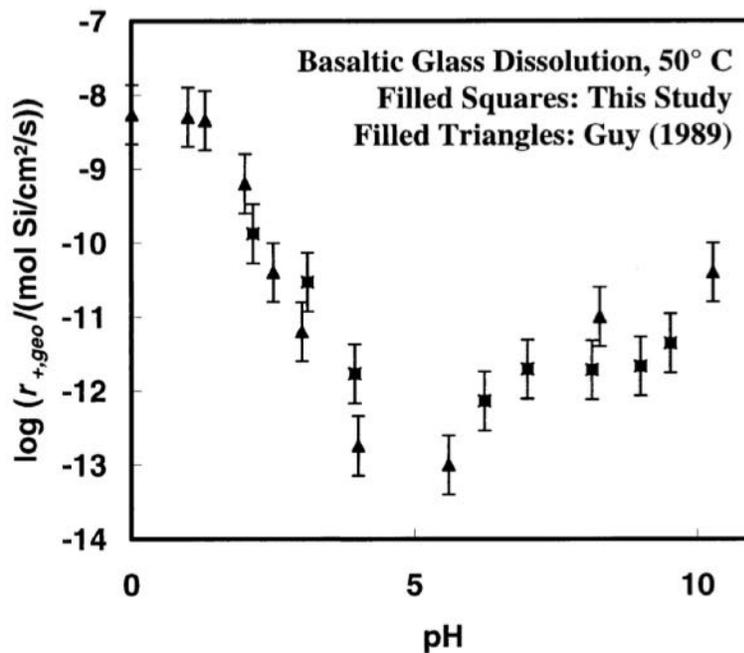
A serpentine dissolution rate was measured in **a natural setting using catchment hydrochemical data which was orders of magnitude slower than published laboratory rates**. Most studies of **serpentine in a natural setting have focused on soil** and secondary mineral formation (see thesis for references).

The authors studied the characteristics of serpentinite weathering from the unweathered parent rock **to the soil surface at two sites in the Klamath Mountains of northern California**. Samples of both soils and rock cores from each study site tested positive for iron-oxidizing bacteria, and signs of oxidized iron were observed on weathering rinds in the soil and rock cores. In the weathered samples, mineral dissolution appears to follow a specific order (from first to dissolve to most resistant): pyroxene > iron-rich serpentine > magnesium-rich serpentine > aluminum-rich serpentine. This mineral order is likely based on mineral dissolution kinetics, possible effects of biological iron-oxidation, and cation substitutions that can act to stabilize the mineral structure.

In addition to the Klamath sites, the authors also examined the dissolution of olivine in a natural environment at Black Rock Flow, **in central Nevada**. These findings help quantify the incipient processes affecting serpentine soil formation and provide the first known dissolution rate for naturally-weathered olivine **in an arid environment**. The **forsterite** dissolution rate measured from etch pits, after adjusting for roughness, is 3.48×10^{-15} mol/m²/s, which is approximately **four to five orders of magnitude slower than published laboratory dissolution rates** at a pH of ~7-9

V. Basalt Dissolution: Laboratory Studies

Gislason and Oelkers (2003) examined the dissolution rates of basaltic glass at 50°C and showed an inverted curve with the lowest rates of 10^{-13} mol Si/cm²/s at pH 5.

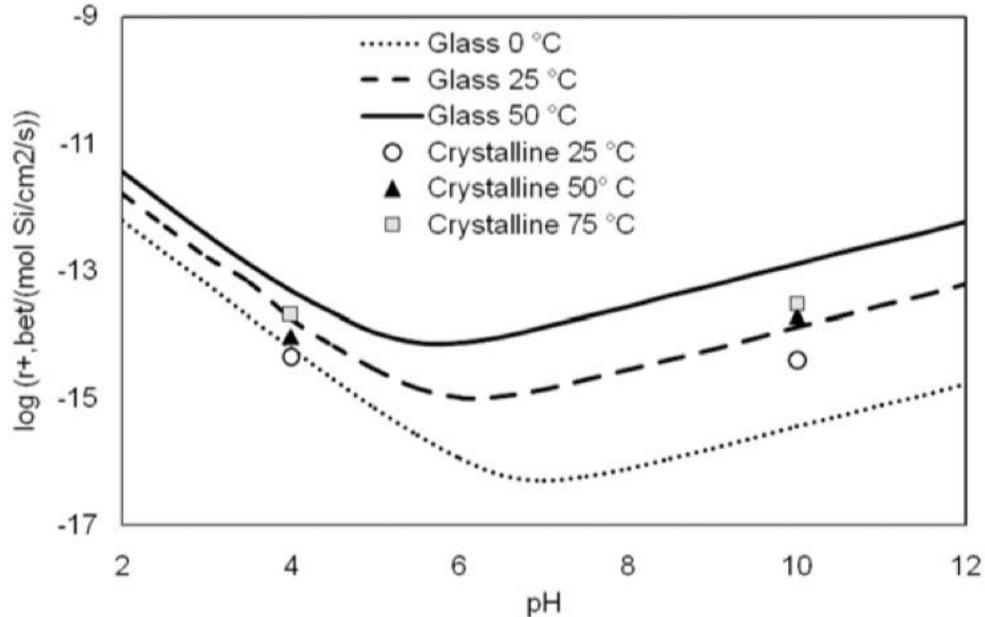


Variation of measured geometric surface area normalized basaltic glass dissolution rates at 50°C as a function of pH.

Golubev et al (2005) also examined the dissolution rates of basaltic glass at 50°C at various pHs and obtained an inverted curve with it lowest rate at pH 6. Their curve is presented above in the diagram shown by Snæbjörnsdóttir et al (2020) above.

Gudbrandsson, S.et al. (2008) examined basalts from a dyke on Stapafell Mountain on Reykjanes peninsula in Iceland because of its similarity with previous experiments on dissolution rates on basaltic glass by Oelkers and Gislason (2001) and Gislason and Oelkers (2003).

DISSOLUTION RATES OF CRYSTALLINE BASALT



Dissolution rates of crystalline basalt (symbols) are compared to modelled dissolution rates (curves) of basaltic glass from the same location (Gislason and Oelkers, 2003).

Comparison of dissolution rates of basaltic glass and of crystalline basalt of similar chemical composition (from Gislason and Oelkers, 2003) indicates slightly lower rates for crystalline material.

These three studies indicate that the unique inverted curve for dissolution rates of basalt by pH is reproducible.

VI. Basalt Dissolution: Field Studies on Cropland or Simulated Field Studies

Kelland et al, (2020) Land-based enhanced rock weathering (ERW) is a biogeochemical carbon dioxide removal (CDR) strategy aiming to accelerate natural geological processes of carbon sequestration **through application of crushed silicate rocks, such as basalt**, to croplands and forested landscapes. However, the efficacy of the approach when undertaken with basalt, and its potential co-benefits for agriculture, require experimental and field evaluation. Here they report that **amending a UK clay-loam agricultural soil with a high loading (10 kg/m²) of relatively coarse-grained crushed basalt significantly increased the yield (21 ± 9.4%, SE)** of the important C4 cereal Sorghum bicolor under controlled environmental conditions, without accumulation of potentially toxic trace elements in the seeds. Yield increases resulted from the basalt treatment after **120 days** without P- and K-fertilizer addition. **Shoot silicon concentrations also increased significantly (26 ± 5.4%, SE)**, with potential benefits for crop resistance to biotic and abiotic stress. Elemental budgets indicate substantial release of base cations important for inorganic carbon removal and their accumulation mainly in the soil

exchangeable pools. Geochemical reactive transport modelling, constrained by elemental budgets, indicated CO₂ sequestration rates of 2–4 t CO₂ /ha, 1–5 years after a single application of basaltic rock dust, including via newly formed soil carbonate minerals whose long-term fate requires assessment through field trials. **This represents an approximately fourfold increase in carbon capture compared to control plant–soil systems without basalt.** Our results build support for ERW deployment as a CDR technique compatible with spreading basalt powder on acidic loamy soils common across millions of hectares of western European and North American agriculture.

Rinder, T. and von Hagke, C. (2021) reviewed the state of research for enhanced weathering of basalt. A < 10 µm grain size could remove ≈2% of Austria's greenhouse gas emissions per year. For larger grain sizes, transport emissions become important. Field weathering rates reduce the sequestration potential estimated in previous studies. Uncertainties related to actual CO₂ drawdown under field conditions are still large.

This article reviews of the current state of research and estimates the CO₂ drawdown for scenarios **using basalt powders of different particle size distribution (<100 µm, <10 µm and <1 µm)**. Calculated with a modified shrinking core model, the amount of powder dissolved within a timeframe of 10 years is approximately **16% (<100 µm), 55% (<10 µm) and 99.9% (<1 µm)**. This corresponds to a gross CO₂ removal of 0.045 t CO₂/ t for <100 µm particle size, and 0.153 t CO₂/ t of <10 µm rock. Our estimates suggest that **enhanced weathering will only significantly contribute to net CO₂ drawdown if grain sizes (<10 µm) are used.** Under these conditions the large-scale application of particles with a diameter <10 µm may remove about 2% of Austria's annual Greenhouse gas emissions.

They discuss challenges towards this goal, including the enormous amounts of rock needed and the energy requirement related to grinding, as well as uncertainties related to actual field weathering rates. Those uncertainties hinder the precise quantification of CO₂ drawdown as of now. While enhanced weathering remains a promising path for climate change mitigation, further research at laboratory and field scale is required to put this technology to optimal use.

Houlton, (2021) Dr. Benjamin Houlton of the Global Environmental Studies, John Muir Institute of the Environment, at the University of California, Davis, has examined the effect of mafic rocks on **a 50 acre test plot in California**. The results have not been published but were described in an *Energypost.eu* July 24, 2021 article entitled *Enhanced Weathering: Crushed Rocks Spread on Farmland can Capture Billions of Tons of CO₂/year*.

Houlton stated that “At the Working Lands Innovation Center, we are conducting **perhaps the largest enhanced weathering demonstration experiment on real farms in the world.** We are partnering with farmers, ranchers, government, the mining industry and Native American tribes in California on some 50 acres of cropland soil amendment trials. We are testing the effects of rock dust and compost amendments on greenhouse gas emissions from the soil, carbon capture, crop yields, and plant and microbial health. Our initial results suggest that **adding basalt and wollastonite, a calcium silicate mineral, increased corn yields by 12% in the first year.**”

“Nations need a portfolio of solutions to create negative emissions. Enhanced weathering is poised for rapid scale-up, taking advantage of farm equipment that is already in place, global mining operations and supply chains that currently deliver

fertilizers and seeds worldwide. By addressing soil erosion and food security along with climate change, I believe rock weathering can help humans escape the hard place we find ourselves in today.”

VII. Wollastonite Dissolution: Field Studies on Cropland or Simulated Field Studies

Hague, et al (2020a) Wollastonite (CaSiO_3) has been commercialized in Ontario as an agricultural soil amendment for several years, but it is not known if or how much CO_2 is sequestered annually. In this present study, wollastonite-amended soils were collected from three commercial-scale fields located in Ontario: a leafy vegetables farm in the town of Paris (Field 1); a potato farm in the settlement of Alliston (Field 2); and a soybean farm in the city of Woodstock (Field 3). The **soil inorganic carbon (SIC)** content was higher in all soils that had been amended with wollastonite, compared to controls, and in **Field 1 the SIC content was 2.6 times higher in soil amended thrice with wollastonite compared to a single application**. This work provides further evidence, here for the first time at a regional scale, that soil amendment with alkaline silicates can be an effective geoengineering tool for climate change mitigation.

Haque et al (2020b) The first objective of this study was to evaluate the effect of **mixing a wide range of dosages of wollastonite**, as a soil amendment, **on the growth performance of two leguminous plants frequently used in agricultural sector: soybean and alfalfa**. The plants were grown with **different wollastonite dosages ($3\text{--}20 \text{ kg}\cdot\text{m}^{-2}$ for soybean and $3\text{--}40 \text{ kg}\cdot\text{m}^{-2}$ for alfalfa)**, for a duration of 14 weeks in a microplot experiment in Ontario, Canada. The second objective was to find evidence of enhanced weathering of wollastonite in soil, in addition to the augmentation of inorganic carbon content in soil. **Wollastonite increased the soybean yield by two-fold in the plot amended with $10 \text{ kg}\cdot\text{m}^{-2}$** . At all dosages, wollastonite increased the alfalfa growth in terms of height and above-ground biomass dry weight, as well as root biomass. The rate of CO_2 sequestration, at optimum wollastonite dosage, reached $0.08 \text{ kg CO}_2/\text{m}^2/\text{month}$. XRD and SEM-EDS analyses indicated accumulation of calcite in wollastonite-amended soil and formation of other weathering products. **The results obtained from this study help to understand the impact of wollastonite soil amendment on agronomy and will aid in implementing such negative emissions technology by informing farmers and industry alike that the use of wollastonite contributes toward global climate change mitigation while supporting crop yield**. The findings of this study add to the existing body of knowledge on enhanced weathering as an atmospheric CO_2 removal technology, providing further evidence that wollastonite weathering in agricultural soils can lead to significant capacity for CO_2 sequestration as inorganic carbon, while concurrently promoting plant growth.

VIII. Concurrent Grinding

Concurrent grinding refers to incorporating low energy, attrition-type grinding during the reaction of serpentine rocks with heat, acid or other chemical or physical treatments. Since several studies have shown that it is a very efficient method of dissolution of serpentine. There are two aspects to the development of this technique. The first is the use of strong acid ($< 1\text{M}$) to the dissolution of serpentine. The second was the use of concurrent grinding while **in the presence of the acid**.

Klaus Lackner et al (1995) were the first to propose carbon dioxide sequestration by the **dissolution of serpentine in strong acid**. They found that the thermodynamics for both the dissolution of serpentine and the formation of carbonates were favorable.

Albany Research Center The Lackner paper led to many studies of the potential role of the carbonation of several minerals. As reviewed above, O'Connor and his team at the Albany Research Center conducted several studies on CO₂ at high pressure for the direct carbonation of serpentine. It was found, however, that pre-treatments such as roasting the serpentine at high temperature and/or grinding to a fine size, were necessary. These treatments resulted in an amorphous structure of the serpentine. This removed the highly ordered structure of serpentine allowing different reagents to interact with the interior metals. The problem with these treatments was that they were very expensive. The level of this expense slowed enthusiasm for these techniques, work continued.

A potential solution of splitting the chemistry into two steps: a chemical extraction of magnesium at low pH and carbon dioxide adsorption at high pH. was proposed by Park et al (2003, 2004). She and her colleagues showed that use of both a mixed acid/organo-ligand solution and internal *in situ* grinding enhanced dissolution. They found that by slowly increasing the pH of the solution, impurities could be precipitated out, and then by addition of carbon dioxide at atmospheric pressures and temperatures, magnesium carbonate would form. It was also demonstrated that the kinetics of **the extraction of magnesium from serpentine could be at least doubled by the incorporation of a low energy, attrition-type grinding during the dissolution, i.e., concurrent grinding**.

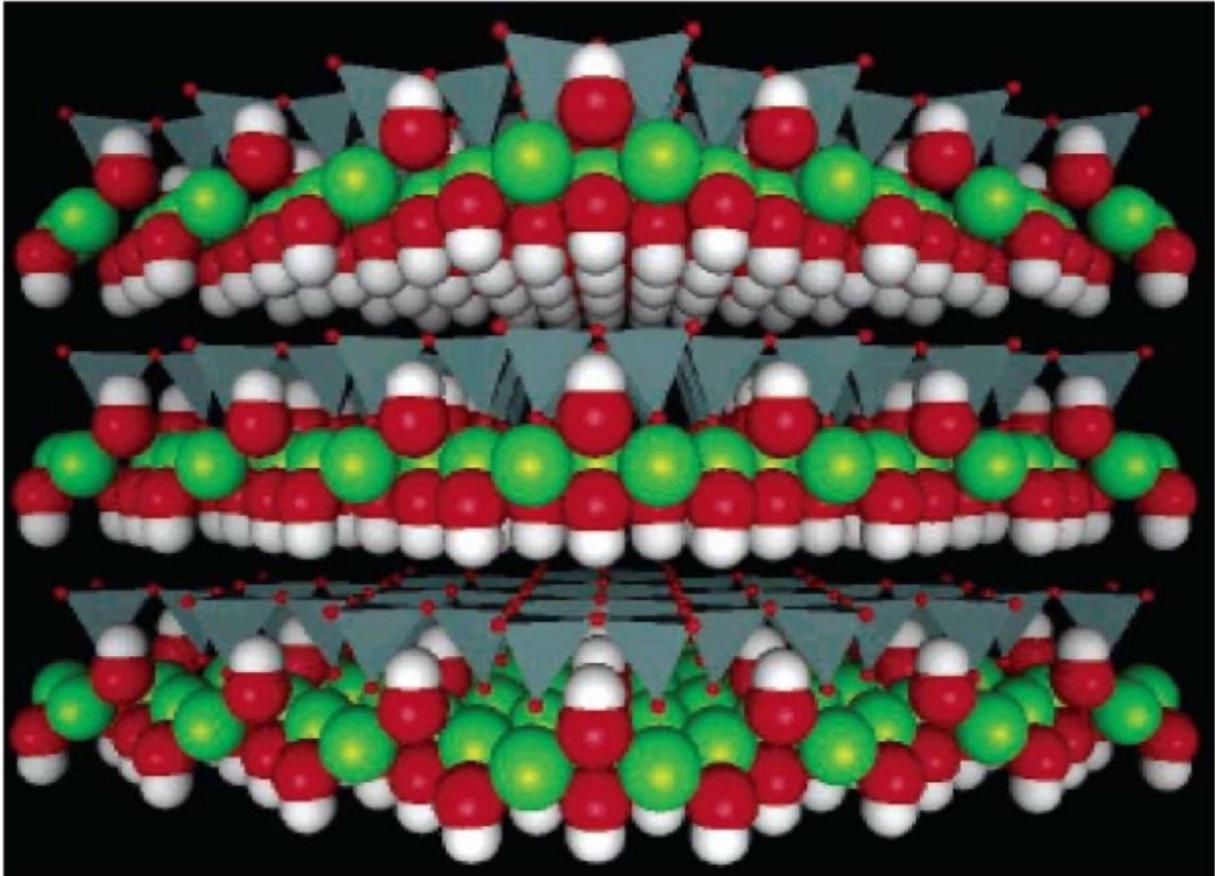
Previous studies demonstrated that **a silica diffusion barrier forms on the surface of serpentine** particles as dissolution occurs and that this can effectively slow or even stop the digestion kinetics of serpentine in acid. The **concurrent grinding solves this problem**. That grinding is done by fluidizing silica beads with the reaction slurry of acid and mineral particles. The apparent advantage is rapid refreshment of the surface at energy levels that are expected to be consistent with a fluidized-bed reactor or a rapidly agitated continuously stirred tank reactor (Park and Fan, 2004). A draw-back was that the fluidization was done in a complex system of expensive chemicals. In addition, kinetics of the system was not provided, thus limiting comparisons to other proposed methods.

Tier, et al, (2007) (see also above) found that sulfuric acid extracted the most magnesium from serpentine in the shortest time and that the extraction yield did not increase past two molar concentration for sulfuric acid and examined kinetics.

Van Essendelft, (2008, 2009a,b, 2010) examined the kinetics of **concurrent grinding in acid**. Serpentine is a highly ordered ultramafic magnesium silicate structure consisting of alternating sheets of **brucite**-like material and **silica**-like material. This highly ordered structure causes the formation of a silica barrier around the mineral particles that can slow or even stop the kinetics as the particles dissolve. The physical behavior of this layer causes a shift in kinetic behavior from surface limited kinetics to diffusion limited kinetics. However, it has been shown that both behaviors are important at the same time and vary by particle size. Further, it has been shown that **the kinetics can be greatly accelerated by incorporating concurrent, low energy,**

attrition-type grinding during the chemical reaction. It was found that particle shape as well as size plays a critical role in the kinetics.

The following diagram shows the three-dimensional structure of serpentine.



The Ideal Structure for Serpentine (McKelvy, et al (2004)

The grey tetrahedrons with red tipped ends are silica groups, the large green spheres are magnesium, and the red and white conjoined spheres are hydroxides. It is a very ordered structure with silica groups bound together in their basal plane and a brucite-like sheet sharing the electro-negativity of the antipodal oxygen of the silica.

There were three important results from this study. First, **simultaneous acid etching and grinding with a single strong acid significantly increase the overall reaction rate and yield.** The author felt that an extraction of such high conversion in such short time with this type of serpentine without solids modification or pretreatment has not previously been reported in the literature. Second, the acid etching prefers grain boundaries and defects, as is expected. This suggests that **a focus on comminution techniques that can impart high amounts of structural defects could be helpful.** Third, and most importantly, **grinding is not sufficient to keep surfaces refreshed under the current conditions.** That is, the initial stages of digestion proceed quickly and appear to be surface-reaction limited, while the later stages appear to be diffusion limited. Using a modified shrinking core model with a hypothetical spherical particle size

distribution (PSD), the effect of grinding appears to change the effective diffusivity of the gel layer surrounding the un-reacted core.

In conclusion, **it was demonstrated that the combination of physical and chemical methods can lead to greatly increased kinetics.** Further, it has been shown that **simple strong acids can be used to greater effect than mixtures of acid and organic agents.**

Rashid et al, (2019) Vast reserves of **peridotite** and **serpentinite** rocks can be utilized for the safe and permanent sequestration of global CO₂ emissions via aqueous mineral carbonation. These, and indeed most feedstocks used in mineral carbonation **require ultrafine grinding and/or heat-activation, to engender significantly enhanced reactivity in the rock such that it can then be carbonated.** Both activation processes are energy intensive and present significant obstacles to the commercial application of mineral carbonation. Here we show that these limitations can be addressed, at least in part, through the application of a **concurrent or in operando grinding technique** which **does not require feedstocks which have been subjected to prior ultrafine grinding nor heat-activation.**

Concurrent (in operando) grinding experiments. the **dunite slurry** was charged into the reactor liner, along with grinding media. The reactor was assembled and **heated** to the desired temperature. The reactor was then pressurized with CO₂ to 65 or 130 bar and carbonation and grinding proceeded simultaneously for the desired time period.

Thus, unlike the previous studies where concurrent meant concurrent with strong acid, in the **Rashid et al studies concurrent meant along with grinding media, heat, and pressurized CO₂.**

Concurrent grinding is shown to result in a significant increase in magnesite yields for non-heat activated feedstock, prepared such that fines (<20 µm particles) were excluded from the feed. They assert that concurrent grinding may be a suitable technique for the processing of feedstocks such as those containing significant proportions of **forsterite and pyroxene**, minerals which are unresponsive to thermal activation for use in aqueous mineral carbonation. This study also investigates the effect of different grinding media particle size on reducing the PSD of the feed. Optimum ratio of grinding media size to feed particle size, optimum grinding media and slurry concentrations, optimum time for grinding and optimum impeller designs are determined for the system under study. The quantitative effect of grinding media concentration, slurry concentration, pressure and temperature on magnesite yield has been investigated.

For ***in situ* grinding experiments, grinding and carbonation occur in separate steps.** **Concurrent (in operando) grinding during carbonation** under the same conditions of pressure, temperature and solids loading **resulted in higher final magnesite yields** compared to *in situ* grinding experiments.

The authors concluded that concurrent grinding may be a suitable technique for the processing of feedstocks such as those containing significant proportions of forsterite and pyroxene, minerals which are unresponsive to thermal activation for use in aqueous mineral carbonation.

Rahsid, et al (2021)

- **Concurrent grinding results six times higher magnesite yields.**
- **Concurrent grinding disintegrate silica-rich layers.**
- Zirconia and stainless steel are better grinding media than alumina.

- Silica re-precipitation on grinding media was observed.
- Dunite is more reactive compared to olivine and lizardite.

Formation of silica-rich passivation layers formed on the periphery of reacting feed particles is one of the primary obstacles in obtaining high magnesite yields during direct aqueous mineral carbonation of peridotites and serpentinites. The disruption of the silica-rich layer around partially reacted grains as a result of concurrent grinding on the degree of carbonation (magnesite yield) was investigated in this work. Three types of naturally-occurring magnesium silicate feedstocks, dunite, olivine and lizardite, as well as three types of grinding media, were examined.

Discrete size fractions of feed samples, with and without grinding media, were carbonated. SEM readily disclosed the formation of a **silica-rich shell around a magnesium rich core** during carbonation. EDS analysis was employed to study the elemental composition of reacted particles' shell and core. The method confirmed that **during concurrent grinding these silica rich layers were removed** and continuously produced a fresh surface available for further reaction. **The removal of the silica rich layer was shown to significantly improve magnesite yields up to a 600 % increase in yield.** Among the three different grinding media used in this work, zirconia and stainless steel media resulted in similar and highest magnesite yields, which is believed to be due to a combination of their high densities and hardness.

The findings of this research showed that enhanced magnesite yields could be achieved for all feedstock without the need for energy intensive pre-treatment steps (e.g., ultrafine grinding and heat-activation). Moreover, concurrent grinding resulted in a magnesite yield when raw lizardite was carbonated.

IX. Olivine: The Potential Role of Electrolysis

Electrolysis played a prominent role in OAE (see below). Does it also have a role to play in EW of cropland?

Zong-ging, (2007) describe a novel method for promoting carbon sequestration by mineral carbonation using electrolysis, which used the electrolytic reactor to electrolyze NaCl solution. The acid solution produced from anode was used to dissolve Mg^{2+} from serpentine, and the basic solution produced from cathode was used to adsorb CO_2 in simulation smoke, then these two solutions were mixed to form $MgCO_3$ deposition. The results indicate that the highest current efficiency could be when current was 0.5A. The acid solution produced from anode can dissolve Mg^{2+} . It was found that the deposition was mainly pure basic magnesium carbonate $[Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O]$, which was both environmentally benign and economical. **The reactions can be processed at low pressure and relatively low temperature, and the pure H_2 , Cl_2 and pure solid products can be obtained in this process**, which makes the mineral carbonation process more economical.

Park, et al, (2015) This study proposes a method to fixate $CaCO_3$ stably by using relatively less energy than existing methods. After forming NaOH absorbent solution through electrolysis of NaCl in seawater, $CaCO_3$ was precipitated at room temperature and pressure. The analytical results showed that the $CaCO_3$ crystal product was high-purity calcite. The study shows a successful method for fixing CO_2 by reducing carbon dioxide released into the atmosphere while forming high-purity $CaCO_3$.

Kaczur et al, (2018) The recent development and market introduction of a new type of alkaline stable imidazole-based anion exchange membrane and related ionomers by Dioxide Materials is enabling the advancement of new and improved electrochemical processes which can operate at commercially viable operating voltages, current efficiencies, and current densities. These processes include the electrochemical conversion of CO₂ to formic acid (HCOOH), CO₂ to carbon monoxide (CO), and **alkaline water electrolysis, generating hydrogen** at high current densities at low voltages without the need for any precious metal electrocatalysts. The latter is an alkaline water electrolysis cell process, where the alkaline stable anion exchange membrane allows stable cell operation in 1 M KOH electrolyte solutions at current densities of 1 A/cm² at about 1.90 V. The cell has demonstrated operation for thousands of hours, showing a voltage increase in time of only 5 μV/h. The alkaline electrolysis technology does not require any precious metal catalysts as compared to polymer electrolyte membrane (PEM) design water electrolyzer.

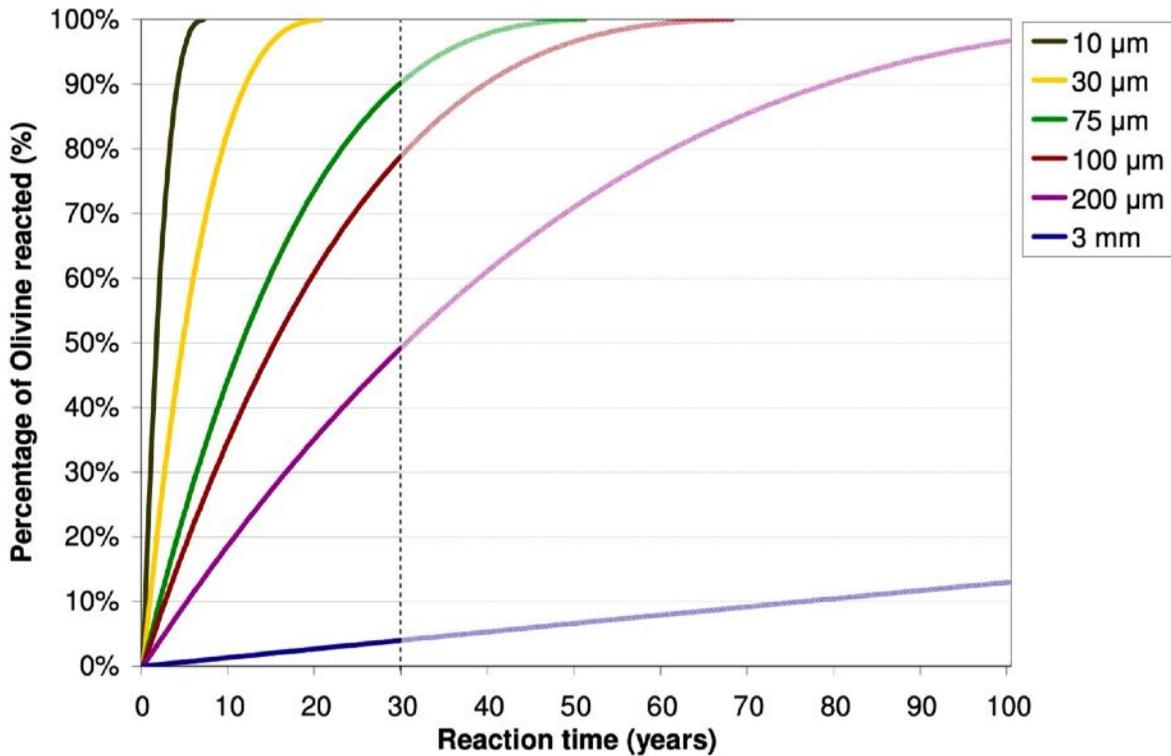
X. Serpentine: The Potential Role of Electrolysis

Li et al, 2009) described a new mineral carbonation process for CO₂ sequestration, using **electrolysis of NaCl solution and serpentine** as the source of Mg²⁺ to adsorb CO₂ in the **simulating flue gas**. It used the electrolysis of a NaCl solution to produce the HCl and NaOH. **The HCl solution was used to dissolve Mg²⁺ from serpentine**, and the **NaOH solution was used to adsorb CO₂** in simulation smoke, then these two solutions were mixed to form MgCO₃ deposition at 358 K, which could be processed at relative low temperature and pressure. In order to further increase the solubility of Mg²⁺ from serpentine.

The heat pretreatment of serpentine under nitrogen was investigated. The results indicated that the **heat activation dramatically enhanced serpentine carbonation**. The best activation temperature was 650°C, at which the crystalline features were changed from lizardite to amorphous followed the decomposition of hydroxyl groups.

XI. The Koorneef et al (2009) Study

Koorneef et al (2009) After the above research was complete, I found this study by Koorneef et. al. (2009). They studied the percent of olivine reacted for different size particles of olivine ranging from 3 mm to 10 um. Their results are shown as follows.



Relationship between reaction time and percentage of olivine reacted for various particle diameters. The rate of dissolution is assumed to be 6.0×10^{-8} moles/m²/minute and molar density is assumed to be 23,245 mol/m³. This is the dissolution rate that corresponds to a pH found in soil and rainwater (Hangx and Spiers 2009).

These results were calculated using the following formula.

$$1 - (1 - X)^{1/3} = \frac{R}{\rho * d} * t$$

X = fraction reacted
R = rate of dissolution (6.0 * 10⁻⁸ moles*m⁻²*minute⁻¹)
ρ = molar density (23245 mol/m³)
d = particle size (10, 30, 75, 100, 200 μm and 3 mm)
t = reaction time in minutes

Since these results are based on the reduction in size of the particles over time, it is clear that the smaller the starting particle the faster it will progress to complete dissolution. Clearly, a particle size of 1 μm would progress to 90% of complete dissolution in a year or less. These results involved no acid, no salt, no high temperatures, no concurrent grinding.

While we will examine this experimentally in our 3-site research proposal (see below), this tends to validate the International Program of **MINE, GRIND, SPREAD** and **SEQUESTER** outlined below.

Summary So what have we learned from this extensive review? There are several lessons.

- Despite the rather voluminous literature on the dissolution and carbonation of ultramafic rocks, **there have been remarkably few actual field studies of EW with olivine on croplands and even fewer of serpentine and basalt on croplands.**

- There are **even fewer studies that examine multiple variables** such as particle size, olivine versus serpentine versus basalt, the need for pretreatments such as high temperature, high salt concentration, use of concurrent grinding and others.

- There have been no studies **comparing research field plots in temperate dry, versus temperate wet, versus tropical wet hot spot sites.**

- Of all the physical or chemical enhancements **grinding to a fine size appears to be the simplest and most economical.** Field tests involving different particle sizes for all multiple rock types, including serpentines, are needed.

- Despite the many studies of the use of acid, salts, pressure and other variables in the enhancement of ultramafic rock dissolution, none of these seem suitable to EW on croplands. As shown in the Koorneef et al (2009) simply grinding to a 1 um size may be adequate for both olivines and serpentines.

Our 3-site research, see below, will test these different variables.

Nitrous oxide N₂O

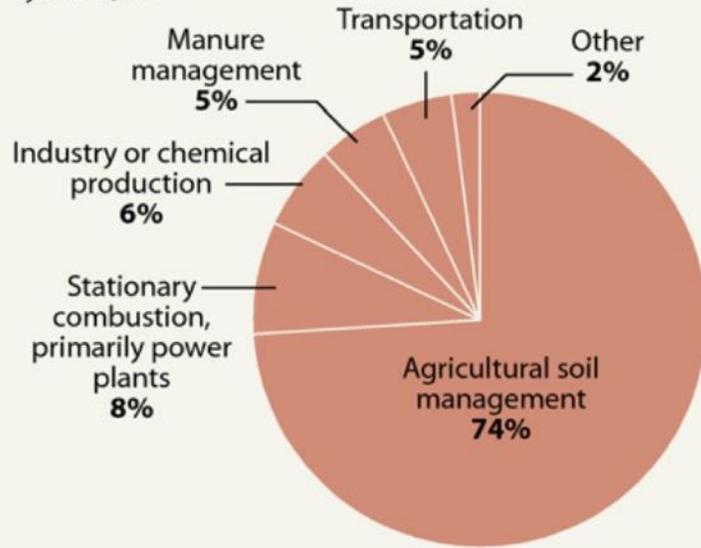
One pound of N₂O warms the atmosphere about 300 times the amount that one pound of carbon dioxide does over a 100-year timescale. Its potency and relatively long life make N₂O a dangerous contributor to climate change. It also depletes the ozone layer. As shown below, about three fourths of N₂O comes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

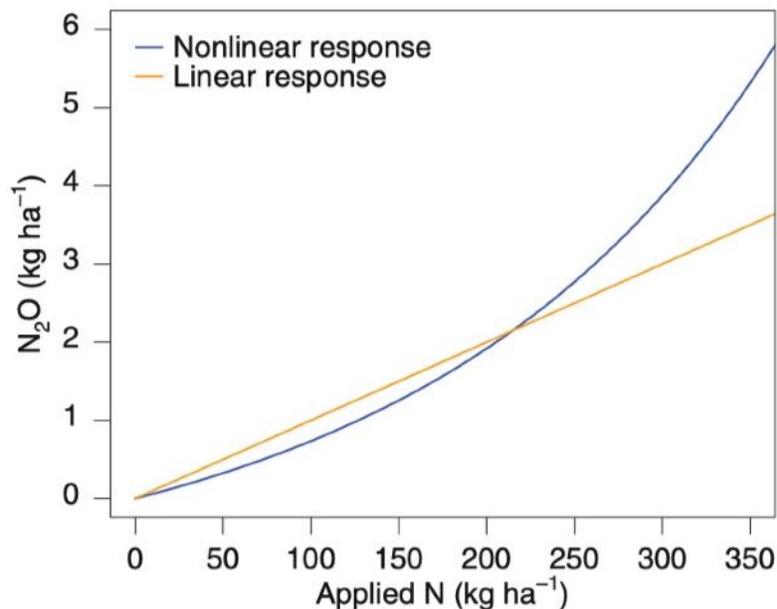
Beerling, et al (2018) concluded that substituting a weatherable silicate rock, such as basalt, or silicate waste, for limestone, and increasing application rates over those used in conventional liming operations, **may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy.**

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, (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.

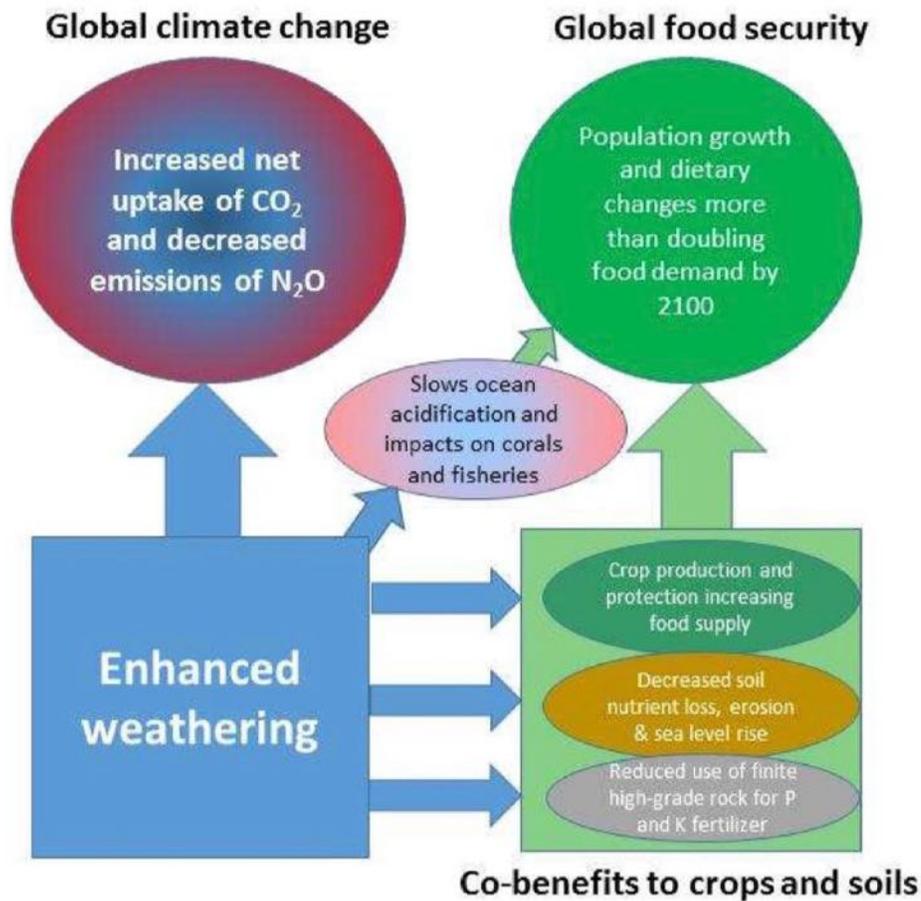
Breider, et al (2019) showed that when pH was reduced, the N₂O production rate during nitrification measured at subarctic stations increased significantly while nitrification rates remained stable or decreased. Contrary to previous findings, these results suggest that the effect of ocean acidification 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.**

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



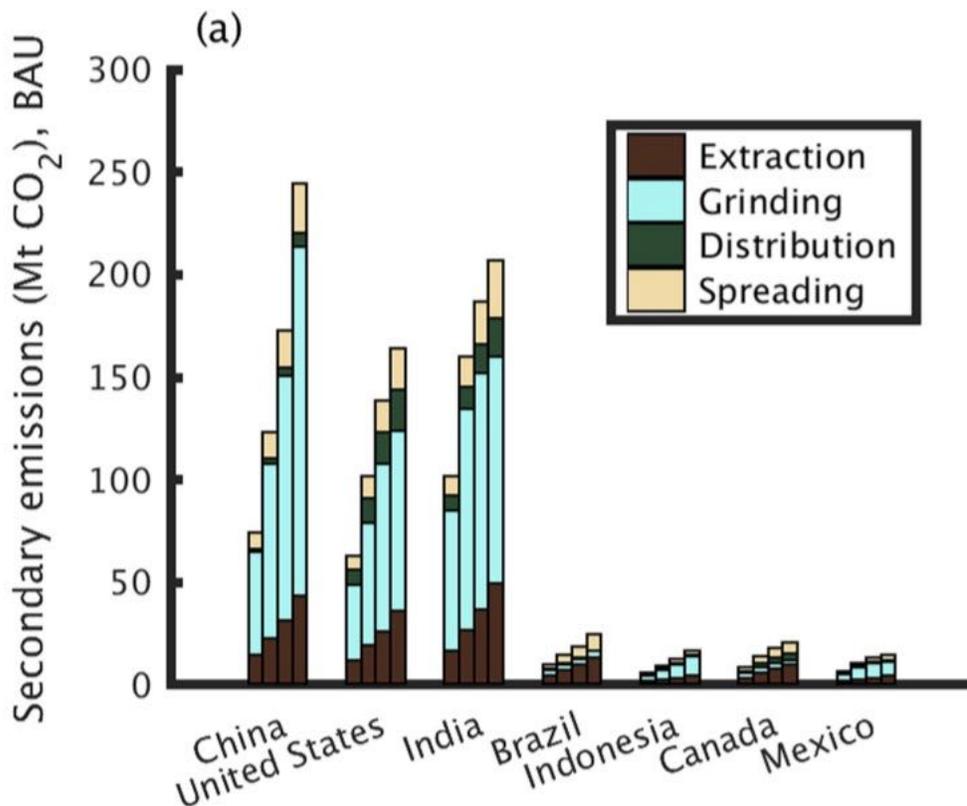
From Beerling, et al (2018)

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. Hangx and Spiers, (2009) examined the costs of grinding by size of the eventual product.

Energy Costs for Grinding Olivine

Crushing size uM	energy consumption kWh/ton olivine
1000	4.94
300	8.17
100	13.40
37	23.71
10	173.71

Getting to a size of 1 μm would be even more costly. The intriguing aspect of these analyses 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 and could totally remove the CO_2 costs of grinding olivine and other minerals. Solar could also work (see below).

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	Feed 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
				20–100 ^b
Impact crushing	10^4 – 10^5	10^2 – 10^3	130–1780 ^b	0.6–1.5 ^b
Cone crushing	10^3	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 Metso technical data sheets.

Sources: Wang and Forsberg [2003], Lowndes and Jeffrey [2009], Fuerstenau 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 placement of a Molten Salt Reactor or other small reactor at a centralized site, such as Twin Sisters (see below) would allow carbon free grinding to 1 μm size prior to distribution of the ground ultramafic rocks.

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

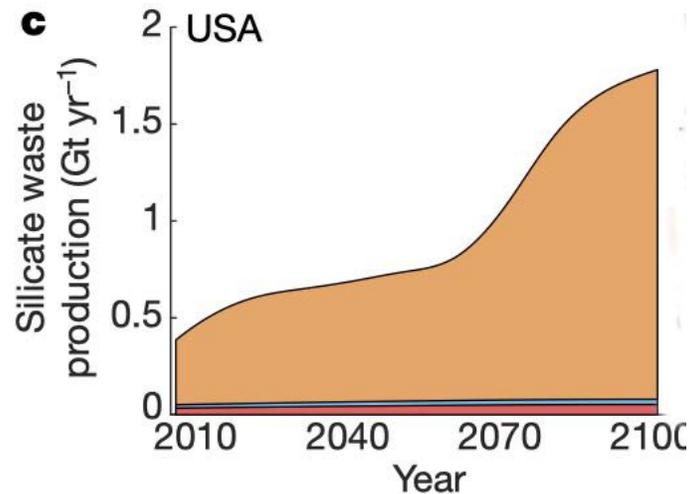
Freight/Haulage Transport Method	gCO_2 Emissions $\text{km}^{-1} \text{t}^{-1}$
Airfreight	602
Road heavy goods vehicle	62
Diesel rail	15
Electric rail	14
Inland waterways	31
Large tanker	7

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, or from the U.S. (Bellingham, see below) to other countries.

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

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).

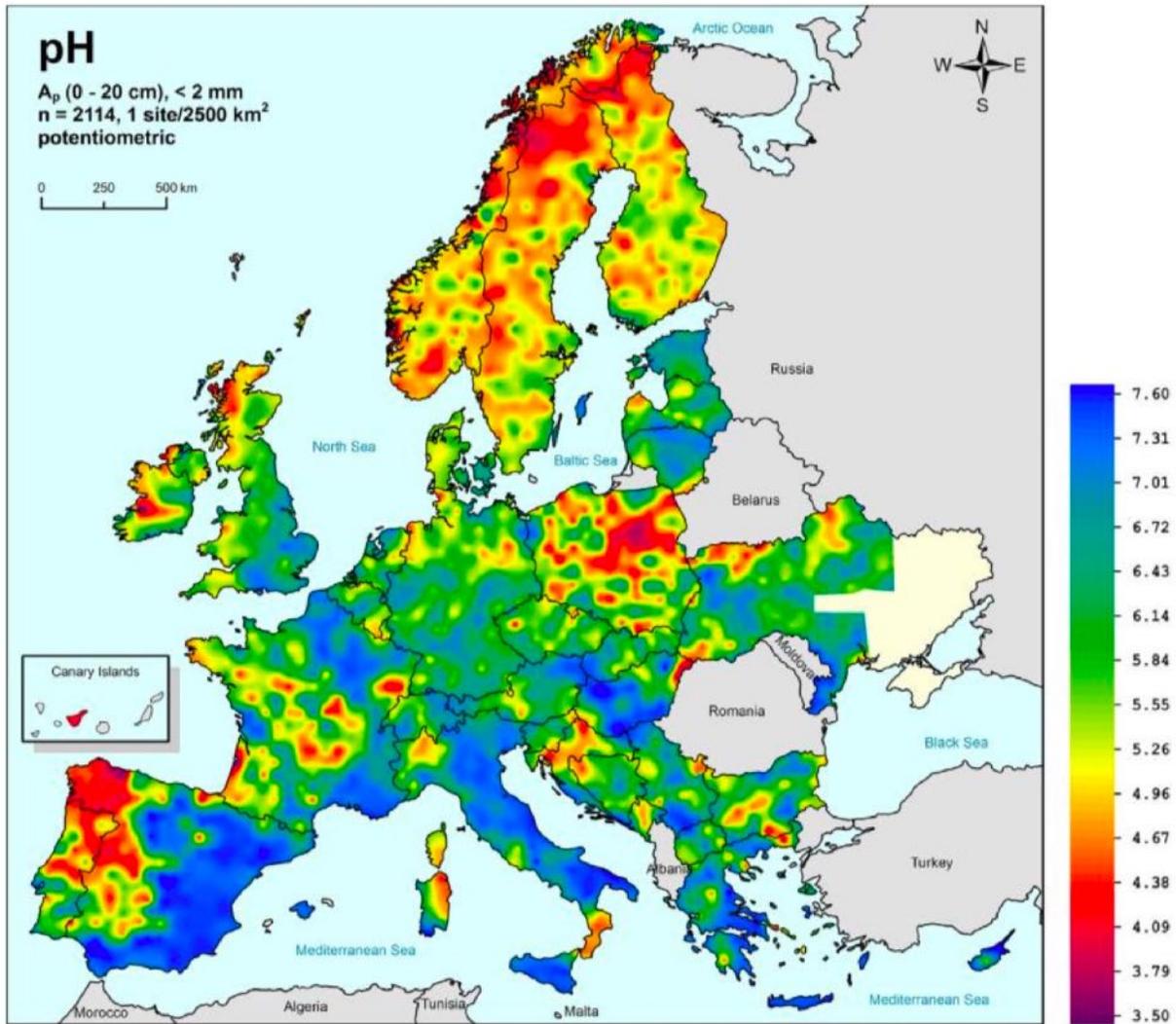


Forecast of increases in national bulk silicate production over the next century. Simulated future increases in bulk artificial silicate by products: slag, cement, kiln dust and cement demolition waste (orange), slag and kiln (blue) and slag (red). production during the twenty-first century are given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

The following map illustrates the marked variation in soil pH, in this case in Europe (Fabian et al (2014)).



Maps of pH in GEMAS soil samples for agricultural soil across Europe (Fabian et al., 2014).

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.

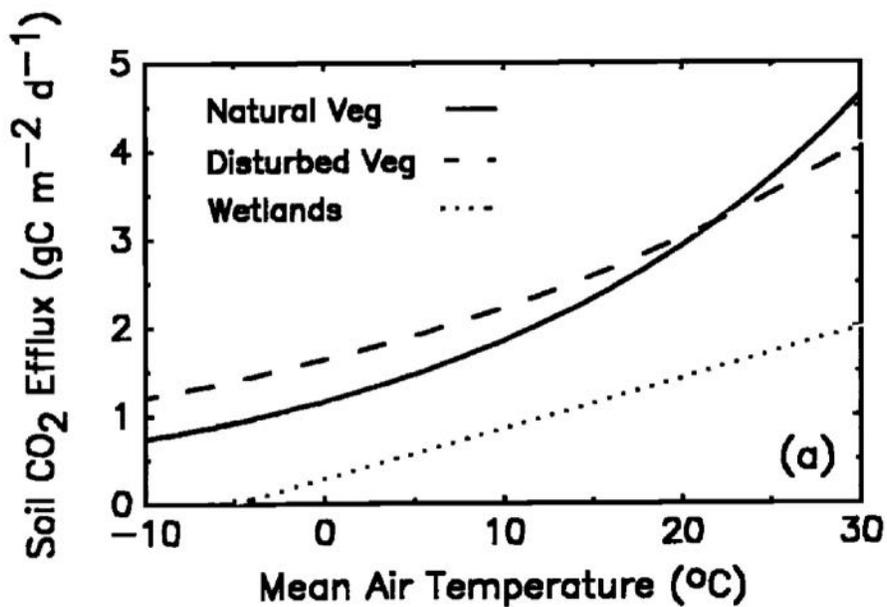
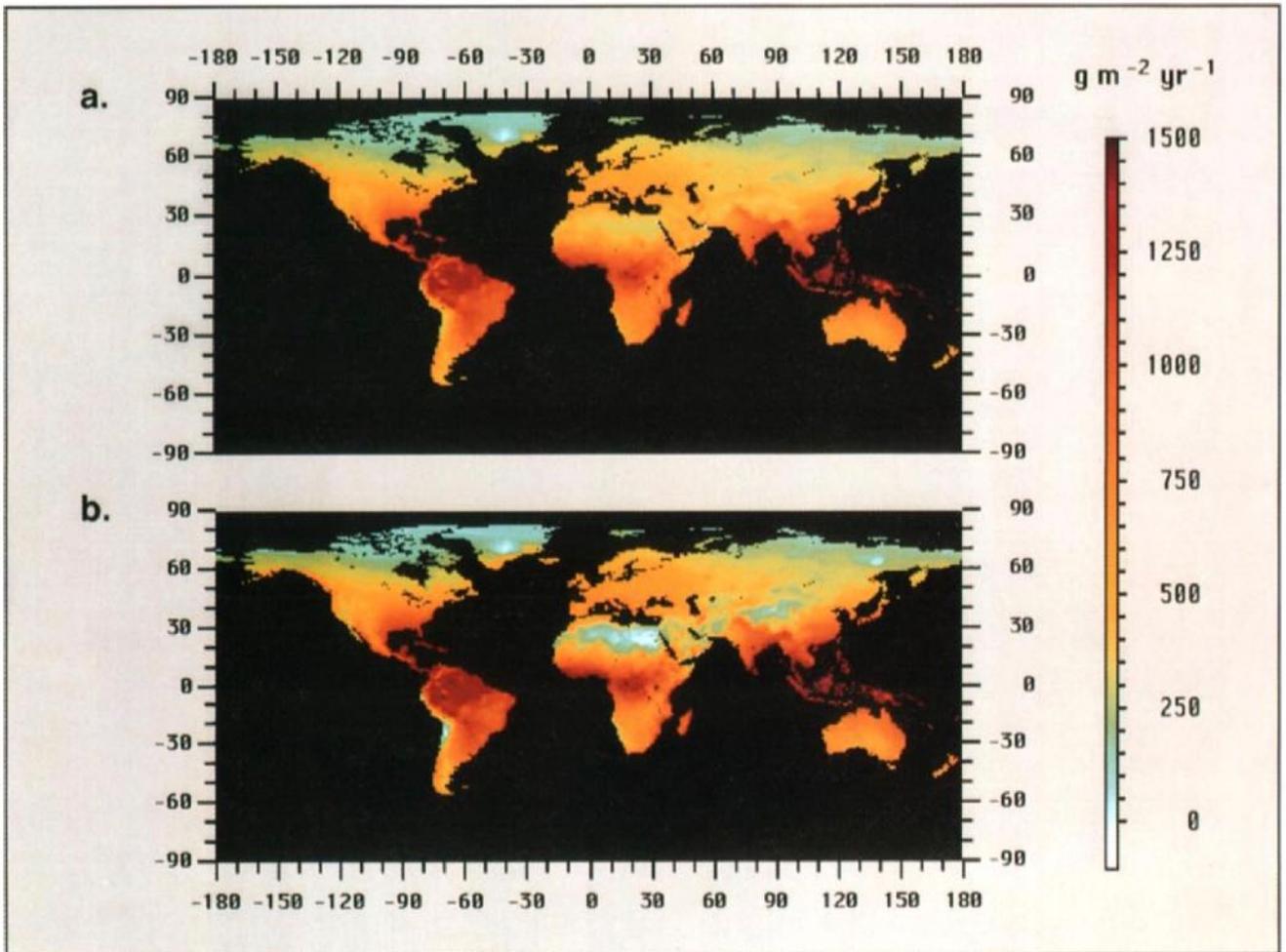


Figure from Raich & Potter, 1995

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. Their 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 emissions 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.

Soil organic matter contains a large reservoir of carbon. Recently estimated at ~1,600 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 be 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 than 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.

Obviously, the Lackner approach to capturing CO₂ could also be used for *in situ* sequestration.

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.**

The following table from Li et al (2018) reviews some of the sites in the U.S where tailings have been used for carbonation.

Table 1. Summary of current studies on ex-situ mineral carbonation of mine waste materials.

Mining Deposits	Majority Minerals	CO ₂ Source	Rock Pretreat	Carbonation Method	Ref.
American Chrome, QC	Serpentine	Flue gas	TA	DC gas–solid	[99]
Old ilmenite mine, QC	Anorthite	Flue gas	NA	DC gas–solid DC aqueous	[100]
Okanogan nickel deposit, WA; Thompson nickel bell, MB	Serpentine	Pure CO ₂	TA, CA	DC aqueous	[64]
American Chrome, QC	Serpentine	Flue gas	TA	DC aqueous	[67,101]
Black Lake mine, QC	Serpentine	Flue gas	TA, MS	DC gas–solid	[102]
Lonmin Platinum mine, South Africa	Enstatite, plagioclase feldspar	Pure CO ₂	CA	IDC aqueous	[70]
Nickel Slag, New Caledonia	Olivine, serpentine	Pure CO ₂	TA, CA, MA	DC aqueous	[74]
Turnagain deposit, BC	Olivine, serpentine	Pure CO ₂	NA	DC aqueous	[103]
Turnagain deposit, BC	Olivine, serpentine	Pure CO ₂	MA	DC aqueous, DC gas–solid	[104,105]
Troodos ophiolite complex, Cyprus	clinopyroxene, anorthite	Pure CO ₂	MA	DC gas–solid	[106]
Black Lake mine, QC; Dumont Nickel project QC	Chrysotile, lizardite	Flue gas	NA	DC gas–solid	[66]
Thetford Mines, QC	Chrysotile	CO ₂ mix	TA	DC gas–solid	[63]
Hitura nickel mine, Finland	Serpentine	Pure CO ₂	CA	IDC aqueous	[107]

Note: TA is thermal activation, CA is chemical activation, MA is mechanical activation; MS is magnetic separation, NA is not applied, DC is direct carbonation, IDC is indirect carbonation.

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.

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	
Basic oxygen furnace slag	12,000	2700-4300	402 ± 17		602 ± 25	-100. Up to 700 in high substitution specialised cements.
Electric arc furnace slag		(286-1080) ^j	368 ± 10	50-540	552 ± 15	<5 as aggregate
Ordinary portland cement	800	200-400	510	300	773	—
		(100-200) ^j				
Cement kiln dust	6900 ^g	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 ^h	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 ± 28	230-264	246 ± 52	
Marine algae biomass ash			31	—	348	
Wood/woody biomass ash			-89-815		-118 to 1766	
Herbaceous and agricultural biomass ash	490	<-16,200	-239-520	80-380	-323 to 1505	-100. Up to 700 in high substitution specialised cements
Animal biomass ash ³⁸			56-376	—	145-724	
Biomass average			186 ± 126	—	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 emission 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 target²⁶ (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.**

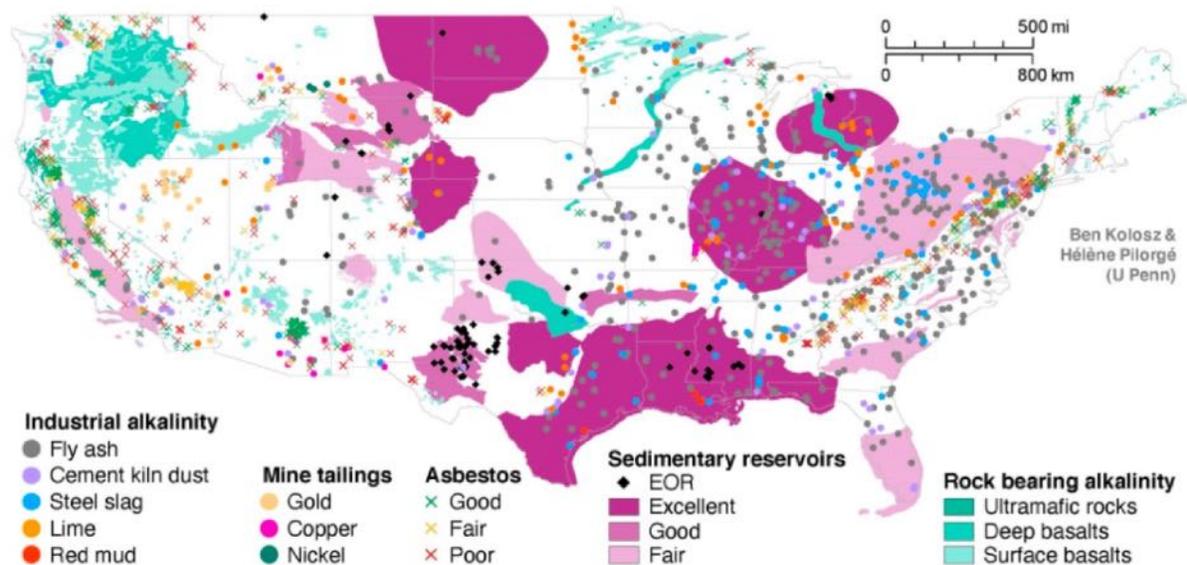
Mafic and ultramafic mine tailings are generated during the extraction and production of asbestos, chromite, diamond, nickel, platinum-group metals, and talc. These tailings react passively with atmospheric CO₂ to produce carbonate minerals under natural conditions (Levitan and others, 2009; Wilson, 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) (Energy Futures Initiative) *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.

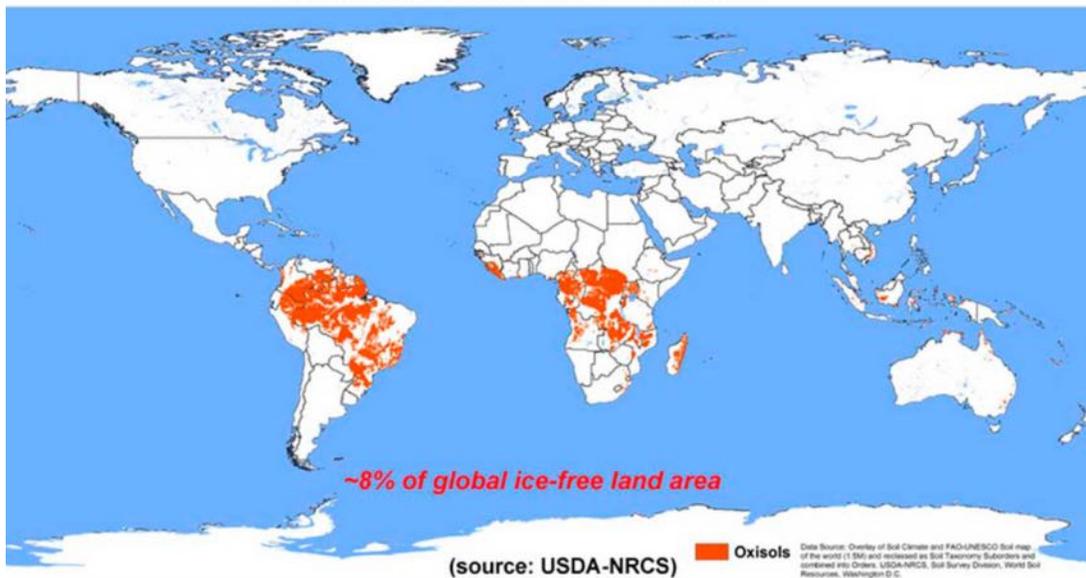


There are clearly a large number of tailings sites.

Oxisols and Ultisols

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

Global Distribution of Oxisols

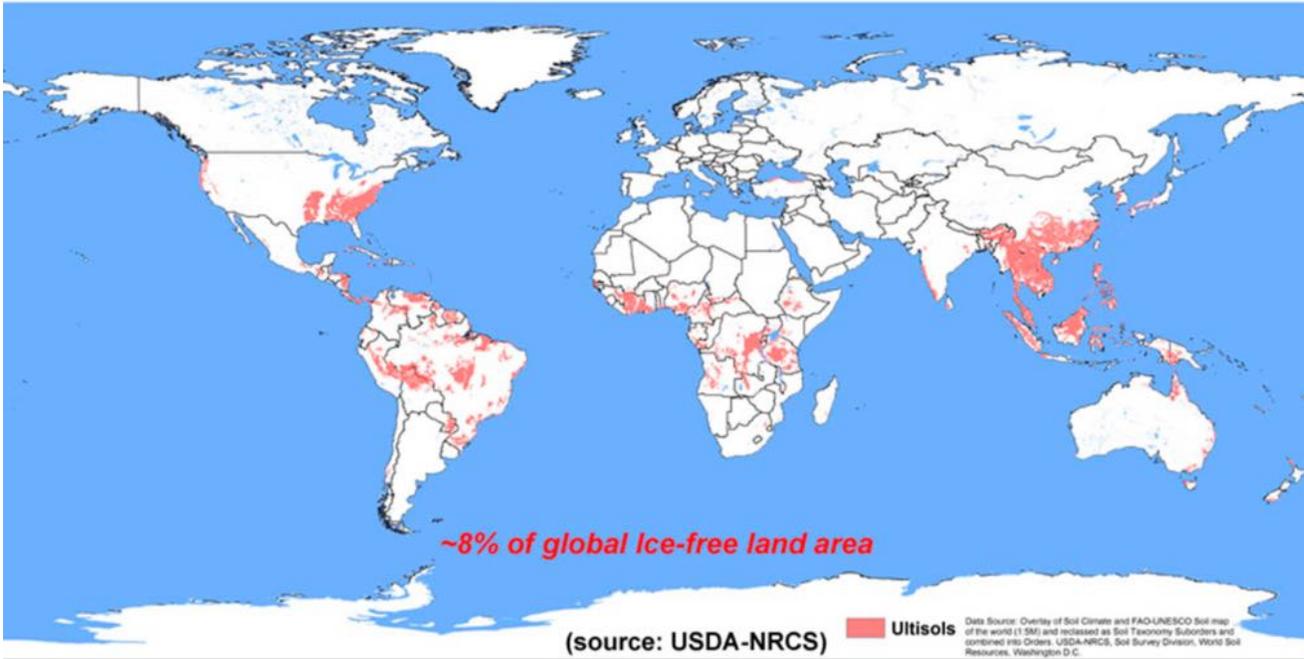


These soils contain few weatherable minerals and are often rich in Fe and Al oxide minerals. Most of these soils are characterized by **extremely low native fertility**, resulting from very low nutrient reserves, high phosphorus retention by oxide minerals and low cation exchange capacity (CEC). Most 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.

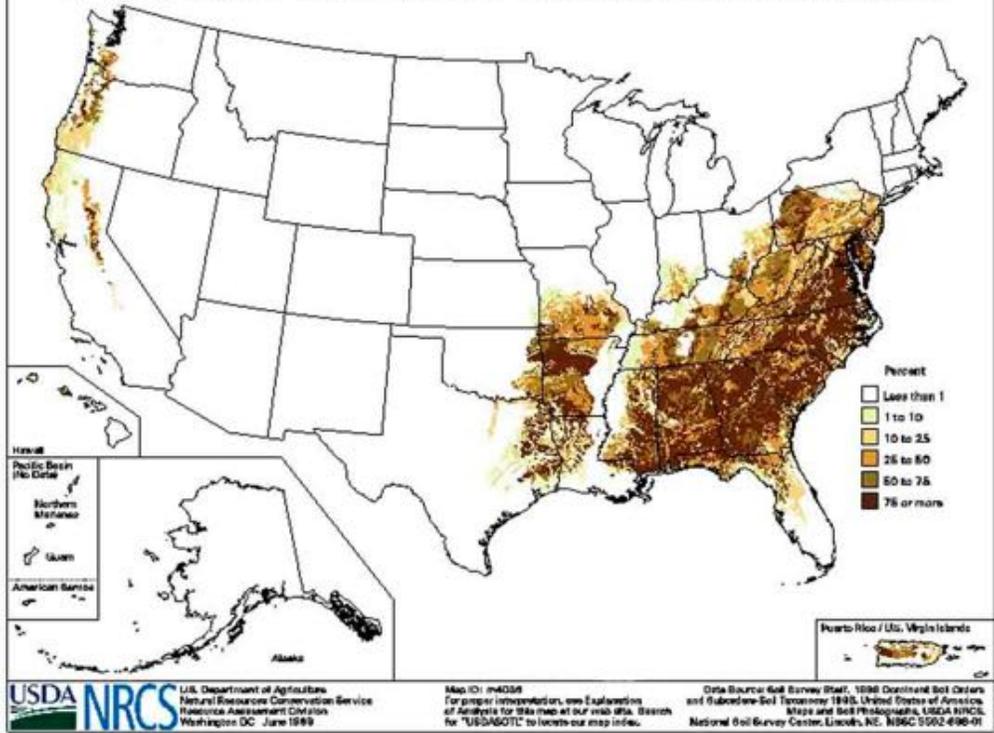
Ultisols (from Latin *ultimus*, "last") are strongly leached, **acid forest soils with relatively low native fertility**. They are found primarily in humid temperate and tropical areas of the world, typically on older, stable landscapes. Intense weathering of primary minerals has occurred, and much Ca, 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.

Global Distribution of Ultisols



Percent of Land Area in Ultisols



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.**

What About Methane?

The contribution of **other GHGs, besides CO₂, 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. Methane leaks from oil wells account for a similar amount. Our proposals on how to decrease methane emphasizes decreasing emissions. This **plan is covered in the section below on Federal Help.**

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 explore this approach.

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.

Regions 1 and 5 contain olivine; regions 2-4 contain lizardite serpentine; region 6 contains antigorite serpentine; and region 7 contains wollastonite.

5 = Asheville Mining District

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 10^{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.

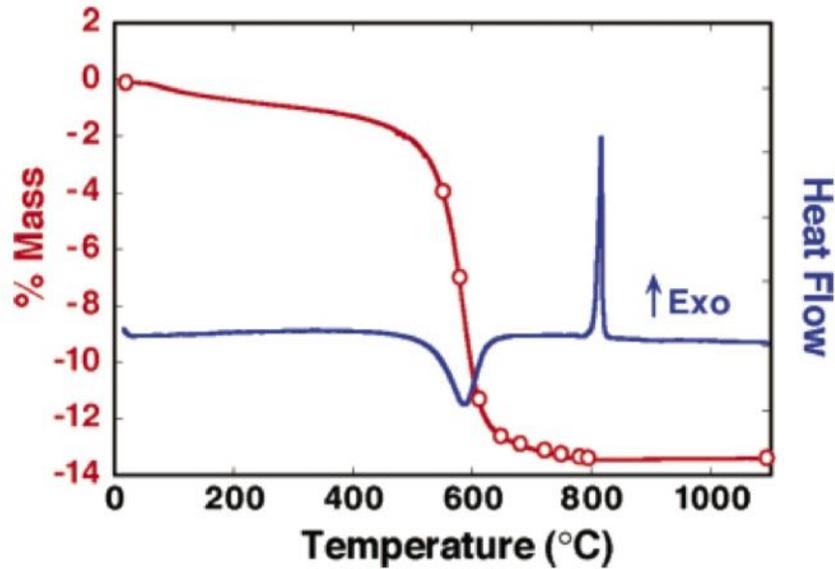
Adding Serpentine to the Soil – Is that a Problem?

Note that the above studies involved adding olivine and other non-serpentinized rocks to the soil. While the dissolution of olivine on croplands has been occasionally studied, the problem is the majority of ultramafic rocks are serpentinized and the **rate of dissolution of serpentine is orders of magnitude slower than olivine** (Daval, 2013). Much of that literature relevant to accelerating the dissolution of ultramafic rocks including serpentines is aimed at the commercial extraction of magnesium, or the extraction of CO₂ from flue gas produced by coal fired power plants. The following table from Azadi et al (2019) illustrates the different methods that have been used to enhance the rates of dissolution.

Table 1. Strategies and methods used to increase the speed and efficiency of the carbonation reaction.

Strategy	Reference	Method	Benefit
Mechanical pretreatment of serpentine rock	[62–66]	High-energy crushing and grinding	Increases the overall specific surface area of the minerals, i.e., the surface per unit mass available for Mg/Ca-extraction
Thermal activation of the hydrated Mg-silicate serpentine	[67–73]	Heating the mineral to 630 °C or above	Destabilises the crystal lattice, thus increasing the reactivity of the mineral Heat activation also creates an even higher specific surface area [46]
Increasing reaction temperatures	[74,75]	Applying operating temperatures above 100 °C	Accelerate the kinetics of the reaction
Increasing reaction pressure	[76,77]	Applying operating CO ₂ pressure above 150 bar	Increases the activity of protons needed for metal extraction. Also counteracts the low solubility of CO ₂ at high temperature
Using organic and inorganic chemicals	[61,78–80]	Adding different substances as catalysts and additives to the reactants	Enhances the kinetics of the carbonation process and precipitation of magnesium carbonate
Applying New double-step and multistep process designs	[81]	The operating conditions are changed between the different stages	Allows to control and promote extraction and precipitation separately
Direct capture of CO ₂ from flue gas stream	[81,82]	Capturing CO ₂ directly from a flue gas stream by mineral carbonation	Provides a simple and straightforward process route

All of these methods are quite energy intensive leading many to question their applicability to the whole problem of CO₂ sequestration. The use of heat has been one of the most frequently sites techniques. The following diagram from McKelvy et al (2004) shows the dramatic increase dissolution of lizardite, a serpentine rock Mg₃(Si₂O₅)(H₂O)₄, at 600°C.



Simultaneous thermogravimetric (TGA) and differential thermal analysis (DTA) of Philips lizardite from ambient temperature to 1100 °C.

The serpentine group of minerals consists of the three polymorphs lizardite, antigorite, and chrysotile. The serpentine minerals are phyllosilicates, or sheet silicates, and share the general formula $Mg_3Si_2O_5(OH)_4$. Serpentine dissolves and carbon dioxide is consumed by the following reaction (Park and Fan, 2004).



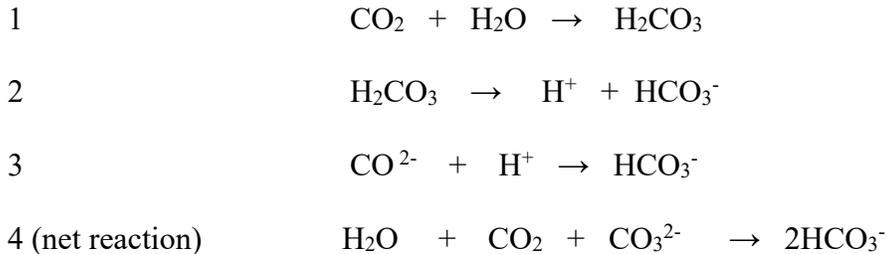
General formula for the serpentines is $Mg, Fe, Ni, Al, Zn, Mn)_{2-3} (Si, Al, Fe)_2O_5(OH)_4$. The serpentine clay minerals are Lizardite, Atlantisite and Infinite, with the chemical composition of $Mg_3Si_2O_5(OH)_4$. They differ in color and where they are found. Lizardite is the most common and most often used in research studies.

The literature on the use of basalt on the soil is also relevant since the rate of dissolution of basalt is also lower than olivine and there are number of studies on the use of basalt on croplands.

In California for the Del Puerto Ultramafic body ranges from 10 to 90 percent olivine while in Wilbur Springs the percent olivine ranges from 60 to 100% (Goff and Lackner, 1998). One solution for serpentines is preheating of the rock, but this is very energy inefficient (Tebbiche, et al, 2021). Krevor and Lackner (2011) reported that the rate of dissolution of serpentine is three orders of magnitude faster in the presence of citrate ions but it is doubtful that this can be used economically at large scale. Dissolution is also pH sensitive, increasing with lower pH, but adding various acids is also is economically inefficient.

The Basics of CO₂ and Ocean Chemistry (Harvey, 2008)

The emission of CO₂ into the atmosphere from human activities leads to an increase in the partial pressure of atmospheric CO₂, and in response to this, there is a net flow of gaseous CO₂ into the **surface layer** of the ocean. Once dissolved in surface water, CO₂ combines with water to form a weak acid (carbonic acid, H₂CO₃), which then dissociates to bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions. The reactions are



Reaction (2) would tend to increase the acidity of seawater as CO₂ is added, except that CO₃²⁻ 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 CO₃²⁻ in the surface layer of the ocean is limited, so as more CO₂ 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 CO₃²⁻ decreases. CO₃²⁻ is a constituent in CaCO₃ (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.

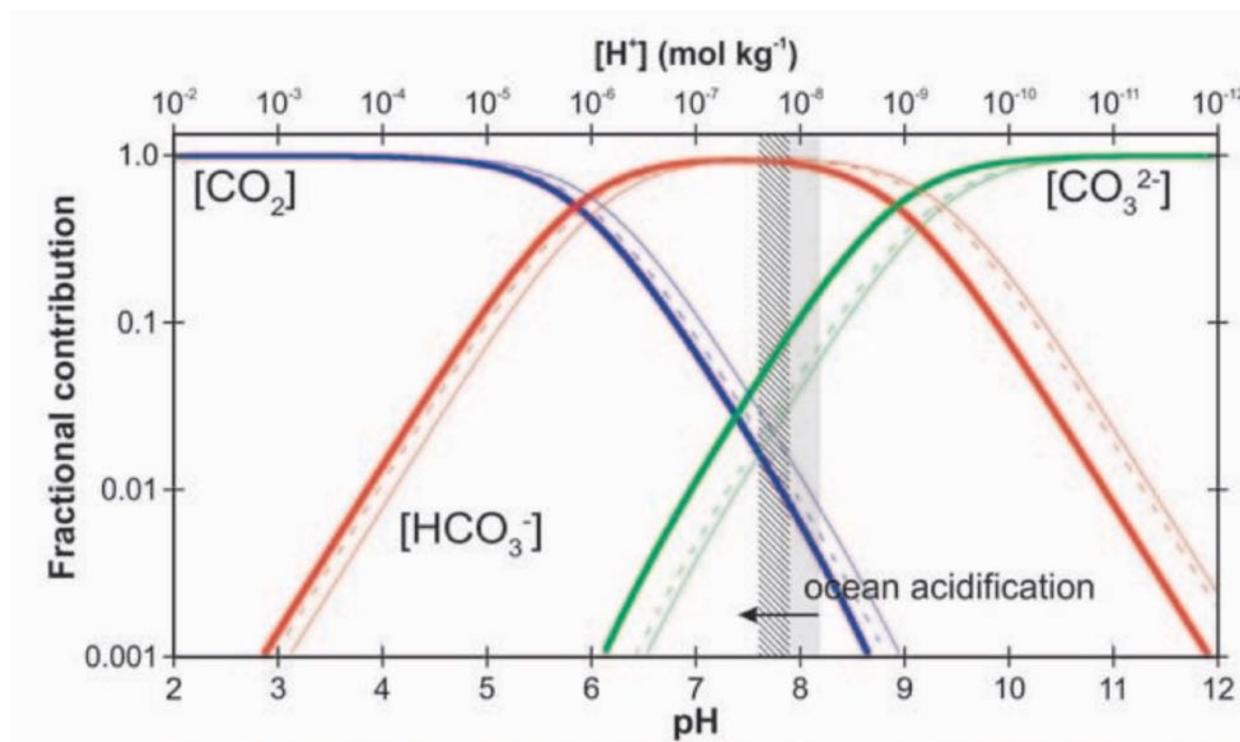
The carbonate concentration required for supersaturation increases with increasing pressure and hence with increasing depth in the ocean. As a result, deep ocean waters are unsaturated with respect to CaCO₃, and carbonate sediments produced by the downward rain of dead calcareous plankton accumulate 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 CO_3^{2-} could be available to absorb more atmospheric CO_2 within as little as a few years after the addition of CaCO_3 .

Harvey (2008) stated their results suggested that ground CaCO_3 could be effectively applied at a rate of 4 billion tons/yr (0.48 Gt C/yr) producing an eventual rate of absorption of CO_2 of about 0.27 Gt C/year a (1 billion t CO_2 /year). This would represent 5 to 10 percent of the total sequestration of CO_2 needed.

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 CO₂ is also affected by temperature. The consequence of this is that, as the ocean warms, less DIC will be partitioned into the form of CO₂ (and more as CO₃²⁻), hence enhancing the buffering and providing a 'negative feedback' on rising atmospheric CO₂. A well-known positive feedback in the carbon cycle arises due to the decrease in solubility of CO₂ 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 CO₂ 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).

Two years later, two scientists in Stockholm, Bert Bolin and Erik Eriksson (1959), explained the sea-water buffering mechanism in clear terms and emphasized what it meant. Unlike Revelle and Suess, they used an ocean model in which, correctly, **only the top two percent. mixed quickly with the atmosphere, which made it that much slower for the great bulk of the oceans to absorb the gas.** Bolin and Eriksson also predicted unequivocally an exponential climb of industrial production and used that to calculate that atmospheric CO₂ would probably rise 25% by the end of the century. Revelle had already guessed that there might be a 25% increase by 2000. It actually reached that mark in 2010. The community of geophysicists began to grasp that we could not rely on the oceans to absorb all our emissions of fossil fuels. However, OAE may help to overcome that.

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 seas, 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 Mg^{2+} and Ca^{2+} leads to an immediate increase of TA.** The “one-time-input” weathering of 10 Gt olivine (e.g., pure forsterite (Mg_2SiO_4)) would result in an input of 1.4×10^{14} mol Mg^{2+} . 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 ($\Delta TA = 8$ mmol kg^{-1} , $\Delta pH = 0.001$). (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 ($\Delta TA = 790$ mmol kg^{-1} , $\Delta pH = 0.11$ 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.

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.

Bach et al, (2019) examined the potential risks and co-benefits of OAE on marine pelagic ecosystems. The molecules or elements generated during chemical weathering of these minerals and sustained in solution comprise for major groups:

- (I) Bicarbonate (HCO_3^-) and carbonate ion (CO_3^{2-}), summarized as “alkalinity”,
- (II) Silicic acid ($Si(OH)_4$) termed silicates,
- (III) Certain alkaline earth metals like calcium (Ca^{2+}) and magnesium (Mg^{2+}) but potentially also alkali metals like sodium (Na^+) and potassium (K^+),
- (IV) a variety of “trace metals” associated with the minerals such as iron (Fe^{2+} or oxidized aqueous species), and nickel (Ni^{2+}). These will be the major subject as these elements occur in high concentrations in basic and ultrabasic rocks (e.g., dunite), which are the most widely recognized source rocks for EW/OAE. If these have a toxic effect on marine life, we will examine the possibility of removing them by electrolysis prior to placement in the ocean.

The authors stated that the most fundamental outcome of more than two decades of ocean acidification research is that carbonate chemistry perturbations affect calcifying organisms disproportionately. Thus, it is important to pay special attention to calcification when considering impacts of increased alkalinity on marine organisms and ecosystems. They concluded that calcifiers would profit in a scheme where $CaCO_3$ derivatives would be used. This may turn the blue ocean into a whiter ocean.

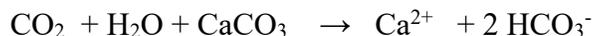
When using silicates, the release of additional Si, Fe and Ni could benefit silicifiers and N_2 -fixers such as cyanobacteria and increase ocean productivity ultimately turning the blue ocean into a greener ocean. As to silicates, dissolving one mole of olivine leads to an increase in total alkalinity by 4 moles and in silicic acid (H_4SiO_4) by one mole. The maximum scale of mineral addition through OAE lies somewhere at **around 10 Gt/year** which is roughly 70 Tmol (trillion moles) of DSi (dissolved silica)/year, if dunite was used. Thus, OAE would be a source of DSi to the surface ocean that is 5–14 fold higher than all natural sources combined.

These considerations call for dedicated research to assess risks and co-benefits of mineral dissolution products on marine and other environments.

1. The Addition of Carbonate Minerals. And here there are also three approaches.

a. **Carbonate rocks can be crushed and 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. Readily solubilized crushed carbonate rocks, such as CaCO₃, produces 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 (2021) 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) as shown below.

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.

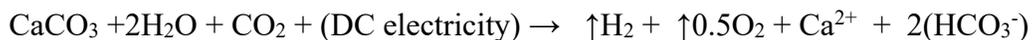
b) If placed on ships it can do OAE in many places thus speeding up its ocean wide dispersion.

- 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 was 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* described the 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. 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⁻). The last two increase the alkalinity of the ocean which leads to increased CO₂ uptake and combats ocean acidification. The first two can be used in fuel cells to produce electricity. 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.**

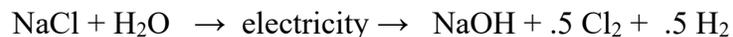
The electrolysis could be done directly in the ocean seawater where the electrodes and carbonate would penetrate the water surface from either stationary (e.g., docks, jetties, platforms) or mobile, piloted, or vessels (barges, ships, buoys, etc.). If non-fossil-fuel electrical power is generated on site using wind, solar and fuel cells, 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 = 2.3).

The exact quantity would be dependent upon the purity and reactivity of the carbonate used. As stated, 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 alkalizing the ocean.



Each mole of HCl removed from the ocean and neutralized increases ocean alkalinity by 1 mol, and on as 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).

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 alkalized 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.

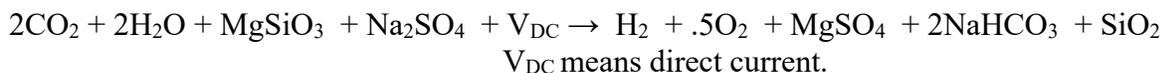
Although silicate weathering is extremely slow under ambient conditions, silicate mineral dissolution and subsequent reaction with CO₂ can be significantly increased in strong acids and/or bases. Because very large pH gradients are produced in **saline water electrolysis cells** [anolyte pH < 2, catholyte 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 was 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 μ m 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, wind and fuel cells. 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 or replaced with electric motors to minimize or eliminate the use of fossil fuels. When docked they could be loaded with CaCO_3 , 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 might be needed. If each ship was capable of onloading, for example, 200,000 tons of rock, and dispersing it in a week to 10 days, then returning for more, each vessel could accommodate 7,300,000 tons of rock per year. A fleet of 100 such boats could accommodate .72 gigatons per year or approximately .30 gigatons of CO_2 per year. While not the total answer to CO_2 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.

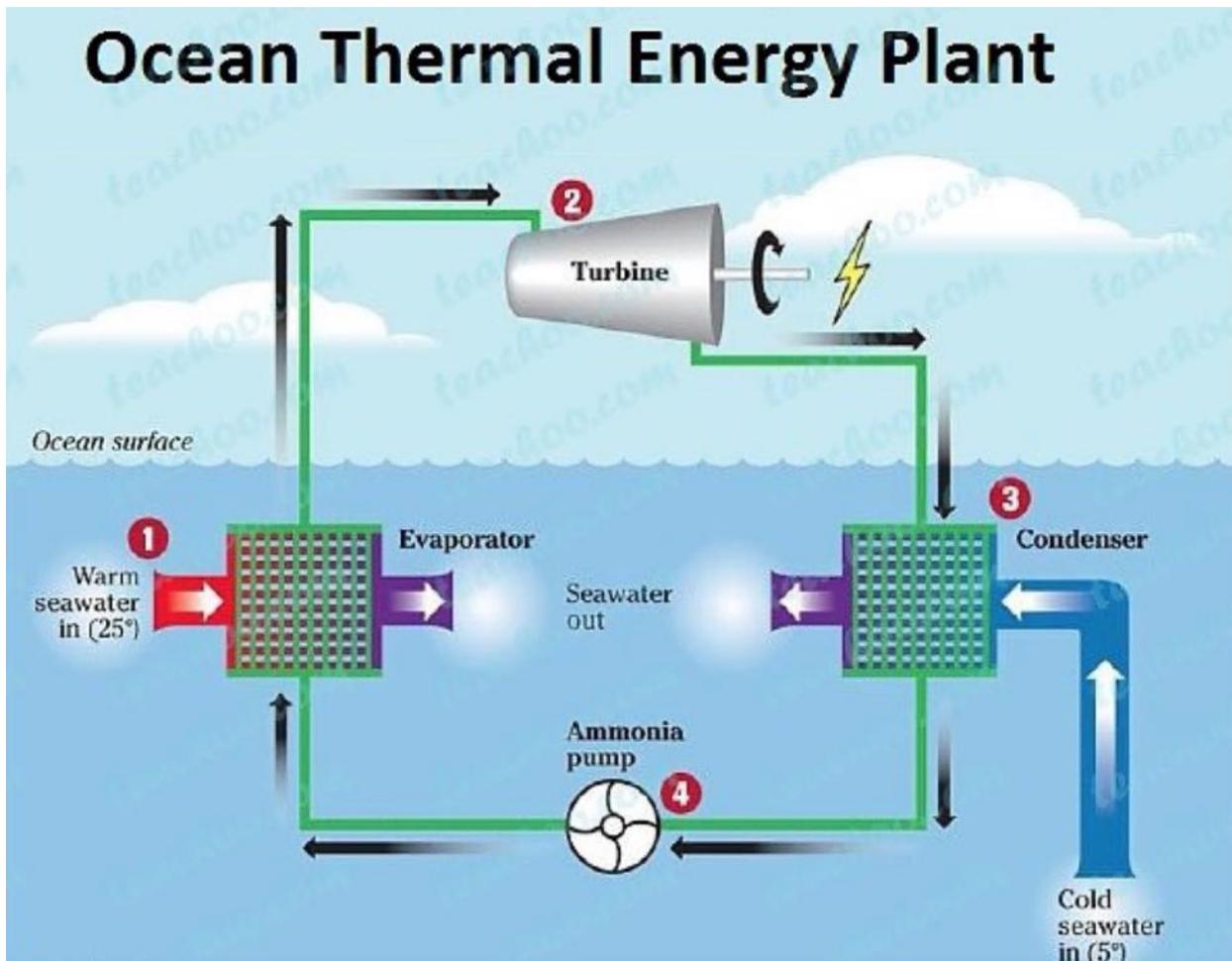
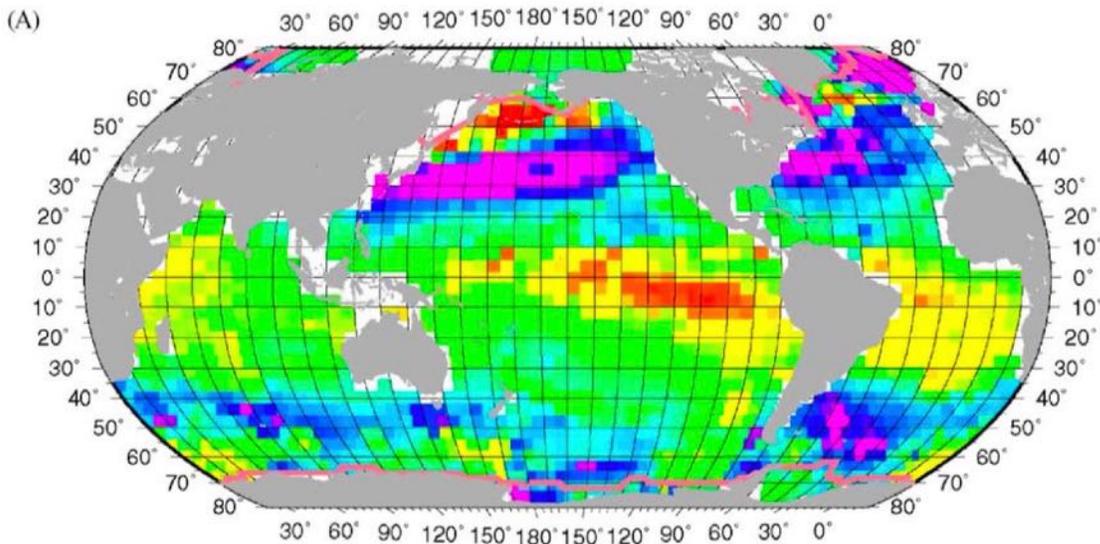


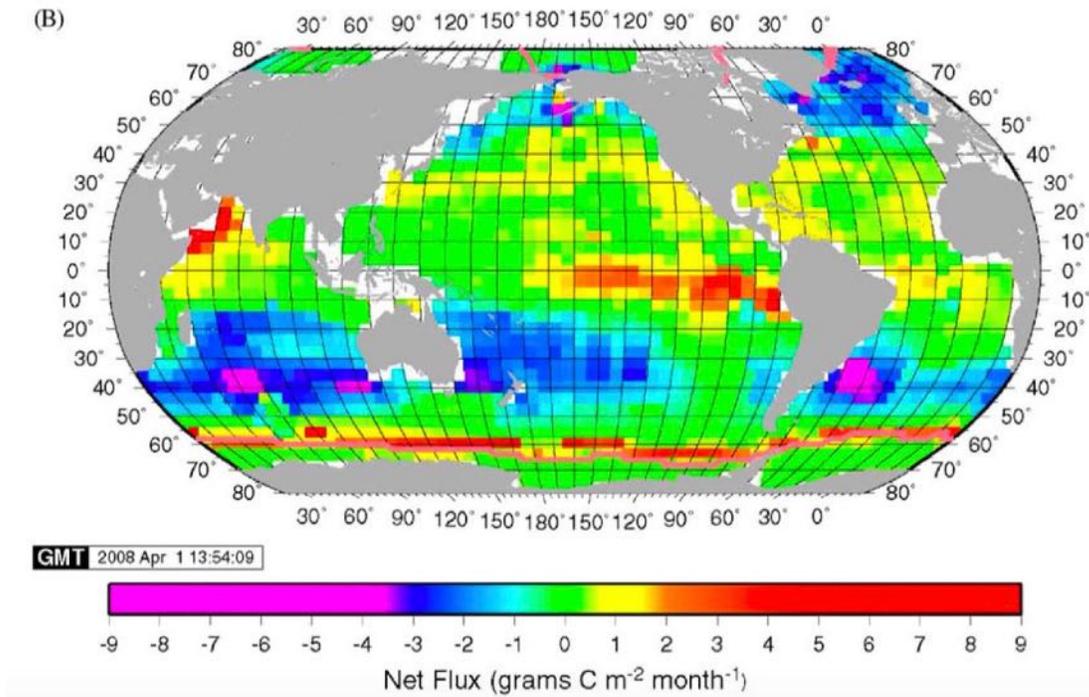
Diagram showing elements of OTEC.

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

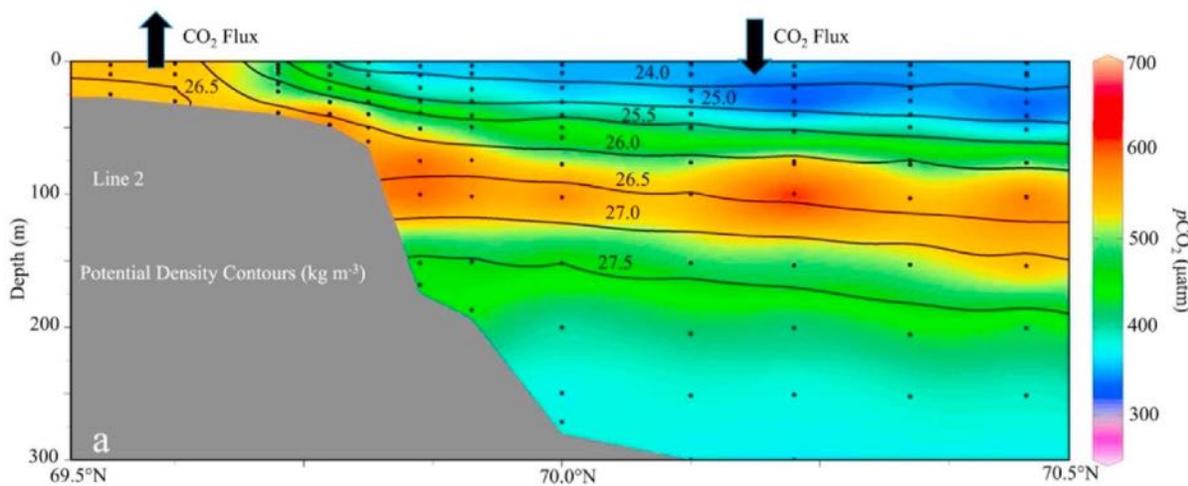
the equator east of about 160°E during non–El Niño periods. The primary source of the upwelled water along the equator is the narrow Equatorial Undercurrent (EUC), which flows eastward across the basin (Feely et al (2006).

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 (pCO₂ > 550 matm) and undersaturated in aragonite (Omega 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 10¹², or 10⁶ 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 pCO₂ (matm) with density (kg/m³) contours along CTD (Conductivity Temperature Depth) line. The black arrows indicate the direction of the CO₂ flux (Mathis et al, 2012).

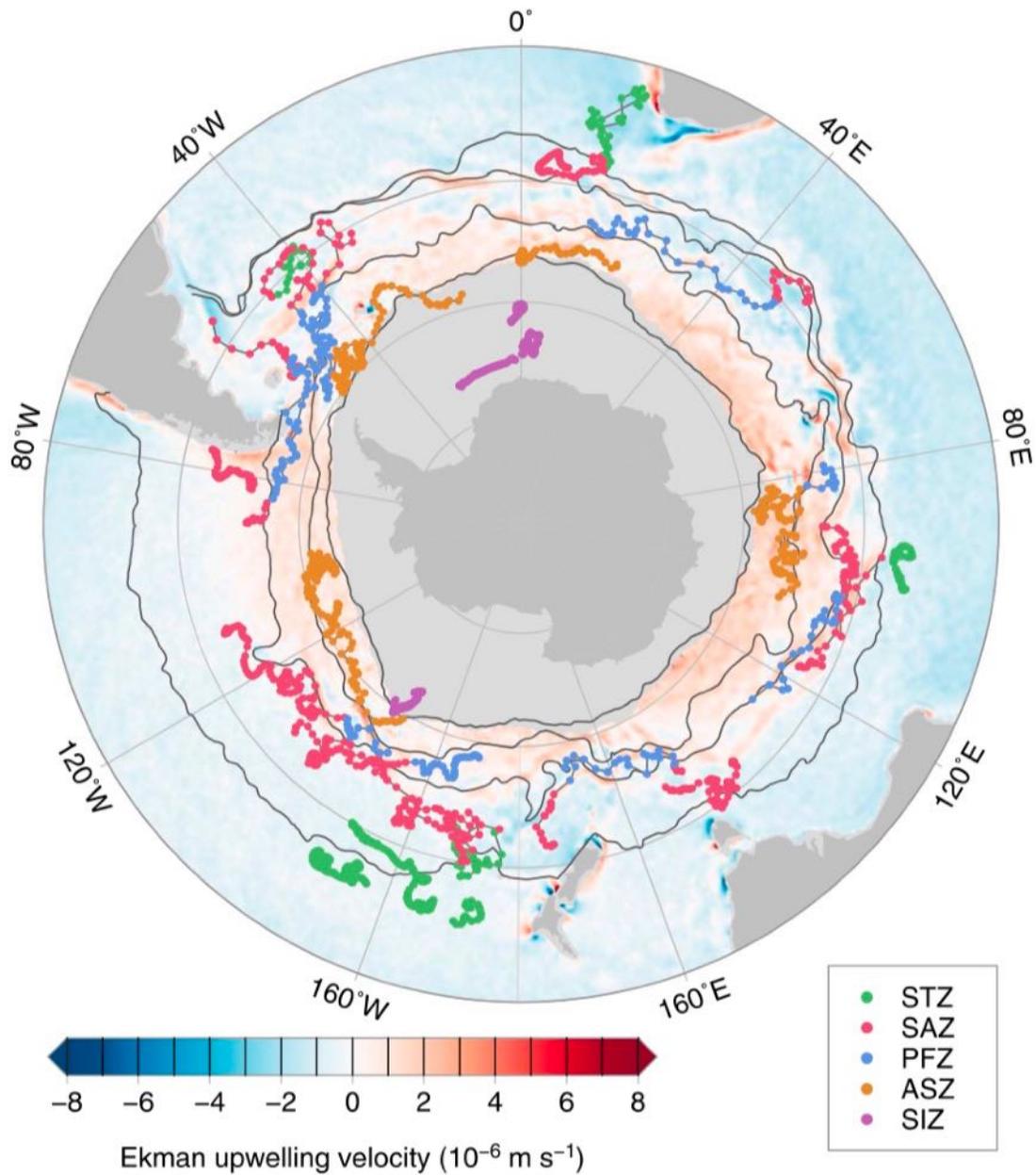
As sea ice retreat continues with global warming, and storms increase in frequency and intensity, further outgassing events and the expansion of waters that are undersaturated in carbonate minerals over the shelf are probable.

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 CO₂ 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 CO₂ flux across the air-sea interface.

Upwelling in the Antarctic - Southern Ocean

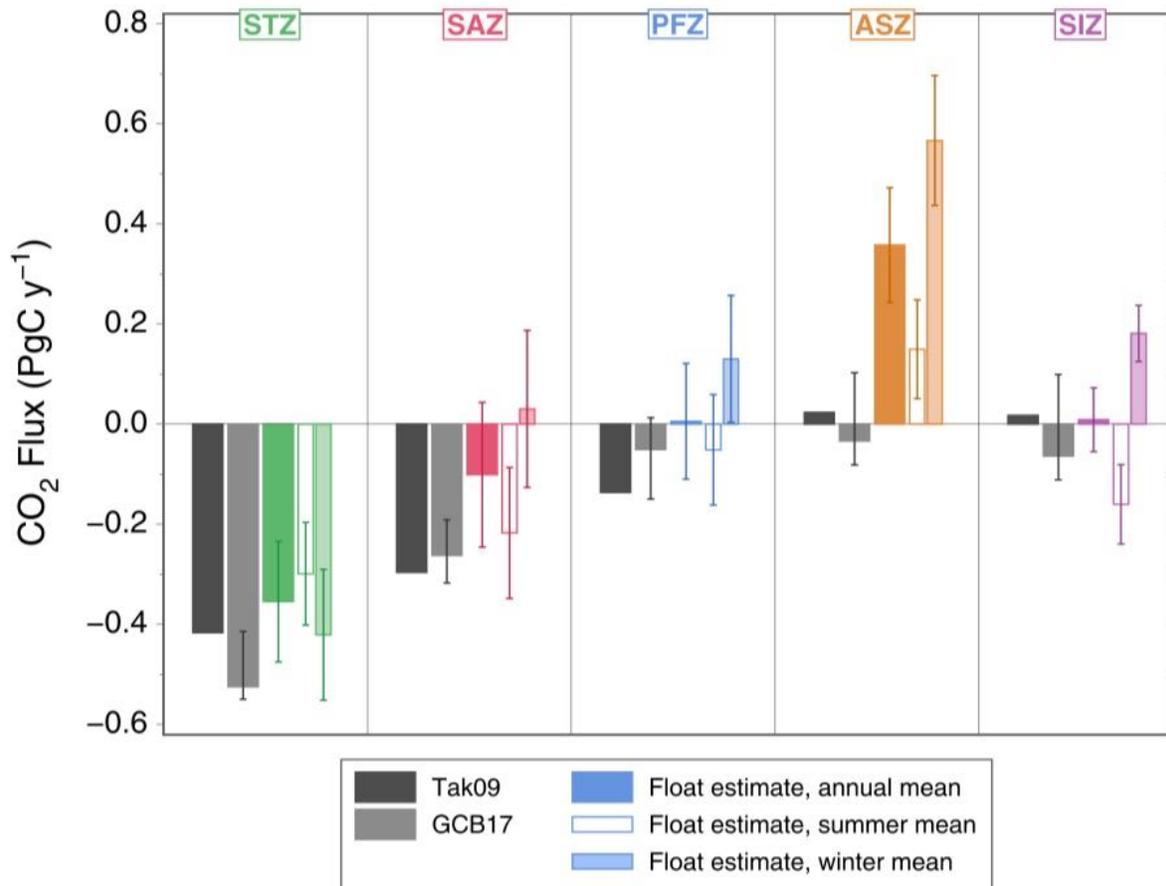
The ocean is able to act like a sponge for anthropogenic CO₂ because of the high concentration of carbonate ions, which react with excess CO₂ to form bicarbonate. That process keeps the oceanic CO₂ concentration low, and thus allows for more uptake. But as the ocean takes up more carbon, the carbonate ions are reduced, which reduces the ocean's ability to absorb CO₂. As ocean surface temperature increases in the future, the solubility of CO₂ will decrease, which will, in turn, increase the oceanic partial pressure of CO₂ 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 CO₂ from the atmosphere, which leads to increased warming** (Morrison, et al, 2015).

So, how much outgassing of CO₂ 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 pCO₂ 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.**

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

In his 2008 article *Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone powder to upwelling regions* **Harvey suggested that the outgassing of CO₂ from the ocean could be mitigated by the direct application of CaCO₃ to the relevant regions of the ocean.** “If this were done in regions where the saturation horizon is shallow and where strong upwelling (>50 m/a) occurs (the two conditions tend to be correlated with one another), water with restored CO₃²⁻ could be available to absorb more atmospheric CO₂ within as little as a few years after the addition of CaCO₃.”

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 alkalization 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.

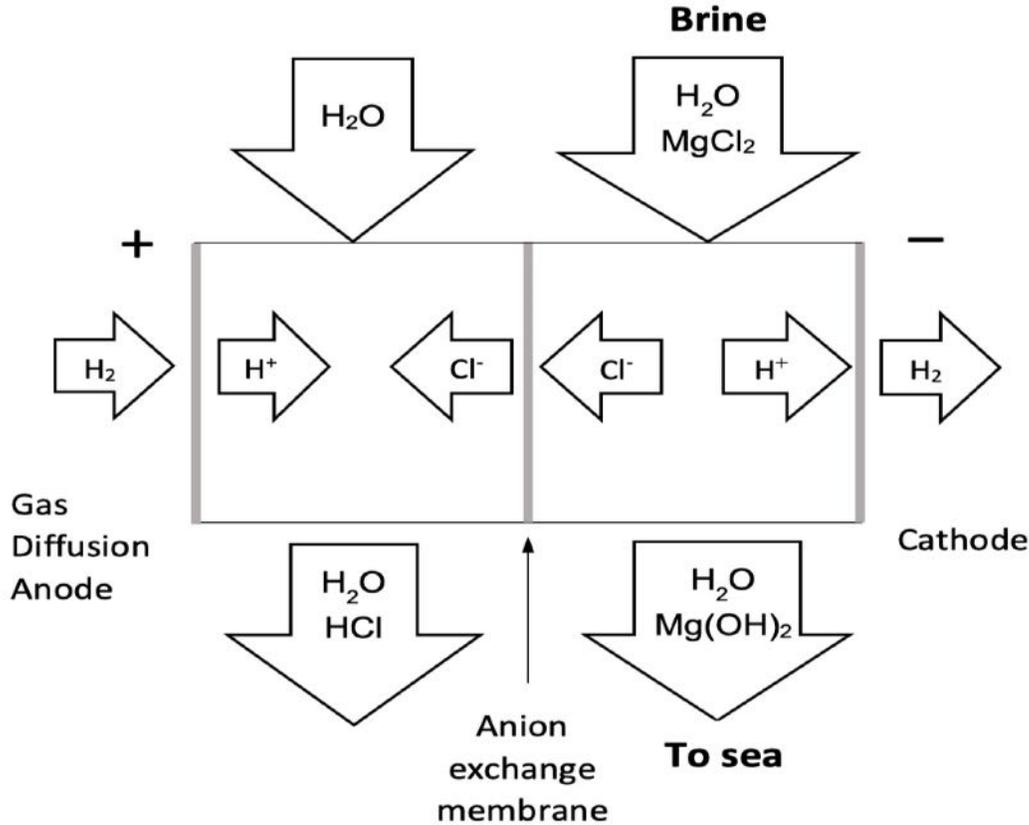
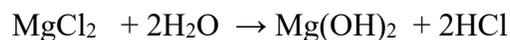


Illustration of the electrolyzer with gas diffusion anode (GDA) for splitting brine containing magnesium chloride into HCl and Mg(OH)₂. Modified from Xie et al (2013). Davies' objective was to estimate the energy and water requirements of such NET-desalination, and to compare these penalties to the other NETs based on values provided in the literature.

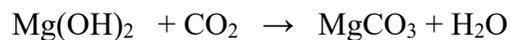
With use of the GDA, the two half-cell reactions are:



The overall electrolysis reaction is accordingly:



Magnesium hydroxide reacts stoichiometrically with CO₂ in seawater to form magnesium carbonate:



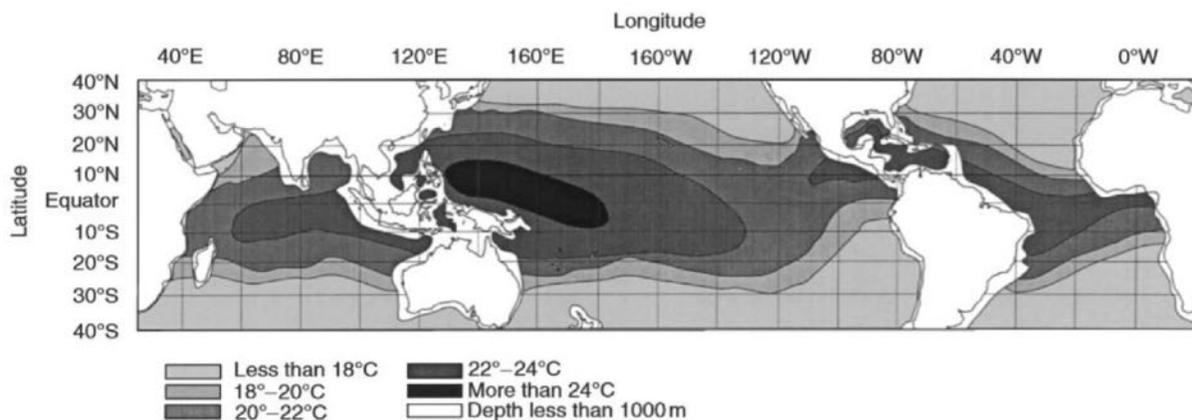
Further reaction to form magnesium bicarbonate absorbs in total of up to 2 moles of CO₂ per mole of magnesium:



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 (2018) calculated a **significant lowering of energy penalty, by a factor of about 1.5–5, using electrolysis-GDA.**

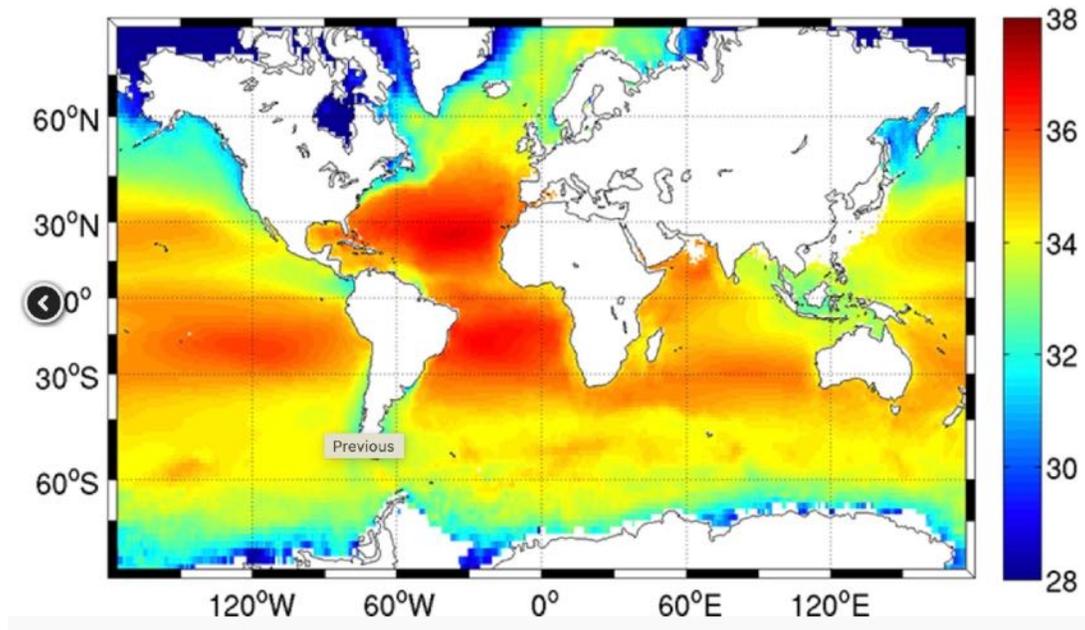
OTEC (see above) could also be explored as a potential source of electrical energy (Rau and Baird, 2018). The following map shows the areas of the ocean where the thermal difference between deep versus surface water is sufficient to use OTEC.



A thermal difference of 20°C of 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.

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.

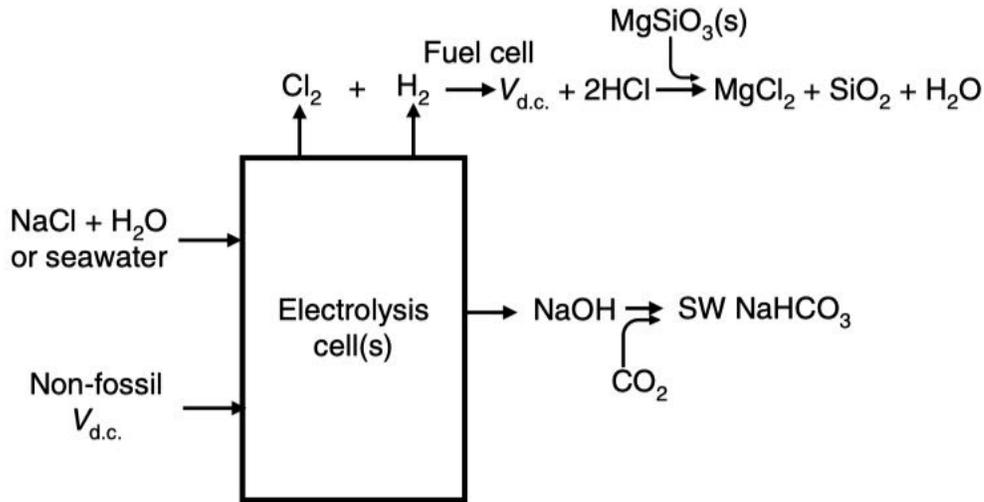
Fig a. Scheme according to House et al, (2007).

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

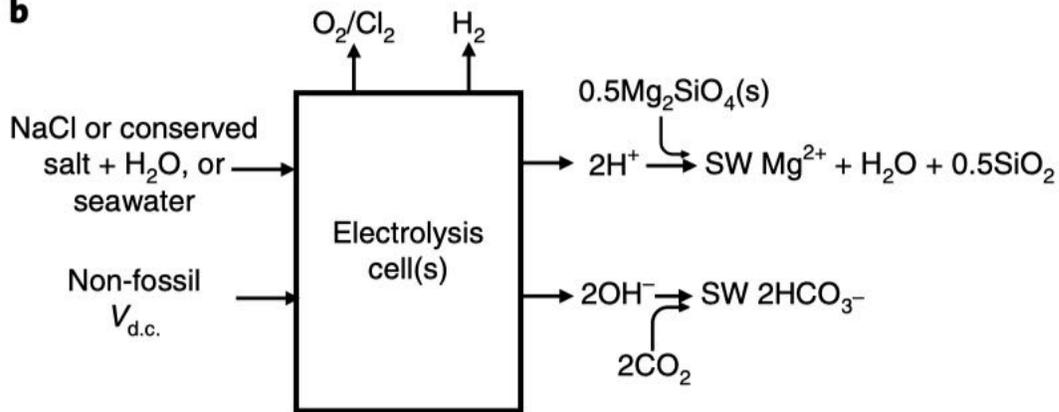
Fig c. Scheme according to Willauer, et al (2017).

SW = seawater; V_{d.c.} , direct current electricity.

a



b



c

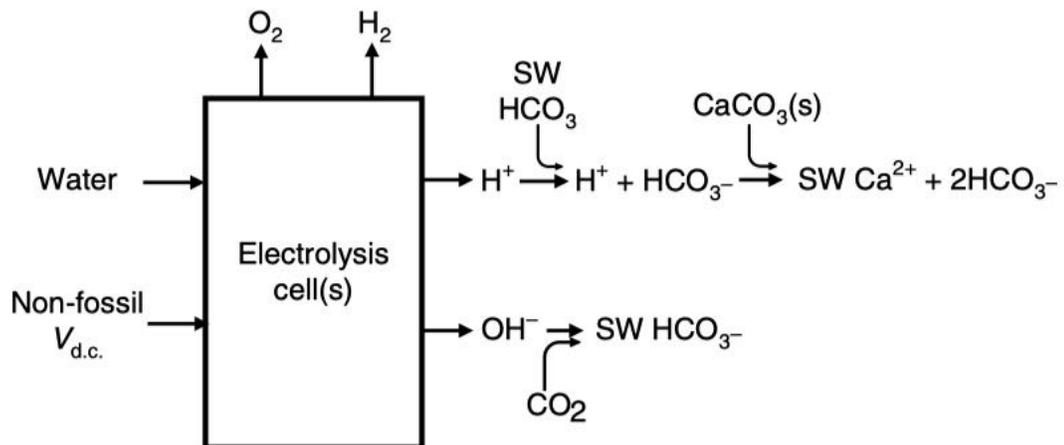


Fig a. Central to these processes is the splitting of water at a cathode to form H₂ (gas) and OH⁻, with the generation of O₂ (gas) or Cl₂ (gas) and H⁺ at the anode. In one approach (House et al, 2007) the Na⁺ + OH⁻ produced during electrolysis of a NaCl solution (**chloralkali process** – see above) 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 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

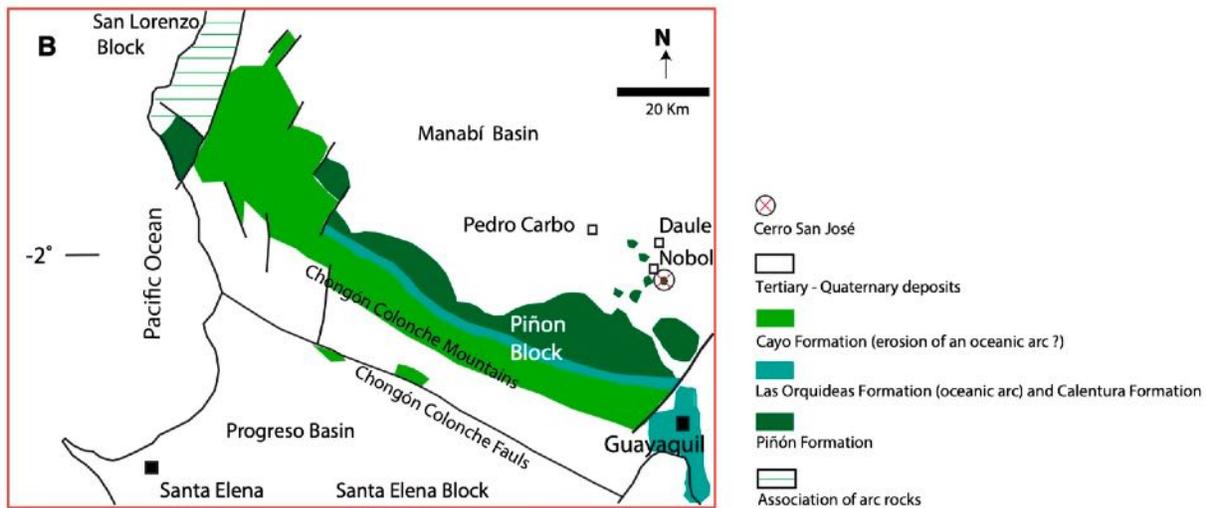
The above review identified an equatorial region along the equator west of Ecuador with the following characteristics:

- 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 Piñon 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 alkalinization.

Protecting the Great Barrier Reef

Feng et al, (2016) concluded that OAE 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. In order to maintain atmospheric CO₂ at RCP4.5 levels under the high-emission scenario RCP8.5, $\approx 114 \cdot 10^{15}$ mol (10^{15} mol = 1 Pmol) of added alkalinity would be needed until the year 2100 in total. This implies an increase in the globally averaged surface TA concentration of around 30%. **In order to produce 114 Pmol of TA, about $4.01 \cdot 10^{12}$ metric tons (Tt or trillion t) of olivine would be needed,** which would require an increase of 3 orders of magnitude in the total olivine production until 2100.

This scenario removes **940 GtC from the atmosphere** and mitigates 1.5 K (or 1.5 °C) 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 Enhanced Weathering 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 alkalization 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 $p\text{CO}_2$ 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 μm . 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.

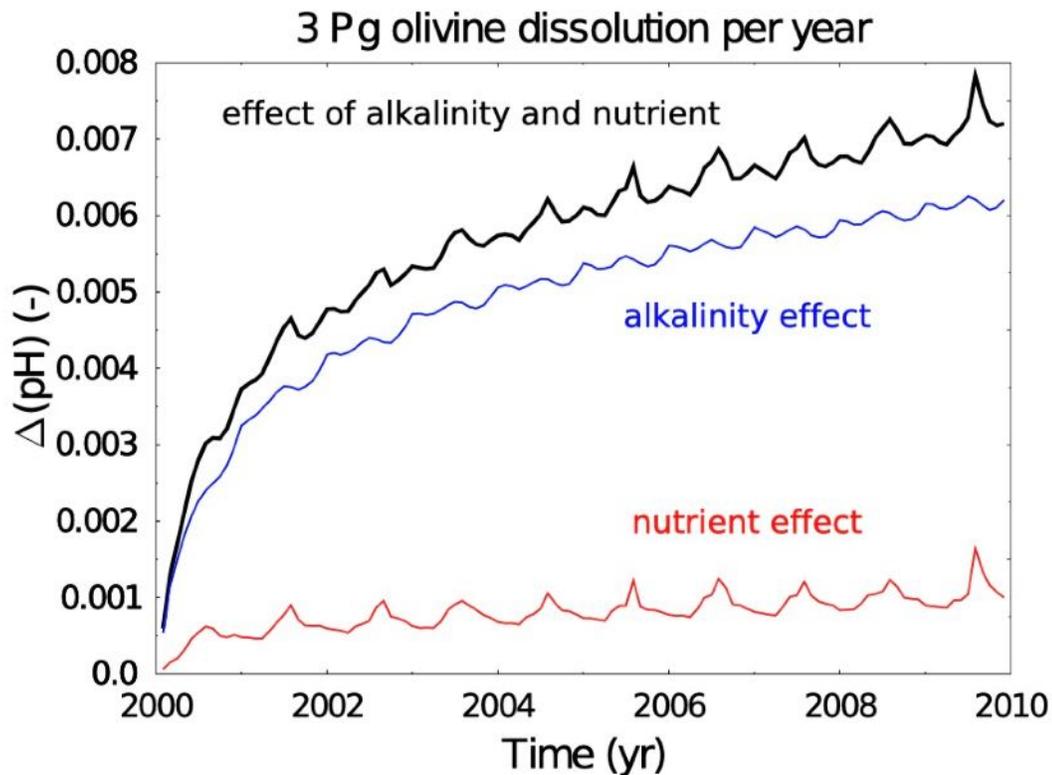
In contrast to the optimistic cheap tool of Schuiling and Krijgsman (2006), Hang and Spiers point out that with the **sand grain size of the Schuiling report it would take 370 to 6,010 years for the complete dissolution of olivine**. Dissolution is significantly accelerated with grain sizes of >10 μm 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 μm 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 CO₂ sequestration on the scale needed. The method certainly cannot replace CCS technologies as a means of controlling atmospheric CO₂ 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.

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. This estimate has not taken into consideration the increased efficiency of utilizing electrolysis.

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 CO_2 . **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 CO_2 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 tCO). There are still many challenge warrants 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 CO_2 and sequestration as bicarbonate and carbonate ions (HCO_3^- and CO_3^{2+}) in the ocean. Dissolution of a mole of Ca^{2+} or Mg^{2+} sequesters close to 2 mol of C. Examination of several natural minerals showed that **olivine (forsterite) Mg_2SiO_4 was the most efficient in terms of grams CO_2 sequestered per gram of mineral (1.25)**. This compared to magnesite MgCO_3 (0.52), Calcite CaCO_3 (0.44),

Dolomite $\text{CaMg}(\text{CO}_3)_2$ (0.48) and anorthite $\text{CaAl}_2\text{Si}_2\text{O}_8$ (0.32). The gCO_2/g mineral is higher for man-processed minerals. These include Lime CaO (1.57), Portlandite $\text{Ca}(\text{OH})_2$ (1.19), Periclase MgO (2.18), and Brucite $\text{Mg}(\text{OH})_2$ (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.

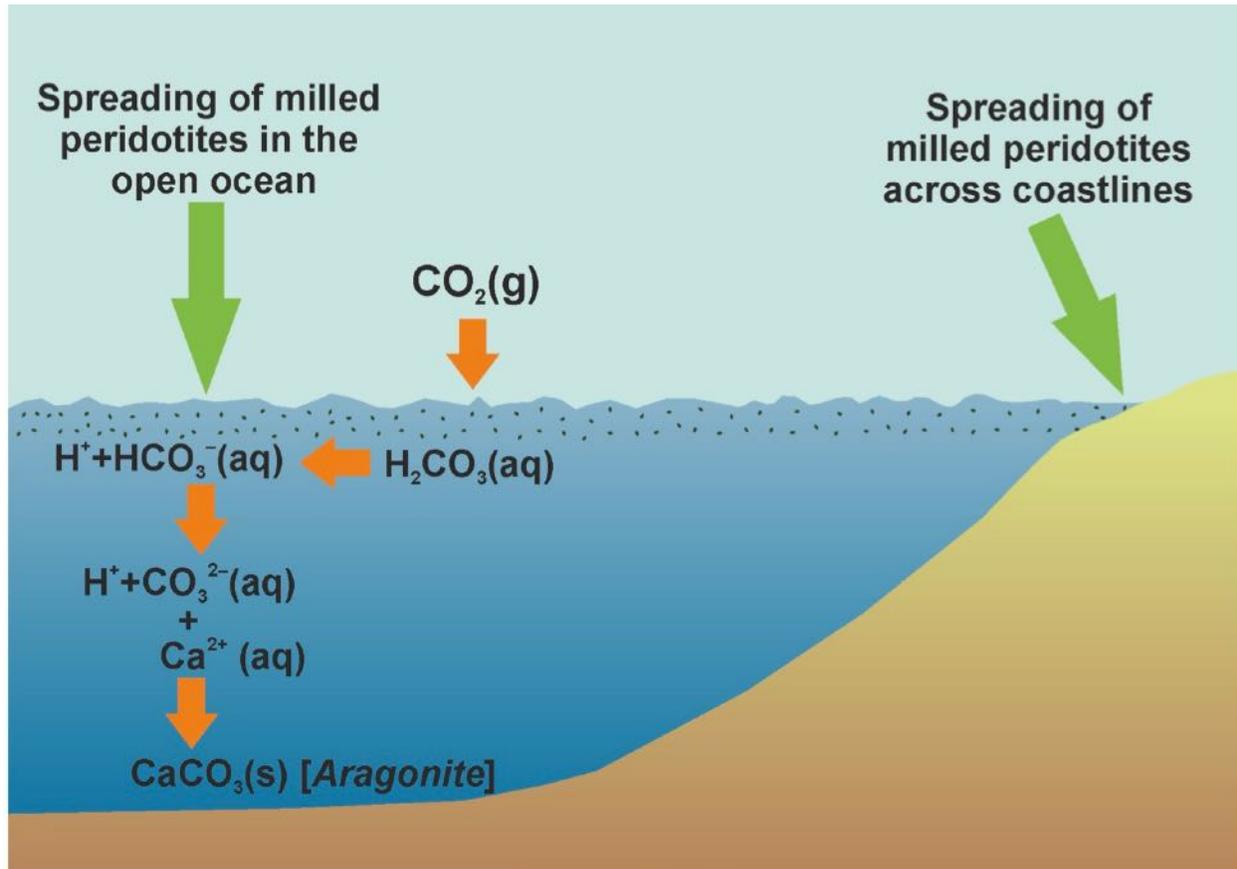
In conclusion, a range of techniques have been proposed for increasing ocean alkalinity, which exploit numerous reaction pathways. However, all require the extraction, processing, and reaction of rocks. It may be possible to achieve CO_2 :rock mass ratios >1 using ultrabasic minerals. It may also be 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 tCO_2/yr and \$50–150 tCO_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 alkalization only happens when more than 1 mol/kg H_2O Mg-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?

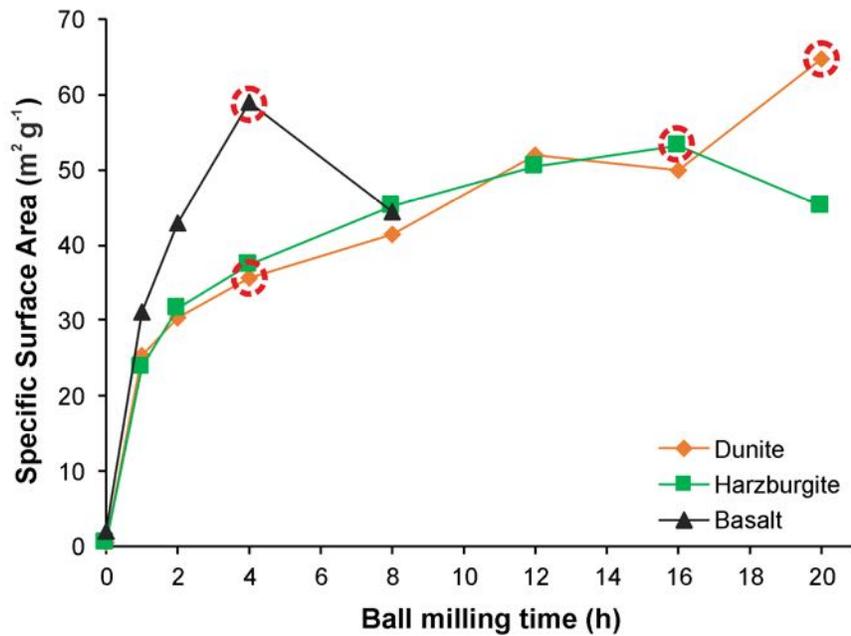


A **ball mill** or **roller mill** is a type of grinder used to grind or blend materials for use in paints, pyrotechnics, ceramics, and selective laser sintering. It works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell. The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

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.

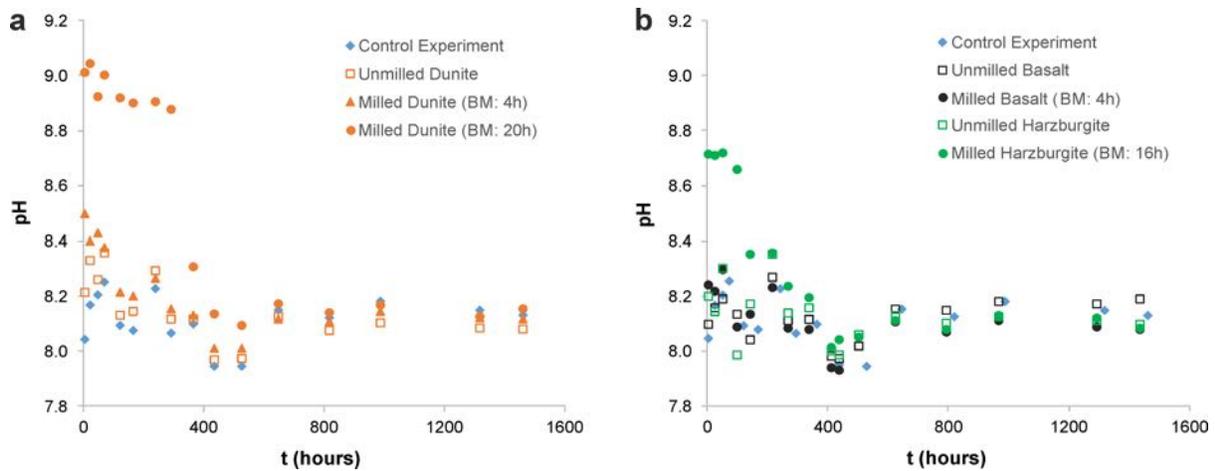
Fuerstenau, and Abouzeid (2002) examined the relative cost of different machines and other factors. The required energy for comminution is proportional to the new surface produced. Efficiencies for the most commonly used mills ranged from 7–32%. In some cases the efficiencies are as low as .15%. The **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:**

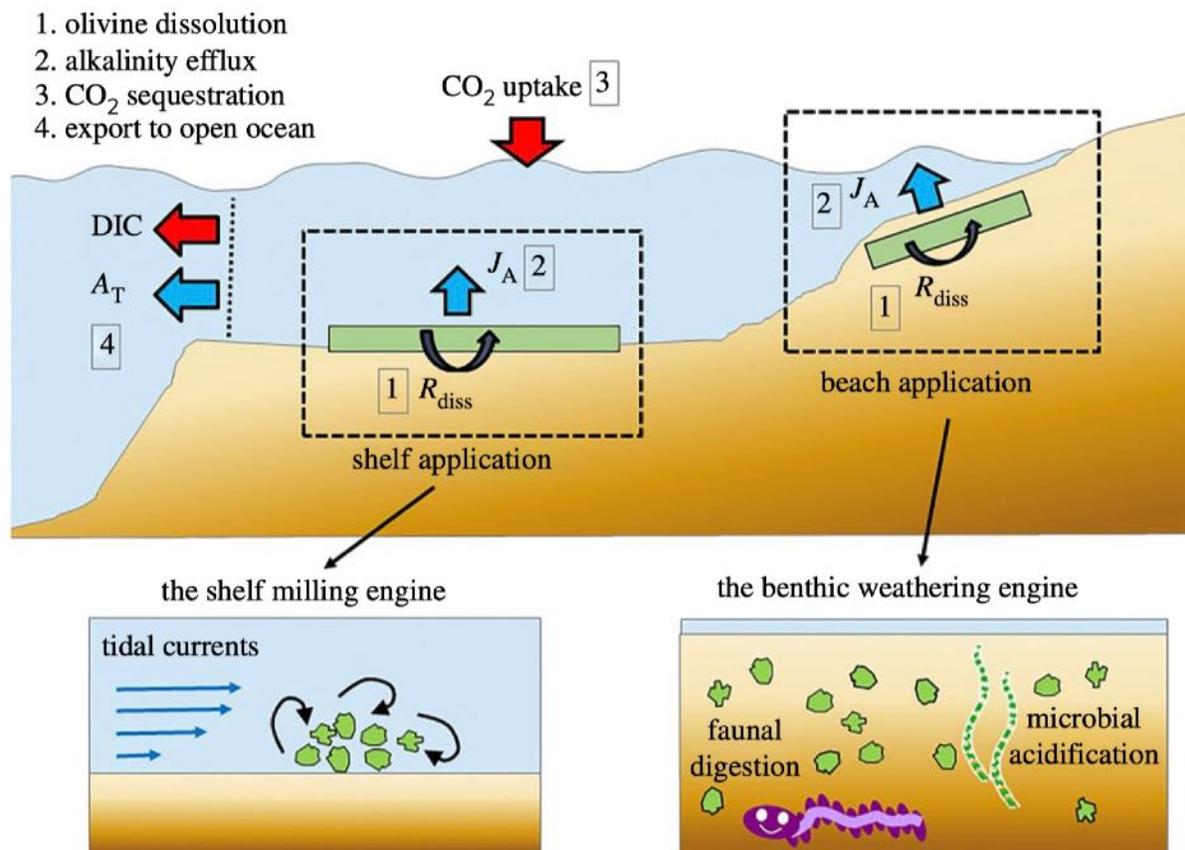
- Peridotites (olivine and mafic pyroxene) induced CO₂ drawdown directly from the atmosphere via mineralization.
- The basalt did not yield any significant changes in seawater composition.
- The precipitation of sepiolite could reduce the carbon sequestration efficiency.

Many more details about the best machines to produce fine and ultra-fine particles by milling are given in **Appendix G Final Stage Grinders**.

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



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').

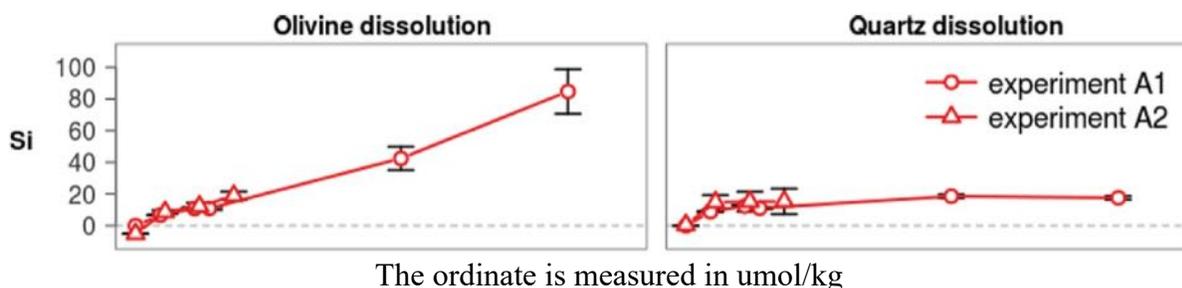
The seabed is characterized by various forms of biological activity, which could induce higher dissolution rates compared with sterile laboratory conditions. Such biological enhancement of silicate weathering has been extensively documented in terrestrial soils, giving rise to the 'mycorrhizal weathering 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) These 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 ($Mg^{2-x}Fe^x SiO_4$) 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 (Fo_{94}). 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 results of forsterite olivine dissolution in the ocean are increases in Mg^{2+} , Si, TA (total alkalinity), DIC (dissolved inorganic carbon), Fe^{+2} , and Ni^{+2} . Their effects on the ecosystem effects need to be assessed.

While increases in alkalinity and DIC are a desired effect for climate engineering purposes, the increase in Mg^{+2} 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*.

Nishimura (1968) showed that the atomic ratio of Ni/Mg decreases regularly with decrease in magnesium content of olivine, i.e., the nickel content of olivine decreases with the decrease in magnesium content.

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 (~100 m²) 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.

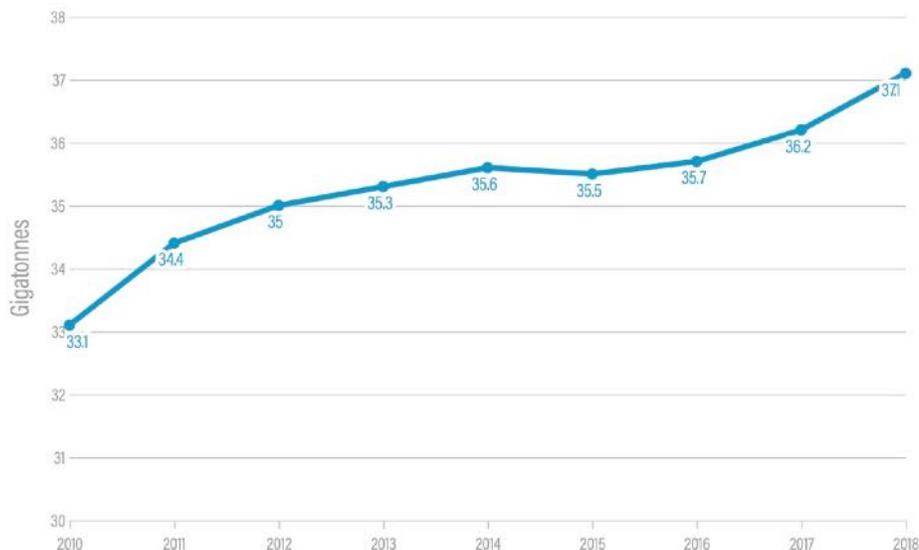
The CO₂ sequestration induced by Enhanced Silicate Weathering (ESW) is governed by the acid–base thermodynamics of seawater, which are well understood, therefore rendering the containment of CO₂ in the ocean highly predictable. The central premise of ESW is that it increases the ocean’s alkalinity, enabling 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.



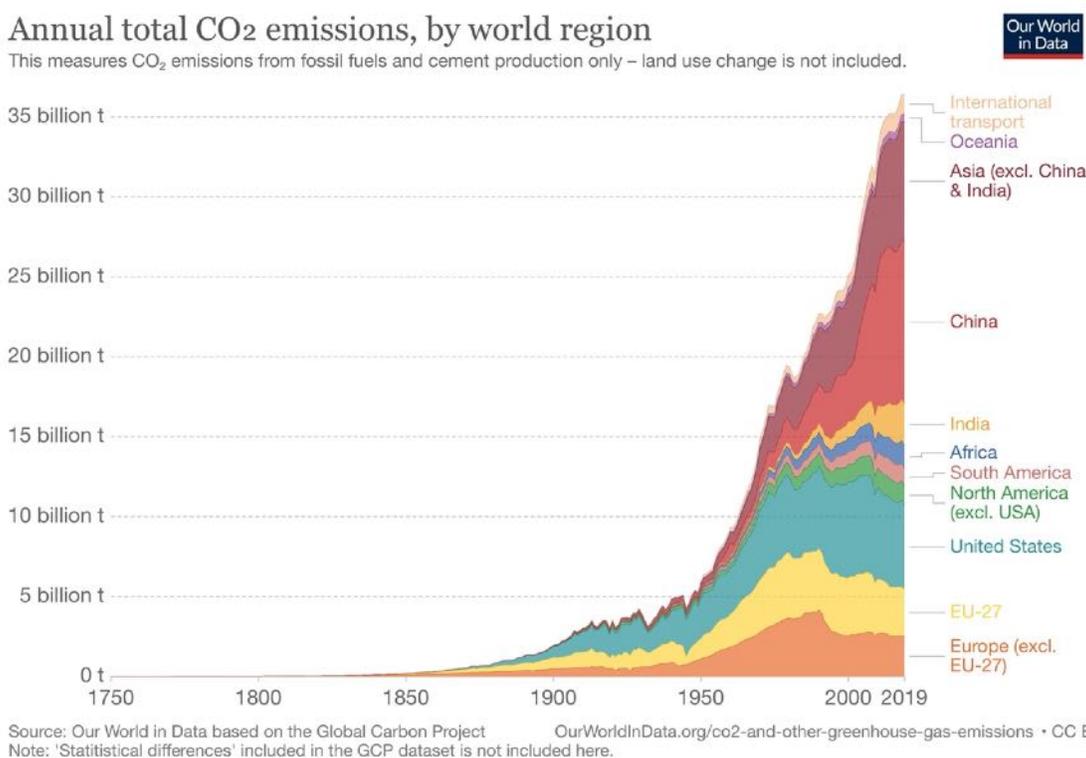
Source: Global Carbon Project

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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⁻¹yr to 70 × 10⁶ 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 × 10⁸ 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) showed 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 x 10⁶ t sequestered C/year if applied homogenously on all agricultural and forested areas of the world. This is equal to 3.67 x 65 or 238 x 10⁶ 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).

The Musk Prize

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 **The Musk Prize** on the web site

www.thecomingsfoundation.net.

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.**”

Schilling 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 homogeneously 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.

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 lower	\$US tonne ⁻¹ upper
Excavation/drilling	0.79	0.79
Grinding (comminution)	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	Rock required (Pg)	Initial 50 ppm CO ₂ drawdown			
			Rock prep. & transport Cost (Tn US\$)		Spreading costs Cost (Tn US\$)	
			lower	upper	lower	upper
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

Pessimism or Optimism about Dissolution Rates? So, what does the Dissolution Rate Mean in More Understandable Terms.

A critical question is: “How long does it take to sequester a given unit of ultramafic rock?” The dissolution rates reported throughout this review are in **log mols/meter²/s**. Not exactly a unit that is instantly meaningful. While many reports of the dissolution rates of olivine are in the 10⁻¹⁴ and 10⁻¹³ range for mol/m²/s, the figures from Hartman et al (2013) for the

dissolution rate of Fosterite Olivine in acidic soil is in the 10^{-9} mol Fosterite/m²/s range. We can convert that into **pounds/acre/year**.

One of the above equations showed that 4 molecules of CO₂ are consumed for every molecule of olivine. The molecular weight of one mole of CO₂ = 44 gm/mol. Four times this = 176 gm. The molecular weight of Fosterite Olivine is 140 gm/mol. Thus, theoretically, based on this equation, one unit of Fosterite sequesters 176/140 or 1.26 of the same units of CO₂. However, because of the many variables such as temperature, rainfall and others, this is a maximum figure.

In converting the molecular weight of Fosterite to pounds, 140 gm = .31 pounds for a sequestration rate of 0.31×10^{-9} pounds Fosterite/m²/s. There are 3.15×10^7 seconds/yr. This then equals a sequestration rate of 0.0031 pounds Fosterite/m²/yr. If this were taken to completion on only one m² it would take 1/.0031 or 322 yrs. To sequester the equivalent of 1 pound of Fosterite Olivine to 1.26 pounds of CO₂ in one year would require placing 1 pound/m² on 322 m². On acre = 4,046 m². Thus, it would require placing 1 pound of Fosterite Olivine on 1/12th of an acre at a rate of 1 pound per m² to sequester 1.26 pounds of CO₂/yr. This equals 15 pounds of CO₂ per acre per year. One metric ton = 2,204 pounds. It would require placing 1 pound of Fosterite per m² on 147 acres of land to sequester 1 ton of CO₂/yr. To sequester one gigaton would require one billion times that. While this provides a very pessimistic assessment there are a number of important considerations and ways to improve on these numbers.

1. The 1 pound/m² figures used above was rather arbitrary. Increasing the amount of olivine placed on the soil would improve these figures. For example, in his simulation of field studies with olivine, ten Berge et al (2012) placed doses equivalent to 1,630, 8,150, 40,700 and 204,000 kg/ha. One hectare = 10,000 m² and 1 kg = 2.2 pounds. Thus 204,000 kg/ha would have been equivalent to 44 pounds/m², far more than that used above. The 40,700 kg/ha would have been equivalent to 5 pounds/m². Thus, one way to improve these numbers is to increase the dose of olivine. Amann, T. et al (2020) used olivine doses of 22 kg/m² with good results on plant growth.

2. A second way of improving the above numbers is to grind the olivine to 1 um size. Renforth et al (2015) stated this **would allow dissolution in 1 to 5 years** a very acceptable result.

3. A third method of improving these numbers is to emphasize the use of weathering hot spots. Taylor et al (2016) reported that these tropical wet regions were **10 times more efficient in rates of weathering**. When all factors were combined hot spots were 29 times more efficient than dry temperate regions.

4. **Use of electrolysis.** As reviewed in the section on OAE, the use of various electrolysis techniques significantly increased the efficiency of the dissolution rates of ultramafic rocks. The use of electrolysis on land may require access to water rich in NaCl. One of the concerns about the use of basalt domes to store CO₂ was that most of them had large amounts of water with three times more saline than seawater, leading to concern about how to get rid of it. Combining EW using electrolysis with DAC and sequestration under basal domes could make a useful partnership.

5. **Ultramafic rocks that have higher dissolution rates.** The report of Westrich, et. al. (1993) (see above) showed dissolution rates of Ca₂SiO₄ in the 10^{-9} range in the same graph that showed dissolution rates of Mg₂SiO₄ in the 10^{-14} to 10^{-13} mol/m²/s range. This illustrates the marked differences in dissolution rate that can occur for different ultramafic rocks. Choice of the type of rock is clearly important.

6. **Concurrent grinding** (see above) proved to be a good method of improving the efficiency of the dissolution of serpentines. As described below, even a relatively small solar array is adequate to provide the electricity for grinding rocks on site. It could also supply the heat used in concurrent grinding at high temperatures.

7. The proposed **3-site Research Proposal** (see below) may identify other ways to significantly improve the dissolution rates.

8. Finally, the rates of dissolution were significantly increased using electrolysis with OAE. This would suggest using more OAE than EW on land.

Taken together there are many techniques that may significantly increase the efficiency of dissolution of ultramafic rocks on croplands and non-croplands and the ocean.

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.

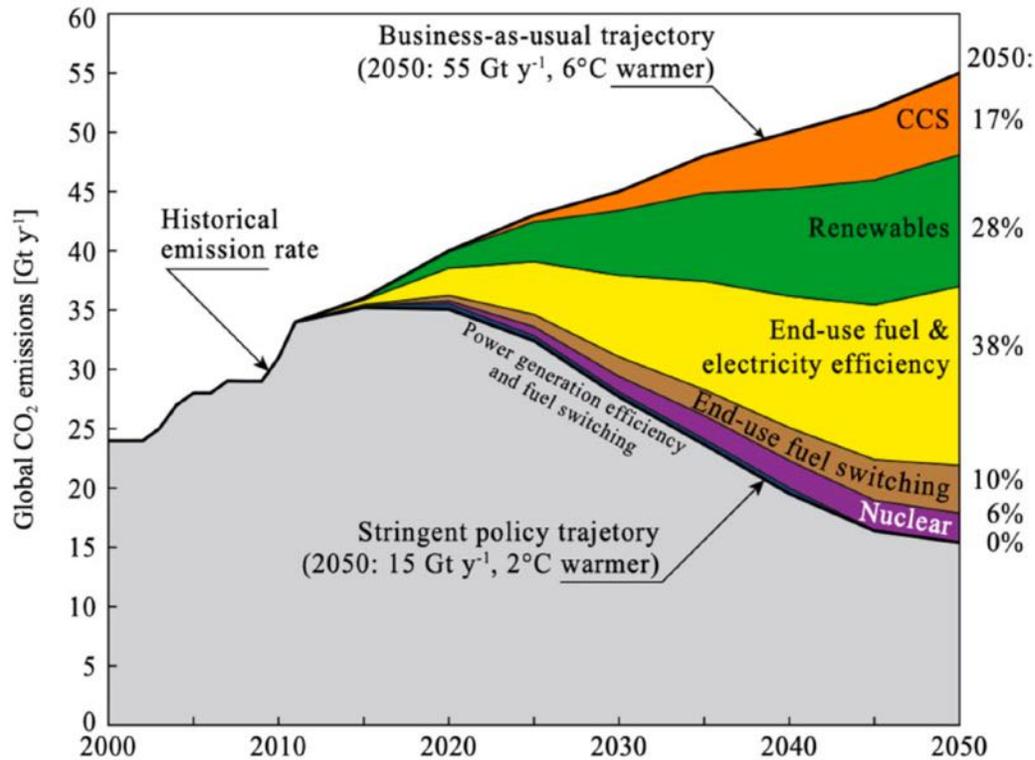
2. Technological enhancements can expand and accelerate natural carbon mineralization, making it feasible **to achieve gigaton (Gt) scale CO₂ removal (CDR)**.

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.

Wedges Importantly, we don't have to do it all with EW and OAW.



IEA. Energy Technology Perspectives (2014), International Energy Agency

This diagram from IEA illustrates the concept of multiple wedges. Renewables, electricity efficiency, and nuclear will all be needed in addition to EW/OAE. However, of these only *in situ* CCS and EW/OAE can actually remove CO₂ from the atmosphere and this wedge will need to account for more than 17%, but not 100% as assumed in the more negative comments.

It has been suggested that to get to zero carbon emissions in the U.S we would need 78 million roof top solar arrays, 485,000 wind turbines, 9,000 solar power plants and massive energy storage. From this point of view, EW and OAE seem easy.

In Conclusion,

- by eliciting the cooperation of many countries,
- by emphasizing the economic advantages,
- 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 increasing ocean alkalization,
- by combating ocean acidification,

- by combating ocean warming,
- by combating ocean deoxygenation,
- by emphasizing the use of EW at weathering “hot spots”,
- by focusing on areas of oxisols and ultisols,
- by using ships for OAE (Ocean Alkalinization Enhancement) designed to be carbon negative,
- by using ships for OAE that utilizes electrolysis techniques,
- by using carbon credits,
- by partnering with New Caledonia to open up their vast reserves of ultramafic rock to serve the south Pacific area,
- by urging the U.S. Military to start a project analogous to the Manhattan Project, to mine, process and stockpile ultramafic rocks at the Twin Peaks site in WA and other sites in the US and throughout the world.
- by partnering with other government agencies such as the Department of Agriculture, U.S. Geological Service, Department of the Interior, NOAA, EPA, the Biden Climate Group, and others,

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

So, What Can We Do?

We propose to do the following things.

1. **A 3-site Research Project**
2. **Develop Blueprints for and build an OAE Research Ship**
3. **Advocate for the Government to Develop A Large Scale Mining and Production Site at Twin Peaks, WA and other sites.**
4. **Advocate for the Global Cooperation for Mining, Processing and using Ultramafics to sequester CO₂.**
5. **Set up an International EW and OAE Panel consisting of many of the experts cited in this review.**

1. A 3-site Research Project

The Basic Plan Essentially this research proposal will set up three field research plots. One in a **wet, tropical rapid weathering hot spot**, one in a **wet temperate site**, and one in a **drier temperate site**. Initially we propose that the wet tropical site will be in Ecuador, Columbia or Central America, the wet temperate site in Mississippi, Alabama, Georgia or Florida, and the drier temperate site in a Midwestern state.

Field studies, rather than laboratory research into weathering is critical since it is known that laboratory based rates can be **1 to 5 orders of magnitude greater than those measured in the field** (White, 1995, White and Brantley, 2003; Maher et al., 2004; Maher, 2010; Zhu, 2005).

The opposite side of the issue comes from **Schuiling - The rate of olivine weathering, an expensive myth**. He claims the opposite, that **the rate of olivine weathering in nature is much faster than the laboratory**. The reader is referred to his web site for a discussion of why

he feels this way. **White, A.F. (1995)** reported the weathering for two minerals, oligoclase and hornblende, where data on rates was available for both “soil” and “experimental”. **The rates for soil were 1 to 4 orders of magnitude lower than for experimental rates.**

These studies and their opposing opinions illustrate one of the reasons why a **3-Site Research Project is important.** Before describing the project, a review of the methods of testing weathering rates is relevant.

Testing Weathering Rates In the field, mineral dissolution rates can be quantified by analyzing river water chemistry in a watershed (April et al., 1986), studying weathering rinds (Sak et al., 2004), or by determining a mineral or chemical depletion profile throughout a soil column samples (White and Brantley, 2003). Testing river water is clearly not suitable for the 3-site study since the conditions at each site are quite different.

Weathering rinds are defined as discolored and permeable crusts enriched in immobile oxides (i.e., Fe_2O_3 , TiO_2 and Al_2O_3) relative to un-weathered cores. Measuring weathering rind thickness is easily done in the field making rinds an effective tool for determining the relative degree of surficial deposit weathering. This technique is most suited to large non-pulverized rocks. It will not be suitable for particles in the 1 to 30 μm range.

Thus, **analyzing core samples (White and Brantley 1995, 2003) is clearly best suited to produce results that can be compared between the three sites and is suitable for small particle size.** The average **silicate weathering rate R** ($\text{mol}/\text{m}^2/\text{s}$) or ($\text{mol m}^{-2}\text{s}^{-1}$) is commonly defined by the relationship

$$R = Q/St \quad \text{Eq 1}$$

where Q is the moles of a mineral reacted, S (m^2) is the surface area and t (in seconds) is time.

As an example, column studies, using freshly prepared Panola Granite, produced ambient plagioclase weathering rates that decreased parabolically over 6 years to a final rate of $7.0 \times 10^{-14} \text{ mol}/\text{m}^2/\text{s}$ (White and Brantley, 2003).

Methods included solid-state compositions determined by X-ray fluorescence analyses (XRF), alkalinity and pH measured using an auto-titrator, and **solute cations** were determined by **ICP/MS - Inductively Coupled Plasma Mass Spectrometry.** This is an analytical technique that can be used to measure elements at trace levels in fluids. This has replaced older techniques such as atomic absorption and atomic emission.

Weathering rates are normalized to the surface areas of the reacting silicates, based either on gas sorption isotherms (BET) or geometric estimates (GEO). BET values are incorporated into almost all of the experimental rate data.

BET refers to **Brunauer–Emmett–Teller** theory that aims to explain the physical adsorption of gas molecules on a solid surface and serves as the basis for an important analysis technique for the **measurement of the specific surface area of materials.** The observations are very often referred to as physical adsorption or physisorption.

In 1938, Stephen **Brunauer**, Paul Hugh **Emmett**, and Edward **Teller** published the first article about the BET theory in the Journal of the American Chemical Society. The BET theory applies to systems of multilayer adsorption and usually utilizes probing gases (called the adsorbent) that do not chemically react with material surfaces as adsorbates (the material upon which the gas attaches to and the gas phase is called the adsorptive) to quantify specific surface area. **Nitrogen** is the most commonly employed gaseous adsorbate used for surface probing by BET methods. For this reason, standard BET analysis is most often conducted at the boiling temperature of N_2 (77 K). Other gases have included argon, carbon dioxide, and water Wikipedia.

A Quantachrome NovaWin BET Analyzer can be used to determine pore volume and surface area of the mineral samples using the BET method.

The scale of geometric surface area measurements, using microscopic techniques such as SEM (Dorn, 1995) and AFM (Brantley et al., 1999), is orders of magnitude greater than the atomic scale of the BET methods. This discrepancy is responsible for consistently higher reported BET surface areas compared to geometric estimates. The calculated weathering rates are inversely related to the surface area (Eq. (1)). This difference partly explains why most of the natural rates, based on geometric estimates, are faster than experimental rates based on BET estimates. A general relationship of **decreasing weathering rate with increasing time** was clearly evident for plagioclase (White and Brantley, 2003).

Some workers have suggested that geometric (GEO) rather than BET surface areas may be more representative of reactive surface areas in the weathering environment (White et al., 1996; Gautier et al., 2001). If such a situation is true, the question is raised as to whether the large apparent decreases in weathering rates with time are artifacts based on a normalization using BET measurements which overestimate actual increases in reactive surface area with time.

Other methods and instruments (Swanson, 2014). • A laser based particle sizer (Beckman Coulter, Inc., LS 13 320 MW) to determine the mean particle size and particle size distributions. • Wavelength Dispersion X-Ray Fluorescence (WD-XRF, Pananalytical Axios). • X-Ray Diffraction (XRD 3000, Inel Inc.) in the range of 20° and 80° and CuK α radiation ($\lambda = 1.5406 \text{ \AA}$) to determine the chemical compositions and the crystalline structures of the mineral samples, respectively. • Loss of Ignition (LOI) test to quantify the water content in the mineral samples.

Common Laboratory Given the wide range of expensive instruments required, using a university lab already set up makes the most sense. A single, common laboratory for the analysis of soil samples throughout the study should be located in the US. We would incorporate such a laboratory as an integral part of the study with input into the study design.

Types of rock Three different classes of ultramafic rocks will be studied – **olivine, serpentine and basalt.**

Particle Size is an important variable to be tested in the 3-site studies. Average sizes of 1 μm , 10 μm , 50 μm and $\geq 100 \mu\text{m}$ seem reasonable. If it proves difficult to sort the samples into different particle sizes, they may be separated on the basis of the duration of grinding followed by a determination of the range of sizes in the sample. Alternatively, with **attrition grinding** the size of the particles will be set by the size of the pores in the pore plate.

Grinding method There will be a need to choose the best method of producing small particle sizes, such as ball mills plus attrition grinding. One question for serpentines will be - is there a need for concurrent grinding in the presence of heat? If so, this would require the purchase or development of an apparatus combining the two. As shown in the **Appendix G. Final Stage Grinders** the ACU group developed such a machine for laboratory studies. A much larger one would be required for field studies. See also below under encouraging creativity.

Use of tailings Some of the macro-plots will be used to test the utility of using tailings as a source of EW rocks.

Test for microorganisms such as bacteria, viruses and fungi which can play an important role in EW. Metagenomic analysis of soil DNA samples may be the best method to do this. We may need to include a microbiologist on the staff to do these analyses. This person could do the testing at all three sites.

Testing the effect of fungi on dissolution rates R. D. Schuiling (2013) has suggested that the dissolution rates of olivine as determined in the laboratory grossly underestimates the speed actual rate in the soil in nature because it fails to consider the effect of fungi on the dissolution. He stated, “One may wonder why there is such a large discrepancy between laboratory experiments, showing low rates of weathering, and the real world, where weathering rates are 100 times larger. The answer is relatively simple. Higher plants live in symbiosis with mycorrhizal fungi in and around their root system. These fungi secrete low molecular organic acids like acetic acid, malic acid and oxalic acid that rapidly attack mineral grains in the soil (Van Schöll et al, 2008). This liberates mineral nutrients that are subsequently taken up by the higher plants. In turn, the higher plants “reward” the fungi by providing them sugars. Lichens act in a similar way by secreting oxalic acid that “eats” the underlying rock (Wilson et al, 1981). In the laboratory, mycorrhizal fungi and lichens are absent, and this is the reason why the abiotic reaction rates that were found in the laboratory are much lower than weathering rates in nature.”

Schuiling based his rates on dissolution of olivine in natural conditions on studies of a lateritic crust in Conakry Guinea. Laterite is an iron rich iron-rich insoluble red residue of the dunite after deep tropical weathering. It no longer contains silica, magnesium or calcium oxides. These were completely leached out during the weathering process (Percival, 1965). This somewhat roundabout method needs to be verified by direct studies of olivine weathering in natural soils, something our 3-site study will do.

In the meantime, Schuiling makes an interesting point. At a minimum this suggests that we need a mycologist on the team to both test for the presence of fungi in our different test plots and more importantly, determine if seeding the test plot with the appropriate fungi spores could assist in the more rapid dissolution of the ultramafic rocks spread on both cropland and non-cropland. If it is possible, for example, to increase the dissolution from 100 years to one year, this would be a game changer.

Different species of fungi produce different rate of rock eating (Van Schöll et al, 2008), which is another reason for having a mycologist on the team. Studies of the effect of different species on the dissolution rates of olivine and serpentine would be an important adjunct to the 3-site study. Determining which fungi species are most effective at assisting the dissolution of olivine and serpentine could be undertaken both at the 3-site research site and independently of this site. The Comings Foundation may fund such studies.

Articles as a Source of Methods Several articles contain detailed descriptions of some of the methods that will need to be used in these studies. The report of Amann et al (2020), Swanson (2014), and White and Brantley (2003) are good examples.

Uniformity of All Study Sites. For accurate comparison of the results at each site it will be critical that studies at each of the three sites be carried out in an identical fashion. Thus, they will all use the same source of olivine, serpentine and basalt, the same common laboratory for analyses, and the same research plan. The level of nickel and chromium will be determined before being used. An exception to this uniformity is listed below under Encouraging Creativity.

Solar Panels. A portion of the acreage will be set aside for solar panels. Renforth (2012) calculated that it would require 1.5 GJ to grind 1 ton of olivine to 1 um or less. In the conversion of GJ to kWh, 1 GJ = 278 kWh. One acre (4,000 m²) of modern solar panels can produce 4,000 kWh of electricity. Since there will be other needs for electricity such as testing the value of pretreatment of serpentines with heat, we anticipate that the placement of solar panels on one-half acre of land should be adequate. If the area is windy wind turbines could also be used.

How much land will be needed? Macro- and Mini-plots. This can best be estimated from the bottom up. We start with the proposed size of each individual test plot. We believe that a plot 8 meters on a side is reasonable i.e., 64 m², is reasonable for the average test plot. These are called **macroplots**. In addition, some macroplots will be divided into four **miniplots** each 4 m on a side for 16 m² (somewhat less since there will be a ½ meter path between the internal parts of the miniplots).

Each 64 m² plot should be surrounded on all four sides with a 4 meter wide border to allow safe separation of each test plot and room to walk and drive tractors between them. Since adjacent plots share borders this is equivalent to 2 more meters around each for a plot total size of 12 m on a side or 144 m².

Five different crops: none, corn, wheat, barley, and alfalfa.

Five different rock sizes: 0 (no rocks), 1 um, 30 um, 100 um and >300 um. As above these may represent different grinding times producing groups with an average of particle size.

Four different rocks: olivine, basalt, and serpentine, and none.

We would multiply this by 1.5 this to provide plenty of micro-plots – 400 of them in all. We do not anticipate using all of them but better to have too many than too few.

Thus $5 \times 5 \times 4 \times 1.5 = 150$ macro-plots $\times 144$ m² for a total of 21,600 m². We would double that to have land for solar panels and buildings (storage, test labs, administration and lodging. Thus, the total area = 43,200 m² = 10.6 acres per site.

Since this is not a large amount of land, we would buy it rather than lease it. This way it would allow the studies to go on for many years, if we wished.

How much does the land cost? An acre of land in the U.S. ranges from about \$2,500 in Mississippi to about \$8,500 in Illinois, or \$25,000 to \$85,000 per research plot in the U.S. The prices are somewhat comparable in Ecuador.

Specialized Mini-plots The average test plot will be 8 m on a side. However, we will also set aside a large number of 4 m on a side mini plots (4 per 8 m plot) with a two foot path between the internal boundaries. This makes it possible to answer a number of specialized questions with the minimum use of land. The following are some examples of this use of mini plots:

- **Maximum thickness of rock?** What is the maximum thickness of olivine that can be placed on croplands or non-croplands and still sequester CO₂? The findings in Oman (Fox, 2021) suggested that the layers can be very thick. This could be tested by using a number of miniplots each covered with increasing amounts of olivine ground to different sizes. This might show, for example, that in a weathering hot spot, olivine can be spread very thickly and still sequester CO₂. It would also determine that maximum thickness that could be applied in the wet temperate and dry temperate sites. **This could result in a dramatic decrease in estimates of the amount of land required to successfully sequester CO₂.**

- **Methods of increasing thickness of sequestering rock on non-croplands.** If one were trying to maximize the amount of finely ground ultramafic that could be used to sequester CO₂, one question is whether there was some type of **supporting matrix** that could hold multiple layers the fine rock powder thus increasing their exposure to the air. If, for example, this could lead to a 10 fold increase in efficiency, instead of using 100 acres only 10 acres would be needed. Pondering this question has led us to the possibility that **the best matrix would be more coarsely ground rocks with the fine powder spread between them.** This would be especially useful on non-croplands. Multiple microplots could be devoted to determining the best size of the larger rocks and the maximum ratio between the two.

• **Effect of ultramafic rocks on different soils?** The following type of soils could be brought in from around the world: acid, oxisol, ultisol and other, to test for the effectiveness of ultramafic rocks to convert them to being usable for crops. Given the small size of the miniplots the amount of soil brought in would be small. This would avoid the need to set up additional studies in other countries or areas with these soils.

• **Effect of added water?** The formula for the dissolution of ultramafic rocks includes 4 moles of water. Since water is so critical, one or more of the mini-plots will be treated with various levels of watering. This will probably be most informative for the Midwest sites. This may indicate the maximum effective rate of watering.

• **Role of fungi and bacteria?** Different miniplots could be seeded with certain fungi or microorganisms to test their effect of the rate of dissolution of the rocks.

• **Effectiveness of *Alyssum* plants to extract nickel?** Several mini plots could be planted with varying amounts of *Alyssum* to determine its effectiveness in extracting nickel from crushed olivine and serpentines. Periodic core samples of soil will be tested for Ni and Cr. We will also attempt to determine if electrolysis techniques can be used to extract nickel from the ground rocks.

• **Effect of ultramafic rocks on growing vegetables?** The emphasis in the few field studies reported has been on the effect of ultramafic rocks on grains such as wheat, corn, and barley. A number of mini plots could be set aside to test the effectiveness of ultramafic rocks on vegetables such as lettuce, carrots, potatoes, strawberries, squash, and others.

• **The need for pretreatments of serpentines?** The majority of laboratory studies on the dissolution of serpentines have suggested the need for pretreatments such as heat, acid, concurrent grinding and others. A number of mini plots could be used to determine the effectiveness of these pretreatments versus only grinding. There are two considerations: are the pretreatments advantageous and if so, are they economically feasible? If they have high energy needs can the solar panels cover it?

• **Encourage Creativity with Site Specific Research.** In addition to the research done in the same way by all sites, some of the microplots can be used by the PI's and their staff to test their own pet ideas, such as testing different types of pre-treatment, different types of grinding, different types of crop, etc. If these seem promising, in the following years they will also be performed at all sites.

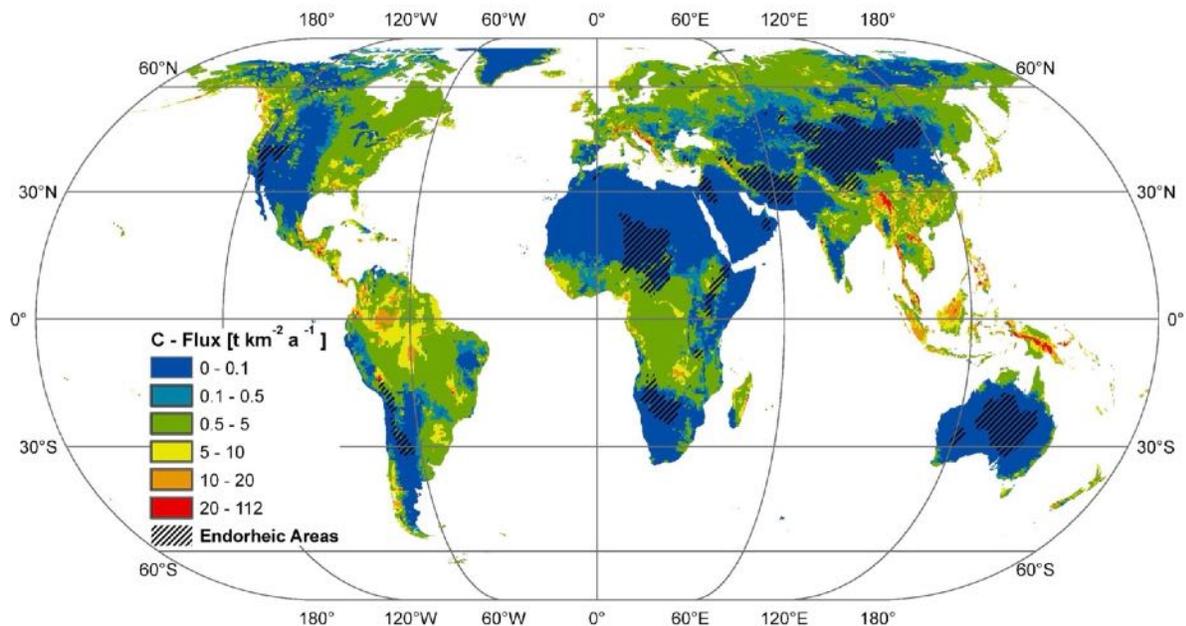
Ecuador's Contribution For the purpose of national pride we would encourage Ecuador to fund and staff the research site in their country. The PI's for each of the three plots and for the whole project will all play a role in the final design and execution of the 3-site research.

Goals The following are some of the questions and goals:

- Examine four different crops treated and untreated on macro-plots.
- Have many additional macroplots for research flexibility.
- Have multiple microplots for a wide range of studies including a range of vegetables, different pre-treatments, grinding methods and other.
- Determine the percent improvement in crop growth for the different crops.
- Can serpentines be used with grinding only or are other pretreatments needed?
- Compare the weathering rate of olivine versus serpentine versus basalt at each site.
- Compare the weathering rates for different sized particles.

- Determine the ideal particle size for both olivine and serpentine and basalt.
- Determine the ideal method of grinding. Roller mills, attrition grinding, centrifugal grinding, and others singly or in tandem. Also examine wet or dry grinding or both.
- Determine if concurrent grinding with heat is required for serpentines or if grinding alone is adequate.
- Determine the amounts of nickel and chromium, and other metals that are leached into the soil.
- Determine if plants such as *Alyssum* can be used to sequester nickel and if that nickel can be economically recovered.
- Determine if electrolysis or other methods can be used to extract Ni and Cr from the ground particles.
- Do we need to hire an experienced soil chemist and soil microbiologist to assist with or run the studies?
- Determine the degree of increase in weathering in the hot spots compared to temperate wet and temperate dry spots. Focusing on moist tropics has been stated to produce 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 (see above). This suggests that the exclusive use of hot spots would produce a weathering rate of 29×5 or $145 \times$ 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. This research would determine if this degree of increase in EW is valid.

Where would the hot spot test site be located? Hartmann et al (2009a) published **hot spot map for the world**.



This shows that some potential hot spots for this study, in the Western Hemisphere, are in Columbia, Ecuador and Central America.

Duration of Study The studies of White and Brantley (2003) had an unusually long duration of 6 years. We anticipate that with much smaller particle sizes, the duration of the study needed to return good data can be considerably shorter, such as 2 to 4 years. However, it is also likely that important information will be obtained by continuing the studies for longer periods of time. We do not believe it will be necessary to wait for these longer times to begin EW in countries throughout the world. **The 3-site study will inform ongoing EW with information on the relative value of focusing on weathering hot spots, optimal particle size, methods of grinding, methods of removing nickel if necessary, and other results.**

Advisory Group. We propose to engage with a number of the authors of previous studies (above) to serve as advisors on the study. We hope that one of these advisors will become the PI for the study or suggest a suitable candidate. We will also need associate PI's monitoring each site.

In 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.**

There are several advantages of funding such studies through a private foundation.

1. Since the foundation has a sizable endowment and runs on the returns of investments, some types of research can run for much longer periods of time than usually allowed by federal grants. If our advisory team feels that continuing the 3-site research for longer periods of time would be productive, we can do so.

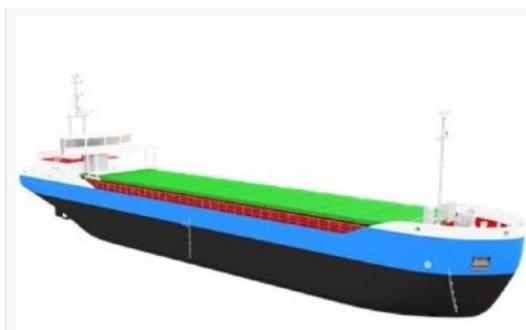
2. Funding is very nimble and can respond quickly to changes in direction dictated by results.

3. Probability of funding is certain. Probability of federal funding is uncertain.

2. Develop Blueprints for then Build an OAE Research Ship

As described above, one option for the alkalization of the oceans is to build a fleet of specialized ships running on carbon free electricity and using electrochemistry for alkalization. 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.

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.)

Wind turbines not shown. We leave that to your imagination)

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

Power Can on board **solar panels, wind turbines, sails, and fuel cells** provide enough power for the electrolytic methods and for on-board grinding of rocks? Considerations concerning the solar power and wind turbines can be found in appendices F and H. As regards fuel cells, which to use? HCl-H₂ fuel cells? Standard O₂ H₂ fuel cells? Both? Can OTEC also be used as a source of electricity? Are these sources of electricity adequate to power a ship moving slowly as it lays down alkalization products? If not, is it possible to add floating solar panels? For details see **Appendix H. Photovoltaic Floats. Appendix F** is a review of **Vertical Axis Wind Turbines (VAWT)** ideal for use on ships.

Sails. An additional possibility is using a ‘rotor sail’, a large spinning cylinder that catches the wind. It reduces fuel needs by up to a fifth (Rotor Ship, Wikipedia, 2021).

Battery Backup Battery Storage Some form of battery storage will be necessary for those days when the sun is not shining, or the wind is not blowing or both. Currently there are to possibilities – lithium and iron-air batteries. A problem with lithium batteries is that they are extremely sensitive to high temperatures and inherently flammable. These battery packs tend to degrade much faster than they normally would, in the presence of excess heat. If a lithium-ion battery pack fails, it can burst into flames and can cause widespread damage. This would be a disaster for an OAE ship that spends a lot of time at the equator. It would not be a good choice.

Iron-Air battery Form Energy's New Low-Cost, Iron-Air Battery.

<https://singularityhub.com/2021/08/02/form-energys-new-low-cost-iron-based-battery-runs-for-100-hours/>

Form Energy's batteries are each about the size of a washing machine and are filled with iron pellets and a water-based electrolyte similar to that used in AA batteries. To discharge, the battery breathes in oxygen from the air, converting the pellets to iron oxide, or rust, and producing electricity in the process. To charge, the application of a current converts the rust back into iron and expels the oxygen. The key to their approach is the low cost of the constituent materials. Today's lithium-ion batteries cost \$50 to \$80 per kilowatt-hour thanks to the expensive minerals required to make them, like nickel, cobalt, lithium, and manganese. According to the Wall Street Journal, Form Energy can make their battery for just \$20 per kilowatt-hour, and they will be able to provide power for 100 to 150 hours, depending on the configuration. We anticipate the Form Battery will be available in time for the OAE ship.

Solid-state Electrolyte Lithium Batteries. These are another much more powerful and efficient type of battery that will soon be available.

Cost How much would such ships 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). Can we purchase and refurbish a second-hand ship?

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? A detailed presentation of the best grinders for ship-board use are presented in **Appendix G Final Stage Grinders.**

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.

Adsorbing Nickel from Solutions The problem of contamination of the alkalization fluids with heavy metals, such as nickel, can potentially be eliminated by adsorption onto a wide range of adsorbents. These include zeolites, bio-zeolites, CaCO_3 maltose and Lignocellulose/Montmorillonite Nanocomposite and many others.

The lignocellulose/montmorillonite nanocomposite is especially intriguing. It is inexpensive and its maximum adsorption capacity of Ni(II) reached 94.86 mg/g at an initial Ni(II) concentration of 0.0032 mol/L, a solution pH of 6.8, an adsorption temperature of 70°C, and adsorption time of 40 min. One advantage is that it **can be regenerated with HCl, one of the biproducts of electrolysis**. Some reagents also adsorb barium and mercury (Liakos, E.V. et al (2021)). We would also explore the possibility of using electrolysis to remove Nickel and Chromium before placing the processed rocks in the ocean.

Efficiency What amounts of OAE and CO_2 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 capability for more than one method of electrolysis?**

Effects on Ocean Chemistry? What are the effects these alkalization projects on the ocean chemistry? This might be answered most easily by having the ship make multiple passes in a semi-enclosed bay.

On-board chemistry laboratory Such a laboratory will be necessary to determine pH, salinity, alkalinity, temperature, pCO_2 , pO_2 , as well as all of the members of the carbonate cycle Ω carbonate, CO_2 , H_2CO_3 , HCO_3^- and CO_3^{2-} for ocean sampling. On board mass spectroscopy? What other instruments? The use of Wave Gliders (Chavez, 2018) to measure surface pH and pCO_2 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, that is be independent of the port facilities? Is there a need for onboard loading towers?

Internal Movement of Rocks The ship needs to be designed to be able to move the ultramafic rocks in the storage bins to the electrolysis chambers automatically. To move rocks from storage bin A to the electrolysis chamber should be done by pushing a button in the bridge, not by sending staff out with shovels.

Governance What governance agreements will be necessary. What departments in the US government handles that?

Crew and Crew Cabins Obviously there is a need for cabins for the crew. But what is the makeup of the crew? Most likely: the captain, first officer, mechanics, engineers, electricians, chemists, marine biologists, cooks, and others. But to save funds we need to keep the crew as trim as possible.

Number of Ships Needed. Harvey (2008) spoke of a fleet of thousands of ships, and time spans of up to 100 years. Hopefully, mechanisms can be found to drastically reduce this

number and time span. He also provided detailed analysis of three different sized ships, with capacities of 2,500, 25,000 and 250,000 tons. Large oil tankers have a capacity of 600,000 tons. To ensure efficiency it is likely the OAE research ship should have a capacity of at least 250,000 tons.

If the results with the initial research ship are positive, multiple countries and many ships could then be involved. The goal is to provide a standardized set of blueprints for proven ships, so each country does not have to design and research its own. There may be a only one or two ship building companies building the ships and different countries would purchase their ships from these companies.

Other Approaches to Carbon Zero Ships The following are two alternative approaches for carbon zero ships.

1. Use of Ammonia as Fuel. Amazon and IKEA have pledged to use only zero-carbon fuel ocean vessels by 2040. The proposed fuel will be ammonia. In March of 2021, several of the major cargo companies including Maersk, Fleet Management Limited, Keppel Offshore & Marine, Sumitomo Corporation and Yara International began a study of a green ammonia supply chain at the Port of Singapore, for this purpose (Doniger, 2021). The use of ammonia fuel is concerning since when heated, ammonia in an enclosed space can blow up

2. Alice Sueko Müller of Ocean Cloud has proposed the use of **olivine itself** to provide a carbon-neutral ship. She proposed having the CO₂ output from the oil burning engines passed thru a slurry of pulverized olivine to adsorb the CO₂. She stated that “1 ton of olivine removes 1.25 tons of CO₂. To mine, pulverize & transport 1 ton olivine costs \$13 today equaling \$10.40/ton of CO₂ removed with olivine; an extremely low price/CO₂-ton-captured compared to other carbon capture technologies. An average cargo ship emits approximately 30.4 tons of CO₂/day (90,000 ships release ≈ 1 billion tons of CO₂ & GHGs/year (ICCT, International Council on Clean Transportation, 2015). Cargo ships hold up to 21,413 TEUs (Twenty Foot Equivalent Shipping Units). 1 TEU (the average container) holds up to 33.2 m³, which will be able to hold approximately 51 tons of olivine powder. During a 10 day ship voyage, such as from the UK to New York, one cargo ship emits approximately 304.4 tons CO₂. To carbon neutralize such a 10 day Transatlantic trip 243.6 tons filling 6 TEUs of olivine would be needed. This would represent less than 1% to 6% of the maximum TEU ship capacity, a very small sacrifice to be made to become a carbon neutral ship.”

Even if somewhat more than 1 ton of olivine is required per ton of CO₂ sequestered and if the cost of 1 ton of pulverized and transported olivine is more than \$13 per ton, this is still an intriguing idea. If all ships in use today were converted to this approach, that would account for 1 gigaton of the needed C sequestration.

Support Scripps Seawater Reference Samples

“Over the past 32 years, Dickson, a marine chemist at the Scripps Institution has sent 150,000 bottles of carefully characterized seawater to researchers worldwide. These are indispensable since they enable scientists to calibrate instruments and ensure their own measurements of ocean alkalinity, inorganic carbon and pH are accurate and comparable even when collected by different researchers working years or ocean apart.” (Catheman, 2021).

Now, however, marine researchers face the prospect of losing access to this obscure mainstay of their research. Dickson, 68, is considering retirement, and it’s not clear whether his lab—the world’s only source of the reference samples—can maintain its funding once he’s gone. As a result, the ocean science community is scrambling to come up with a plan to keep the

bottles flowing. The issue “is very high on our risk register,” says marine scientist Elaine McDonagh of the United Kingdom’s National Oceanographic Centre.

Dickson says it took a “slightly twisted mindset” to develop and implement the system, which relies on meticulous measurements—conducted by Guy Emanuele, a senior technician at Scripps—to ensure each sample has known characteristics. So far, no one has been able to rival Emanuele’s accuracy although many have tried.

The COVID19 pandemic resulted in a backlog of 7,000 bottles. The pandemic exposed the fundamental issue of having just one point of failure said Elizabeth Jewett, director of NOAAs’s Ocean Acidification Program.

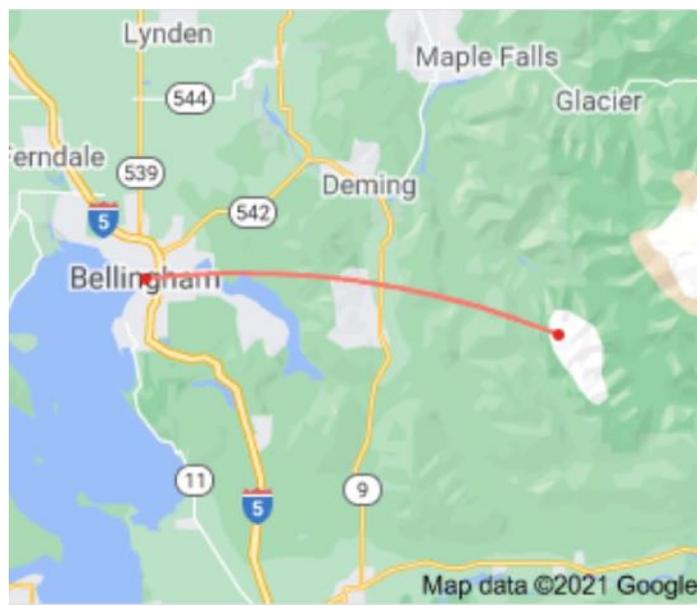
At the time that Dickson began his work in 1989 reputable labs were repeatedly producing different numbers when analyzing the same samples of seawater. These samples became critical for a wide range of oceanographic studies including assessment of ocean acidification.

Last year a U.S. Interagency Working Group on Ocean Acidification began to explore ways to keep these samples available. The price tag is about \$700,000 per year or more. Dickson’s lab is funded to March 2024. This would seem to be something NOAA could fund. However, if no funding is available by that time the Comings Foundation will step in and fund it.

3. Advocate for the Government to Develop A Large Scale Mining and Production Site at Twin Peaks, WA and other sites.

We recommend that the U.S. Military (or other U.S. government organization) develop a centralized facility of olivine mining, grinding, and distribution at the Twin Sisters site in WA. A critical aspect would be the closeness to a major port at Bellingham and the availability of renewable energy. This could come from the hydroelectric power in Southern Washington, or from the utilization of a Molten Salt Nuclear Reactor or other Microreactor on site, or a wind or solar farm.

It is only 22 miles from the Twin Sisters site to the Bellingham port. Since this site is so close to the ocean it could serve as an ideal site for suppling pulverized olivine to the OAE ships described above.



An advantage of utilizing the U.S. Military is that they would be able to accelerate the use of Molten Salt Reactor or Microreactor technology as a source of energy for grinding the ultramafic rocks, given the speed with which they initiated the Manhattan Project for the development of the atom bomb and then the development of nuclear submarines and air-craft carriers. In fact, the launching of a new Manhattan type Project for rescuing the world from destruction by global warming may be necessary.

In the U.S. the **Army Corp of Engineering** which already has a **Climate Preparedness and Resilience Program** could be given the job of mining and developing such stockpiles here. Given their almost magical ability to complete large projects, this would be the ideal agency to develop these facilities.

The best approach might be to work closely with Unimin Corporation since they are already mining this site. The government could fund them to dramatically increase the amount of ultramafic rocks they mine and ensure they are used for EW and OAE.

4. Advocate for the Global Cooperation for Mining, Processing and using Ultramafics to sequester CO₂.

This type of world-wide cooperation is not unique. For example, in 2006 when it was realized that fusion works better the larger the tokamak, a group of 35 countries meet at Elysée Palace and signed an agreement to **build the ITER**. It has been estimated that by the time researchers attain ignition (more energy out than in) in a fusion machine and build functioning **power plants** such as DEMO (Demonstration Power Plant) or LIFE (Laser Inertial Fusion Energy) (Turrell, 2021) this will not have occurred until around 2050, after other methods have probably reached zero carbon emissions. And despite putting all that money and effort into achieving fusion energy it contributes nothing toward an NET to remove CO₂ from the atmosphere. Surely if all that money and effort can be spent on a technology that will NOT be quick enough to save us from the devastation of global warming, we should be willing to spend even less than that amount to rapidly develop EW and OAE, that can save us in time.

Another example of the speed with which many countries can come together for a common goal is the **Sustainable Development Goals (SDGs) project**. In September 2015, 193 countries came together at the United Nations to adopt and commit to a long-term, comprehensive strategy to tackle the world's greatest challenges related to global sustainable development. The result was the SDGs, a list of 17 goals to achieve a better and more sustainable future for all by 2030.

We need a comparable group of countries to come together for a **Save the Earth** conference devoted to an international effort for all countries with deposits of ultramafic rocks.

So, what is the magnitude of the problem? How much is 10 gigatons of Rock?

Since visuals are better than text, we will give that a try. In the NOVA production *Polar Extremes*, Kirk Johnson showed a picture of 12.5 gigatons of charcoal representing part of the amount of carbon humans put into the atmosphere each year. **The pile was over a mile high and 4 miles wide.**



A 12.5 gigatons of rock

If it takes about 1.5 tons of ultramafic rock to sequester 1 ton of CO₂, it will require a pile almost 2.4 times as large as this to remove 20 gigatons of CO₂. Since other NETs will probably be contributing to the removal of CO₂ this is a top estimate. Nevertheless: **it is impossible to extract and sequester huge amounts of CO₂ from the atmosphere without an equally huge stockpile of processed ultramafic rocks. This will clearly require an international effort.**

There are many sites, in many countries with deposits of ultramafic rocks. However, there are three major problems.

1. It is estimated that approximately 10 – 20 gigatons of olivine will be needed for the EW NET. Norway produces 2 mt/yr and this represents half of the world’s supply. **The olivine currently mined is a tiny reaction of what is needed.**

2. Virtually all of the current world’s supply of mined olivine and related ultramafics is being **used for purposes other than CO₂ sequestration**, such as in steel smelters and foundries and brick, tile, concrete, aggregate and abrasives manufacturing. **Virtually none of it is currently used for sequestration of CO₂.**

3. Most of the deposits described are known as a result of geologic studies reported in geologic journals and only represent potential sources, i.e., the ultramafics we need are all still in the ground.

In conclusion, **there is currently zero supply of mined olivine and other ultramafics specifically for use as EW/OAE NETs. We are essentially starting at ground zero.**

Ultramafics in the US

The United States contributes 25 percent of the total greenhouse gases to the atmosphere. The optimal approach to beginning to initiate the EW and OAE NETs will be to determine if enough dunite sepienite is available in the US to get operations started. The following table from Taylor et al (2016) Supplemental indicates there are significant deposits in the US and Canada alone.

Estimated Global Dunite Reserves Taylor et al, (2016)

Only the largest sites are included

Country	Location	Potential Reserves*
Australia	Owendale complex	3.7
	Tout complex	11.6
	Avondale	1.5
Canada	British Columbia	45.0
China	Songshugou massif	33.2
	Unmeasured ultramafics	66.0
	Ophiolites	11.5
Greenland	Greenland	8.2
Japan	Horoman Hill	10.5
New Zealand	Almklovdalen	7.8
Russia	Galeomean complex	17.2
	Kondyor massif	33.5
Sweden	Arutats	1.8
USA	Twin Sisters	256
	Alaska	43.9
	North Carolina & Georgia	1.6
Turkey	Ophiolites	48.0
Oman	Ophiolites	1,650
Totals	USA & Canada	346.5
	Total – Oman	601.0
	Total + Oman	2251

One of the best sources about deposits in the US has been provided by Golf and Lackner (1998) in the section of their paper called **Best Ultramafic Ores for Carbonate Disposal**. The following summarizes these sites.

1. **Twin Sisters Dunite** This is **the largest body of dunite in the United States** (Ragan, 1963), It occurs in the Cascade Range of northwestern **Washington**. This dunite body covers about **90 km²** and is presently mined by **open-pit methods** for refractory (foundry) sand. An examination of a 20-kg sample provided by the operator showed that it contains only about 4% serpentine and other secondary reaction products.

2. **Green Mountain Peridotite** The relatively large, un-serpentinized Green Mountain Peridotite (about 5 km²) occurs in the Appalachians of **North Carolina** and is also mined primarily for foundry sand. An examination of this material showed that it contains about 5% orthopyroxene and about 10% of high-grade metamorphic products including talc and Mg-rich amphibole. This material is less desirable than is dunite as a CO₂-sequestering ore even though it contains nearly comparable amounts of Mg (Goff et al., 1997).

3. **Belvidere Mountain** prospect in **Vermont** (Labotka and Albee, 1979).

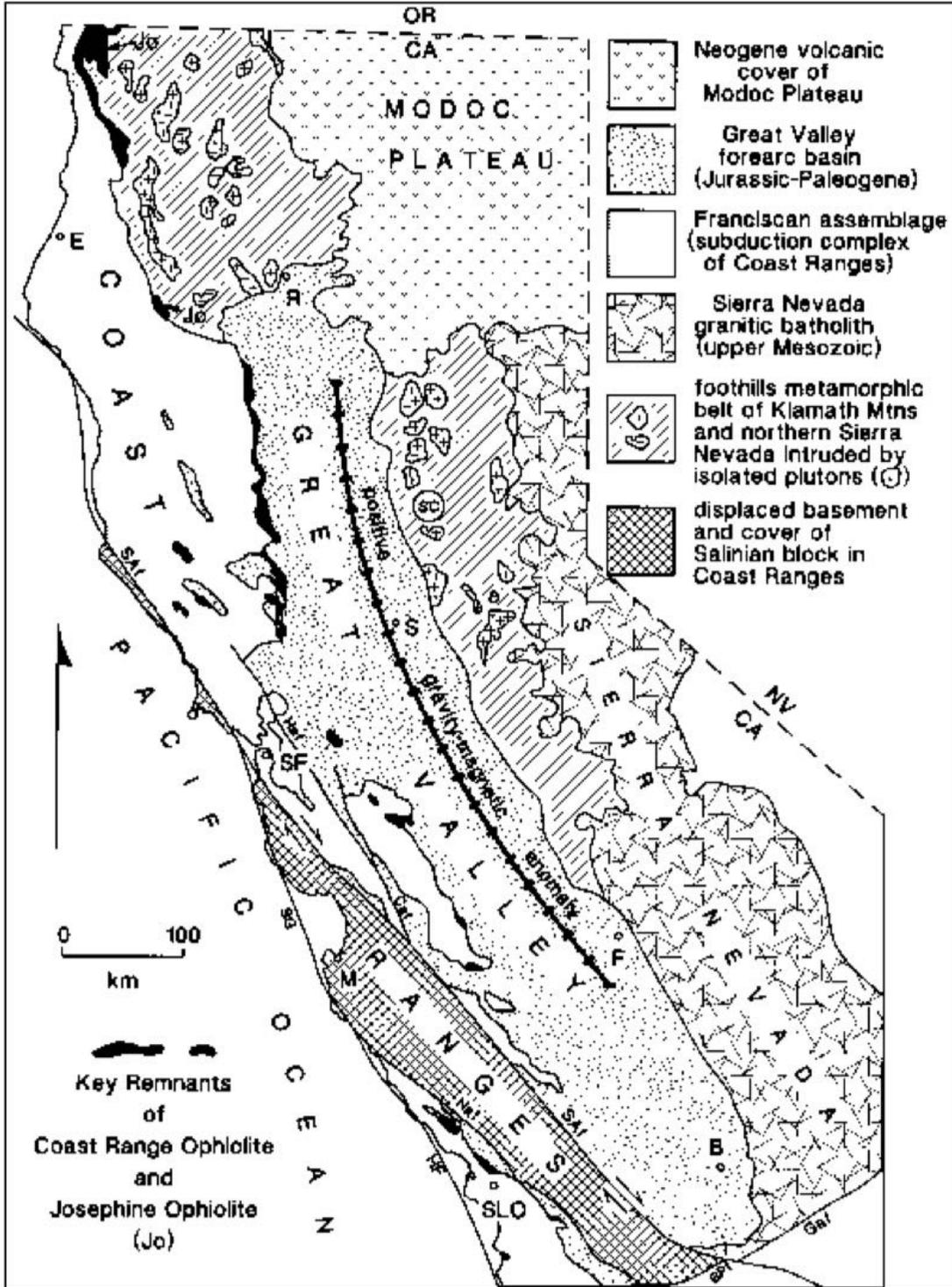
4. **Canyon Mountain and Vulcan Peak** deposits in **Oregon** (Himmelberg and Loney, 1973; Thayer, 1977).

5. **Del Puerto and Burro Mountain. California** This is part of an elongate slab of ophiolite whose ultramafic part (up to 300 m thick and about 40 km²) is variably serpentinized (Evarts and Schiffman, 1982), (Page, 1967; Himmelberg and Coleman, 1968; Goff et al., 1997).

6. **Stillwater Complex**

7. **Wilbur Springs Serpentinite**. The serpentinite is the preserved base of an extensive, north-trending sheet of ophiolite that is about **50 km long and averages 2 to 6 km wide**. The thickness of the deposit varies from a few tens of meters on the west to several hundred meters on the east (McLaughlin et al., 1989). Most of the land occupied by the serpentinite **belongs to the U.S. Bureau of Land Management** or to a few cattle ranches.

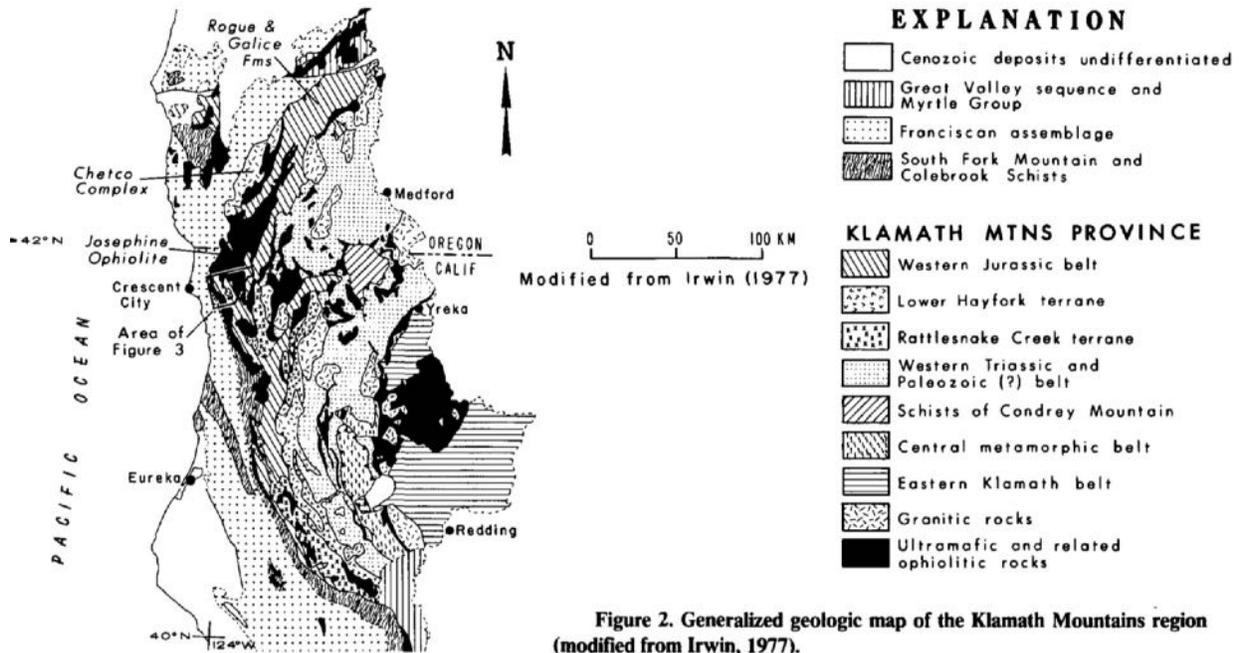
8. **CA Coast Range Ophiolites and Josephine Ophiolite** Perhaps the largest body of continuous serpentinite outcrop in the United States occurs at the **Josephine Ophiolite of northwest California and Oregon, which extends over about 800 km²** (Harper, 1984). These deposits, although some are huge, are mostly serpentinized harzburgite and are **not as desirable as the unaltered dunites**. As Josephine Ophiolite forearc spreading progressed, arc magmatism to the east waned. By the cessation of spreading, arc magmatism relocated along the outer edge of the Josephine Ophiolite basin, capping both rifted screens of older Klamath (or Sierran) terranes and part of the Josephine Ophiolite basin floor (Dickinson et al 1996).



Geologic sketch map of part of California showing the regional relation of the Coast Range Ophiolite to key lithotectonic belts; SC—location of Smartville ophiolitic complex within foothills metamorphic belt; trend of Great Valley gravitymagnetic anomaly (high) after Cady (1975).

Note the presence of key remnants of the Coast Range Ophiolite stretching from Oregon border along the western edge of the Great Valley to central California. Additional details about

the **Josephine Ophiolite Complex** at the Oregon-California border are shown in the following map.



The minerals in this complex consist of harzburgite, gabbro, dunite and other ultramafics (Harper, 1984)

The Belvidere, Vulcan Peak, Del Puerto, and Stillwater bodies contain small zones (4 km²) of relatively **unaltered dunite**.

Completely serpentinized peridotite is exceptionally common in certain areas of eastern and western North America. Ultramafic rocks in the Baltimore Complex contain about 80% serpentinite and **most of the California deposits consist of mostly serpentinite**.

Goff & Lackner (1998) stated that small ultramafic bodies of about **1 km³**, can **potentially sequester about 1 gigaton of CO₂**. A single large deposit of dunite (about **30 km³**) could dispose of nearly 20 years of current (1998) U.S. CO₂ emissions. Given that most of the sites reviewed above are of that size or larger, given sufficient effort we should be able to develop a very large stockpile of ultramafic rock both native and serpentinized, in the US alone. That is an effort that needs to be started.

Ultramafics Worldwide

The following figure shows the **current world's production** of periodite (minerals rich in olivine).



World production of periodite (Current numbers for the production from the producers of the investigated samples. Data from O’Driscoll, 2004). Figure from Kremer et al (2019).

The total world supply of periodite is between 4,200 and 5,400 kilotons/yr or 4.2 to 5.4 gigatons/yr. However, if the goal is to sequester 20 gigatons of CO₂/yr and it requires at least 1.5 tons of ultramafic rock to sequester one ton of CO₂, and olivine constitutes about 80% of peridotites, that means a total of up to 38 gigatons of periodite per year will need to be mined. In addition, as stated, the vast majority of the current supply of olivine is already spoken for and used for other things. To obtain a huge supply of olivine and ultramafic rocks for CO₂ sequestration and EW we virtually have to start from scratch. Some countries such as New Caledonia, New Guinea and others have large undeveloped supplies of periodite.

See **Appendix C. Worldwide Ultramafic Mining Sites and Companies** for a detailed presentation of world-wide deposits of ultramafic rocks.

Funding the Mining start-ups in other countries. We believe that the **Green Climate Fund**, with its billions of dollars, could supply the necessary funding to countries around the world to begin these mining, processing and using operations.

In conclusion, EW and OAE cannot work without the international development of huge stockpiles of processed ultramafic rock. As was so readily done with the ITER and SDGs, we would strongly urge a similar meeting of all countries with deposits of ultramafic rocks to begin mining operations to produce, process, stockpile and use these rocks solely for the purpose of EW and OAE. Money in the Green Climate Funds could be used to jump start these projects.

5. Set up a Department for Enhanced Weathering

As outlined in this review the science of EW and OAE consists of both a lot of agreement and a lot of variable levels of disagreement. The U.S. and the World needs an international panel of experts in all aspects of this effort. EW and OAE is a complex subject and a wide range of inputs will be necessary to optimize the effort. We suggest setting up a Department of Enhanced Weathering with an international group of advisors. For more on this, see below.

How Can the U.S. Federal Government Help?

There are many Federal agencies that should have a programmatic interest in combating global warming and would be of great help in supporting the various efforts in the area. The following are some of the agencies that can be of help. Most research on CO₂ subsurface *in situ* injection and carbon mineralization at the laboratory have been financed by the DOE and the National Science Foundation (NSF), with support from the Environment Protection Agency (EPA), the US Geological Survey (USGS) and the Bureau of Land Management (BLM).

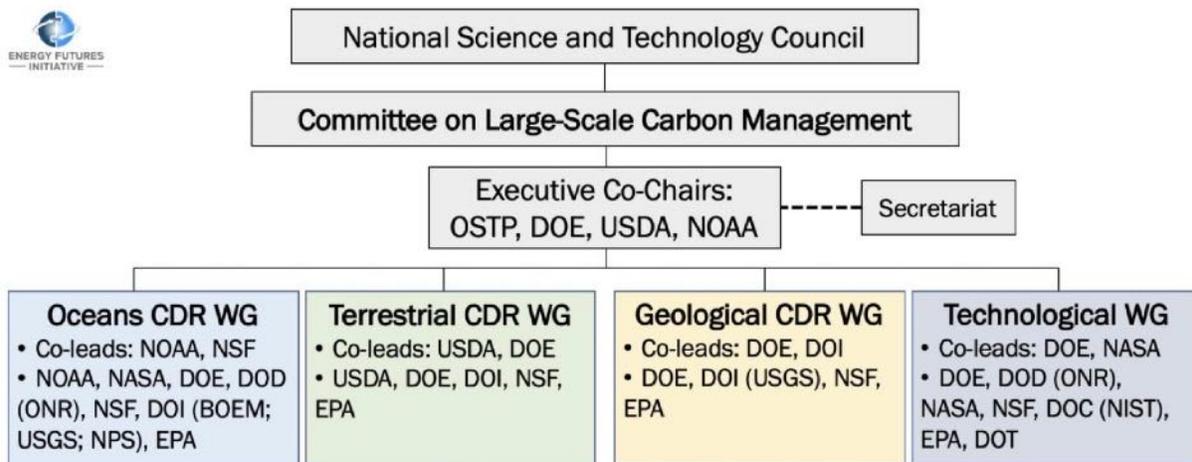
The magnitude of CDR is so immense that the authors of EFI (2019) proposed the involvement of following multiple federal entities.

Federal Participation in CDR RD&D Initiative



EFI (2019) 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



The Military

In his book, *All Hell Breaking Loose. The Pentagon's Perspective on Climate Change*, Michael Klare documents in detail the **US Military's deep concern about how climate change is impacting the security of the United States.**

“Top military officials perceive climate change as a secondary but insidious threat, capable of aggravating foreign conflicts, provoking regional instability, endangering American communities, and impairing the military’s own response capabilities. Worse yet, warming’s impacts are expected to grow increasingly severe, complicating the Pentagon’s ability to address what it views as its more critical tasks.”

The risks to the military were felt to occur on two fronts.

1. The risk to military installations world-wide.
2. The risk that droughts, desertification, excessive heat, rising seas, hurricanes, floods, and forest fires will cause instability of some nations resulting in mass migrations, disputes and wars.

In regard to the first, Congress directed the Department of Defense to conduct a full-scale assessment of climate-related threats to all US military bases – a total of 3,500 installations. An interim report *Climate-Related Risk to DoD Infrastructure: Initial Vulnerability Assessment Survey* was released January 2018. The greatest reported impact was from drought with 782 facilities (22% of all bases) experiencing some drought conditions, 763 bases reported impacts from strong winds, 706 from severe flooding, and 210 from wildfires. It was stated that these bases are launch platforms and “You can’t fight a war unless you have a place to leave from.”

As if to emphasize the danger, a few months after the report was released Hurricane Michael inflicted catastrophic damage on Tyndall Air Force Base in the Florida Panhandle, home of the super-sophisticated F-22 Raptor fighter planes, each costing \$339 million. Senior military officials agree that climate change is not some far off future problem, **it is happening now.**

In regard to the second, “Pentagon analysts highlight the deleterious effect of climate change on vulnerable populations, fragile states and brittle institutions around the world. They

see climate change as ratcheting up global chaos, which in turn means greater likelihood of U.S. involvement in ugly foreign wars.”

Rear Admiral David Titley, former chief oceanographer of the U.S. Navy, noted that this, “can exacerbate or inflame tensions within or between states. These problems can lead to state failure, uncontrolled migration, ungoverned spaces...and terrorist activity”

Climate change will produce an increased call on U.S. Forces to provide humanitarian aid and security services known as “stability operations.”

The collapse of economic and governmental institutions in numerous areas of the globe would disrupt vital trading networks and help foster deadly pandemics. In worst case scenarios, the major powers will fight over water and other vital resources, producing new global rifts and potentially involving the United States in full-scale war with nuclear armed belligerents.

The American military will lose its capacity to defend the nation from multiple foreign perils, while the homeland itself will be ravaged by storms, floods, droughts, fires and epidemics. And this was only the first few pages of the book!

In the most recent report by the DOD (2021) includes the following statement, “There is little about what the Department does to defend the American people that is not affected by climate change.”

Klare stated, “**As we write this, in September 2021, all of the above is already happening.**”

U.S. Stockpiles of Ultramafic Rocks

So, how does all this relate to our immediate goals? The situation with EW/OAE is similar to the problem with hydrogen powered cars. No company will make such cars when there are no hydrogen fueling stations in place around the country. And no one is willing to front the expense of setting up hydrogen fueling stations if there are no cars to use them. As pointed out above, there are currently virtually no mining companies that mine ultramafic rocks just for their use in EW/OAE projects, because currently, there are essentially few of these projects.

Given the U.S. government’s agreement that climate change is a critical issue for our national security, and given the reality that prevention is cheaper and better than endless mitigation, they have a pressing reason utilize the help of the many government agencies that could be involved. In the following sections we illustrate the magnitude of the problem, propose some critical programs, and suggest which different government agencies might be involved.

The U.S. Navy and the OAE Research Ship

Michael Klare pointed out in his book, that the U.S. Navy has an interest, short of atomic powered vessels, of decreasing the use of fossil fuels for its fleets. Thus, they may be interested in lending their expertise to our goal of developing a OAE Research ship running entirely on renewable energy sources.

Perhaps, given the concern of the Military about the world-wide destabilizing effects of climate change, the Navy would find it would be very much in their interests to build a fleet of OAE ships and **initiate a program to train the specialized crews needed to man them**. Since the U.S. has the largest Navy in the world, this would go a long way toward combating global warming and the destructive effects of ocean acidification.

NOAA

The National Oceanic and Atmosphere Administration has an interest in many different aspects of climate change and many of these could be of help in our projects. Some of the specific areas they might be of help are as follows.

- Help with the design and building of the OAE Research ship.
- Help with the governance and international laws potentially involved in spreading the electrostatic products of ultramafic rocks in the ocean.
- Help with the question of whether focusing alkalization efforts to areas of CO₂ outgassing is reasonable.
- Help with the question of whether focusing on the area of the great barrier reef would be worthwhile.

The following may be a helpful contact.

The Geophysical Fluid Dynamics Lab (GFDL) When the Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report, **Vaishali Naik** and many of her colleagues at the GFDL contributed to the scientific results. As a physical scientist at GFDL, she is a part of the biogeochemistry, atmospheric chemistry and climate division for the NOAA laboratory in Princeton, New Jersey. She is a coordinating lead author of the chapter on “Short-lived Climate Forcers,” contained within the Working Group I Sixth Assessment Report. **National Ocean Service** should also be interested in this project.

EPA

If there was ever an important issue related to environmental protection it is global warming, which has the capacity to devastate our environment.

Nuclear Regulatory Commission (NRC) and Oak Ridge National Laboratory

The U.S. Nuclear Regulatory Commission (NRC) was created as an independent agency by Congress in 1974 to ensure the safe use of radioactive materials for beneficial civilian purposes while protecting people and the environment. The NRC regulates commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements.

Because of some scary nuclear reactor accidents, such as Chernobyl, Three-mile Island and Fukushima-Daiichi, many people are justifiably afraid of nuclear power. This was such a problem for some governments that all the nuclear power plants in Germany were shut down and the building of new reactors in the U.S., has come to a stand-still. In the 1960s Dr. Arvin Weinberg, then Director of the Oak Ridge Laboratory, had an operating MSR (Molten Salt Reactor) successfully running for two years. Ironically, President Nixon shut down this program because it was too safe and did not produce the plutonium needed for bombs. A **Molten Salt Reactor** is super safe and cannot suffer a melt down since it is in a constant melt down state, which is an inherent part of its operation. If an earthquake or tsunami occurs, if all the operators die, if all the electricity stops, and other ifs, a freeze plug melts and the molten salt drains to underground holding tanks and the reactor stops. In addition, nuclear waste is a fraction of that of LWRs and in fact can use as fuel, the waste from CWRs. For details on Dr. Weinberg and the MSR technology see www.thecomingsfoundation.org Go to Molten Salt Reactors.

It could be argued that if MSRs rather than LWRs were used for the production of electrical power, their inherent safety, lower cost and modularity would have resulted in the rapid replacement of coal powered electricity and **the rapid accumulation of global warming CO₂ would never have happened. It is not too late to resurrect this important technology.**

If one were to fantasize about an ideal solution to replacing fossil fuels with renewable energy some of the requirements would be:

- zero carbon footprint,
- able to burn up waste from LWRs,
- cheaper than coal,
- inexhaustible energy supply,
- minimal waste,
- capable of producing both electricity and fuel,
- relatively inexpensive,
- no environmental impact – (no threat to birds as with wind turbines or the desert as with solar).
- modular (thus avoiding the gigantic gigawatt reactors).
- does not require long power lines as with wind and solar.
- very safe.
- resistant to earthquakes (i.e., Fukushima)
- resistant to meltdowns (i.e., Chernobyl, Three Mile Island)
- resistant to terrorism
- affordable to developing nations.

MSRs satisfy all these requirements. Ironically, several years ago China downloaded all the available information on MSR publicly available at the Oak Ridge National Lab and committed five billion dollars to the effort. They recently announced the development of working MSRs. Thus, they are taking our technology and **doing what we should have done decades ago.**

There are several companies that are developing Molten Salt Reactors. We believe that **Terrestrial Energy** is the furthest along. There are two parts of this company – **Terrestrial Energy Canada** and **Terrestrial Energy USA**. In personal communications the Canadian branch expects to be approved in 2025 and the U.S. branch in 2030.

The US Government needs to do all it can to support and facilitate the development and approval of Molten Salt Reactors and the associated companies. They are capable of solving all the needs for the energy of grinding and heating, if needed, to facilitate the dissolution of ultramafic rocks on cropland and the ocean.

In addition, **it is obvious that this exciting technology can play a major role in replacing coal, oil and gas fired power plants with carbon zero plants.**

FEMA

According to its director, Dianna Chriswell, The Federal Emergency Management Administration has placed fighting global warming as a goal. When funds become available a question for them is how to help. We suggest that assisting in the projects outlined in this document would be a good place to start. They stockpile many items as part of their emergency management. We suggest that stockpiling ultramafic rocks to have them available for use on croplands and the ocean, would be an important part of their efforts.

DOE Department of Energy

If nuclear power was used to grind ultramafic rocks at the Twin Sisters site, the DOE would play a major role. See also above under the DAC, the proposals from Fossil Energy and Carbon Management at the Department of Energy.

Recently, DOE Secretary Granholm launched Carbon Negative Earthshots program to Remove Gigatons of Carbon Pollution from the Air by 2050 and keep the price below \$100 per ton of CO₂ sequestered. This is an excellent beginning, but I suspect the approach is direct air capture and storage under basalt domes. The potential problems with this are listed above. We believe EW and OAE is the better approach. If the potential problems of DAC can be solved, it can be an adjunct to EW and OAE.

CIA

The CIA assessed that the effects of a changing climate and environmental degradation will create a mix of direct and indirect threats, including risks to the economy, heightened political volatility, human displacement, and new venues for geopolitical competition that will play out during the next decade and beyond. The degradation and depletion of soil, water, and biodiversity resources almost certainly will threaten infrastructure, health, water, food, and security, especially in many developing countries that lack the capacity to adapt quickly to change and increase the potential for conflict over competition for scarce natural resources.

Clearly the CIA should have an interest in these projects.

US Department of Agriculture

The use of EW on cropland should be of critical interest to the USDA. They could play a critical role in farmer education in the use of this NET.

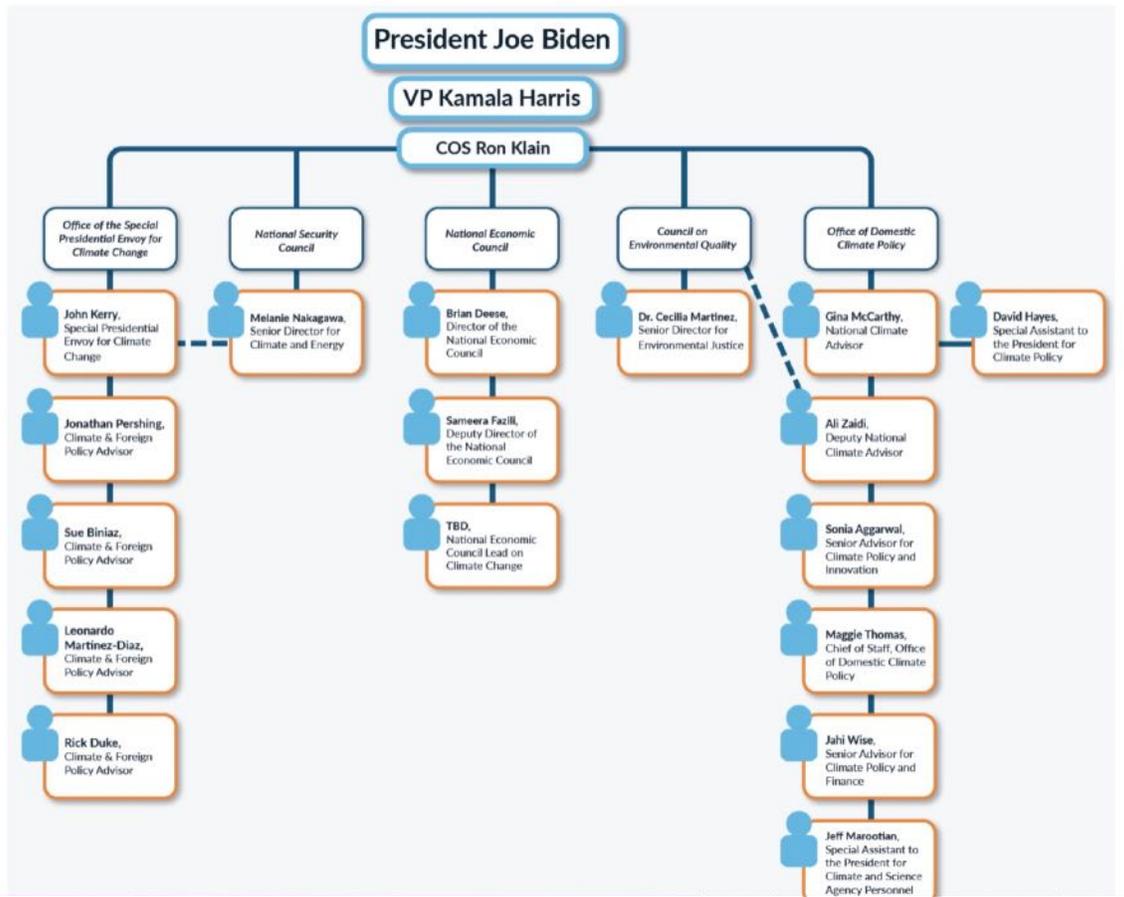
Department of the Interior

Since some of the ultramafic deposits are on federal land the Department of Interior can play an important role on these projects.

The Biden Climate Team

Of all the above federal agencies the Biden Climate Team may be the most important. 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 will ask the Biden Group to help with the following proposals.

1. The 3-site Research Project. Determine if Columbia or Ecuador or a Central American Country with weathering hot spots, would be willing to participate in this research by sponsoring the 3-Site Research project's wet, tropical hot spot site. Also, would the Biden Group contribute financially to this project? A request from the Biden Team would probably be more effective than our efforts.

2. Provide assistance with the development of an OAE Research Ship and interaction with the Navy and NOAA to build and man the needed ships.

3. Initiate the Twin Sisters Project.

4. Develop Global Cooperation for Mining Ultramafics

Here we would also ask the Biden Climate Team for assistance in following.

- Initiate an International Enhanced Weathering Consortium.
- Put together in each country an NET EW team of experts, including the US.

- 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 coastal 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.
- We would envision that each country put together a team consisting of geologists to identify the best deposits of ultramafic rocks, mining engineers to determine the best approach to the mining, environmentalists to help minimize environmental impact, electrical engineers to set up the solar panels, mechanical engineers to determine the best methods of grinding, farmers to monitor to use of the rocks on farmland, economists to determine the amount of CO₂ emitted based on amount of gasoline, oil, natural gas and coal consumed, PR people to develop public support and politician's to ensure the smooth operation of the whole undertaking. If any of these specialists are not available, the UN could supply them.

A sub-set of this is working with New Caledonia. This nation could become a major supplier of ultramafic rocks in the Pacific Area including for combating equatorial CO₂ outgassing. It is also a potential site for massive storage of CO₂ by *in situ* hybridization. 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 published studies this area, such as Pierre Gautier? Is this essentially a task for the U.S. government? For the Biden team? The recent political push for independence from France needs to be considered.

5. Set up a Department for Enhanced Weathering We would also urge the Biden Climate Team to set up a department in one of the government agencies with a title, such as Department for Enhanced Weathering, with a consulting staff consisting of many of the

investigators listed in this document. This department would have a budget for initiating EW and OAE activities in the U.S. and possibly abroad. In addition to funding from the government, it should also be positioned to accept Carbon Tax funds, if they ever become available.

Carbon Tax and Enhanced Weathering There has been considerable discussion of instituting a carbon tax on all fossil fuel positioned to be used in the U.S. This has especially been advanced by the Citizen's Climate Lobby. The bills in congress to institute this have not yet been approved and may never be. They propose giving the resulting money back to U.S. Citizens. We have great concern about how long this approach would take to actually produce a significant decrease in carbon emissions, probably many years if at all. We also have concerns that this taxed fuel would then be used anyway and would emit CO₂, the only difference being that the CO₂ was 'paid for.' CO₂ is still being emitted into the atmosphere.

We would suggest an alternative, that the funds received be given to the Department of Enhanced Weathering. This would **allow the sequestration of the amount of CO₂ equal or greater than what the taxed fuel would produce**. Once the mechanisms for EW are in place, this would result in the carbon neutralization of all fossil fuels used in the U.S. It would be an **instant result**, not a hoped for result after many years. An additional advantage of this approach is that any proposed bills incorporating this proposal might be far more acceptable to a wide range of congressmen and actually get passed. If this approach were to result in a significant reduction in CO₂ emissions and in atmospheric CO₂, the economic benefit would be far greater than distributing the funds to U.S. citizens.

Other ways the Biden Team could help

Methane Biden has addressed this issue at the COP26. Methane is a far more potent of a greenhouse gas than carbon dioxide. The concentration of methane has increased from around 700 ppb in preindustrial times to nearly 1,900 ppb by 2020. An article in *Nature* entitled **Control methane to slow global warming — fast** reviewed a paper by Ocko et al, 2021.

In the first 20 years after its release, methane is around 80 times more powerful as a greenhouse gas than CO₂. It breaks down much more quickly than CO₂, with an average lifetime of around a decade, compared with centuries for CO₂. Today, satellites are part of the monitoring effort. Research shows that a relatively small number of '**super-emitters**' are responsible for a significant share of methane emissions, particularly in the oil and gas industry .

What are the major sources of methane and where are the worst offenders? Livestock is the largest source, responsible for 31% of the global total. Reducing this by putting red seaweed in cattle food is discussed on our website. Oil and gas (O&G) operations rank a close second. Other sources include landfills, coal mines, rice paddies, marshes and water-treatment plants.

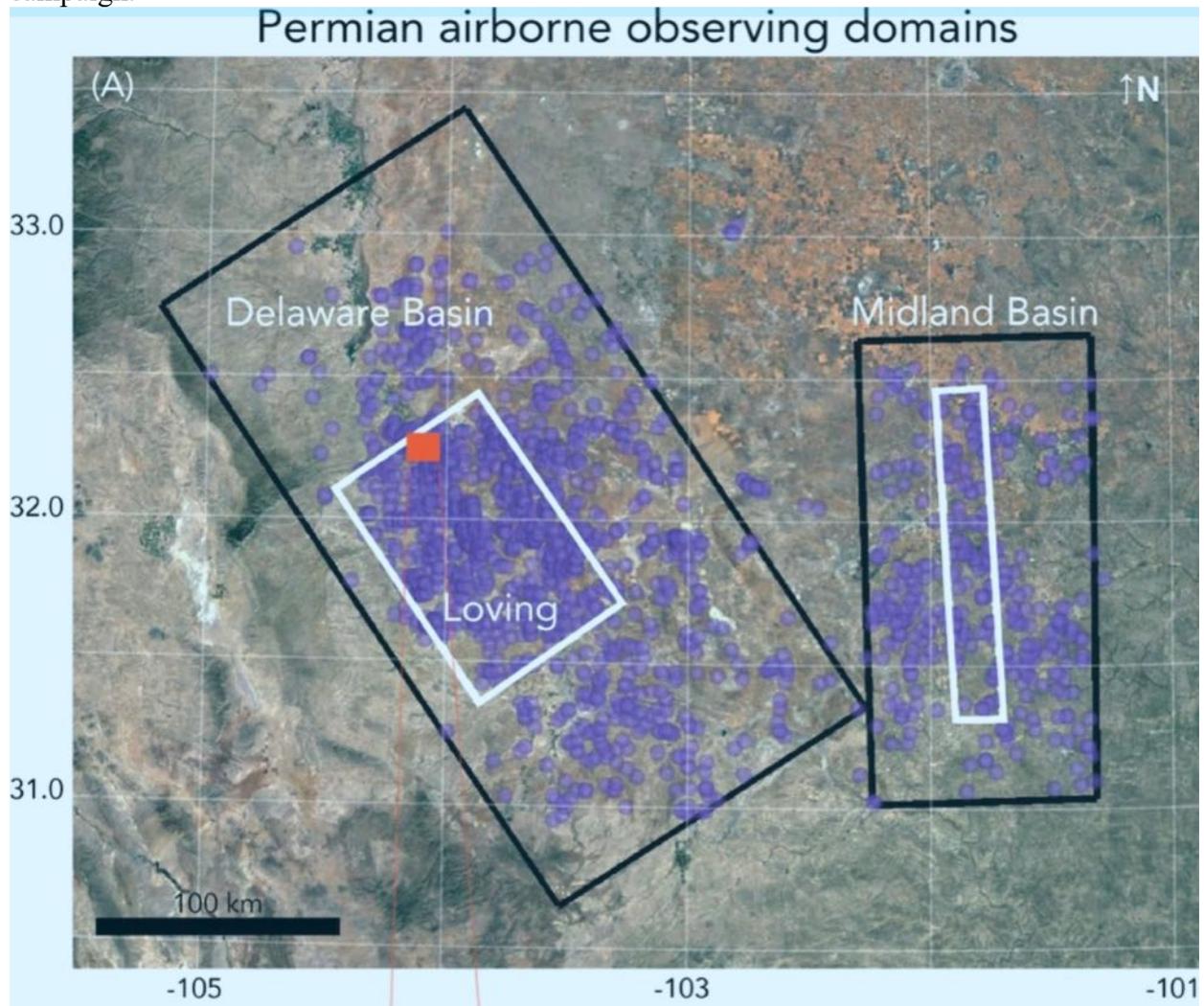
Ocko et al (2021) state that global methane emissions **could be cut by 57% by 2030 using existing technologies and almost one-quarter of the global methane total could be eliminated at no net cost**.

The Obama administration passed rules urging the O&G industry to carefully monitor their oil wells to cut down on rogue methane emissions. The Trump administration reversed this, despite the fact that the O&G industry was opposed to this reversal. The Biden administration reversed the reversal.

Using satellites, Cusworth, et al.(2021) identified **super emitters** in the Permian Basin, the largest and fastest growing oil and gas producing region in the United States. They identified 1,100 unique and heavy sources. They state that frequent, high-resolution monitoring is

necessary to accurately understand intermittent methane super emitters across large, heterogeneous O&G basins and efficiently pinpoint persistent leaks for mitigation.

Diagram below. Domains surveyed by AVIRIS-NG and GAO during the airborne campaign from Sep-Nov 2019, covering 55,000 km² of total area, including 39,000 km² in the Delaware Basin and 16,000 km² in the Midland Basin. Black boxes represent the area surveyed at least once by the Global Airborne Observatory (GAO) instrument. White boxes represent where sites were revisited with the AVIRIS-NG instrument at least seven times during the campaign.



The Purple dots represent detected methane emission sources.

This shows the extent of the problem and the precision of the satellite monitoring. We would urge the **formation of a methane task force** to provide close monitoring of this problem and possibly penalties for emitters. Rewards for reducing emissions are built in since the O&G industry should be delighted with such a program since methane leaks controlled is money in their pockets in the form of more natural gas to sell. This task force could also work with the Department of Agriculture to develop and support the use of food additives to **cut down on the emission of methane by cattle.**

A group monitoring methane emissions overseas identified methane emission sources on the west coast of Turkmenistan (Irakulis-Loitxate et al, (2021). It was **one of the largest methane emission hotspots in the world**. The same group found 29 different super emitters active in the 2017-2020 time period, 24 of them being inactive flares that are now just venting gas. **We would urge the U.S. to provide assistance in halting this source of methane emission as well as monitoring gas leaks world-wide.**

In other sectors, the operators of landfills, coal mines and wastewater-treatment plants could capture the gas and use it to generate electricity. And rice producers could minimize emissions with better irrigation and soil-management practices. The task force could also monitor and assist in these activities. If these measures were implemented worldwide, projected increases in **global warming could be reduced by 0.25 °C by 2050, and 0.5 °C by 2100.**

Hexafluoroethane (C₂F₆) The powerful greenhouse gases tetrafluoromethane and hexafluoroethane have been building up in the atmosphere from unknown sources. Modelling suggests that China's aluminum industry is a major culprit.

The gases are **thousands of times more effective than carbon dioxide** at warming the atmosphere. Official tallies of tetrafluoromethane and hexafluoroethane emissions from factories are too low to account for the levels in the air, which began to rise in 2015 after seven years of relative stability.

Seeking to pinpoint the sources of those emissions, Jooil Kim at the University of California, San Diego, and his colleagues analyzed air samples collected roughly every 2 hours between November 2007 and December 2019 on South Korea's Jeju Island. The scientists also modelled the weather patterns that transported air across the island during that period, to track the gases' origins. The results suggest that **aluminum smelters in China account for a large proportion of these chemicals in the atmosphere**. Semiconductor factories in South Korea and Japan are probably also to blame (Kim et al, 2021, and Research Highlights, Nature 596:464, 2021.

Perhaps, if China does not clear this up on their own, the U.S. government can get involved to pressure China to either stop the smelting or find alternatives to using fluorocarbons.

Refrigerant Gases The book *Drawdown* compiled a list of 100 projects that would help combat global warming and assessed the relative impact of each. **Number 1 on the list was the release of refrigerants into the atmosphere.**

One kilogram (1 thousandth of a ton) of a typical refrigerant gas contributes as much to the greenhouse effect in our planet's atmosphere as two tons of carbon dioxide, **a two-thousand fold greater effect**. One method of combating this is the development on non-greenhouse gas refrigerants. Materials called **plastic crystals** have been found to undergo huge temperature changes when subjected to small pressures near room temperature. Such materials could form the basis of safe future refrigeration technologies. (*Nature* 567:506-510, 2019). The Biden team should place fixing this problem high on their list of priorities.

A Need for Rapid Action UN Assessment Report - AR6 - Climate Change 2021 This scientific report, 3,000-plus-pages from 234 scientists, was released in August 2021 by the UN and Intergovernmental Panel on Climate Change (IPCC). They found that even if nations impose the strictest cuts to atmosphere-warming greenhouse gas emissions today, global warming is

likely within the next two decades to surpass 1.5 degrees Celsius. There is wide agreement that the agreements at the COP26 fall far short of what is needed.

“The recent changes in the climate are widespread, rapid, intensifying, and unprecedented in thousands of years,” said IPCC Vice Chair Ko Barrett, senior climate advisor for the U.S. National Oceanic and Atmospheric Administration. “The changes we experience will increase with further warming.”

The world has already warmed about 1.1 degrees Celsius, or roughly 2 degrees Fahrenheit, since the 19th century. And the consequences are evident.

A previous U.N. climate report that examined the effects of surpassing 1.5 degrees of warming found that an additional half a degree would expose tens of millions more people to extreme heat, cause coral reefs to “mostly disappear” and result in greater habitat loss for animals that depend on Arctic summer sea ice.

Rapidly Stopping Global Warming

The finding, mining, grinding and spreading of ultramafic rocks on croplands, non-croplands (EW) and oceans (OAE) is not technically difficult and virtually every country in the world has ultramafic deposits (see Appendix C) and most have access to the ocean. In addition to having all nations commit to stringent progressive reductions in emissions, there should also be a requirement that each nation commit to extracting from the atmosphere an amount of CO₂ equal to its current yearly output of CO₂. While we believe that EW and OAE are the easiest and best way to do this, if the problems with storage can be solved Direct Air Capture techniques could also be used. This would rapidly halt the increases in global temperature.

Since just sequestering the amount of CO₂ produced each year would not lower the amount of CO₂ in the atmosphere, it would be better to sequester the amount of CO₂ emitted each year + 30%. Then, as this continued each year the level of CO₂ in the atmosphere would decrease.

This approach might be called MINE, GRIND, SPREAD and SEQUESTER. Since the amount of CO₂ a country needs to sequester would be pegged to the level of their emissions, for if a country wished to free themselves of this task, this would provide a powerful incentive to further reduce emissions

We emphasize that this plan is not an excuse to stop reducing emissions. Continued reduction in emissions is critical to the success of the plan. We believe this proposal could result in the atmospheric levels of CO₂ returning to pre-industrial levels by the middle of the century - and mankind’s struggle with global warming would be over.

Fairness is an additional advantage in that each countries’ contribution would be directly proportional to its level of emissions. In addition, the total cost would be distributed among all countries, proportionate to the level of their emissions. Since it is likely that emissions will never totally reach zero, the continuation of EW and OAE, at a scaled back level, would ensure that the level of atmospheric CO₂ would never again be a problem.

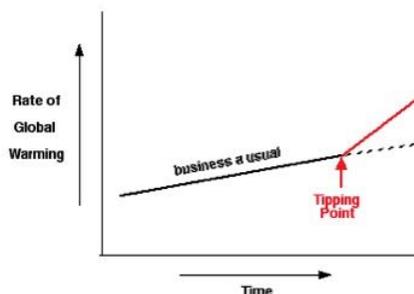
Conclusions: Advantages of the EW/OAE Solution to Global Warming

The above EW/OAE proposal will stop global warming far faster than relying only on reducing emissions. We have been relying on reduced emissions for the past two decades and in that time the amount of CO₂ in the atmosphere and global warming has only increased. In

addition to all the destructive aspects of global warming there are some that are quite scary. These are called tipping points and they especially emphasize that time is of the essence.

Tipping Points

A tipping point for global warming is a temperature at which events begin to happen that produce a positive feedback loop, accelerating further temperature rise above the previous rate. The following figure illustrates tipping point effects.



Many tipping points have been identified for climate change (Fabbri, et al 2021). They are all scary, but the following are some that are really scary.

1. *Plants switch from photosynthesis to respiration.* As global temperatures increase a point is reached at which all plants on earth begin to switch from photosynthesis (consuming CO₂ and producing oxygen), to respiration (consuming oxygen and producing CO₂) (Sullivan, et al (2020). Duffy et al, (2021) state that at the current rate of temperature rise this process will be well underway by 2040.

2. A temperature at which the *vast amounts of permafrost begin to melt* with the release of huge amounts of methane, a greenhouse gas far more potent than CO₂. This has already started in parts of Siberia (Shakhova, et al. 2010; Welch (2019); Kindy, 2021).

3. *Loss of albedo.* The frozen ice in the arctic, Greenland and the Antarctic reflect large amounts of solar radiation back away from the earth. The current melting of this ice destroys this albedo effect. (Riihelä, et al (2021)

4. *Die off of phytoplankton.* It is rarely appreciated that phytoplankton in the ocean sequester as much CO₂ as all the trees on land (Longhurst, et al 1995; Field, et al, 1998; Falkowski, 2012; MacRae, 2020). If these die off because of ocean acidification, this huge reservoir of carbon dioxide will be lost.

5. *Collapse of the AMOC* Atlantic Meridional Overturning Circulation which would alter the North Atlantic air temperatures by 7°C. The AMOC is a critical part of the Earth's Climate System that transfers warm water northward (to Europe) and cold water southward (NIC-NIE, 2021)

The existence of these and other tipping points add additional urgency the need to quickly stop the rise in the mean earth temperature past 1.5°C. Despite COP26 many scientists believe these efforts are **inadequate** to prevent the earth from passing the 1.5°C point (Masood and Tollefson (2021).

The EW/OAE proposals outlined in this document provide a pathway to halting this temperature rise despite the continued emissions of CO₂. The following are some additional advantages.

1. EW and OAE has Economic Advantages Instead of Disadvantages.

For over two decades the countries of the world have pledged to decrease emissions and yet the level of CO₂ in the atmosphere continues to rise. Why? Because until massive renewable energy and electric cars are in place it is economically and politically costly to significantly reduce emissions leading to the resistance of many countries to meet their pledges. In addition, in some countries the mining and sale of natural resources such as coal, oil and gas, is an important part of the economy. Eliminating this would have significant economic repercussions and lead to resistance.

By contrast, one of the over whelming advantages of the EW and OAE NETs is that they come with an economic advantage rather than a penalty. When you ask a country to cut emissions toward zero that is equivalent to asking them to significantly cut down on their energy supply - something that is both economically and politically disastrous. In contrast, when you ask a country to start using EW and OAE it comes with economic advantages such as improved crop yields, reduction in soil acidity, expanded land suitable for agriculture, protection of fisheries by combating ocean acidification AND combating global warming by sequestering CO₂ and decreasing N₂O production on land and in the sea. In addition, the mining industries of that country would become very profitable and if the country could produce more ultramafic rocks than they needed internally, they would enjoy an economic boon by selling the excess to other countries. This could be “the new oil.” This plan would also generate new jobs worldwide.

2. Would not Cost \$Billions.

An additional significant advantage of the EW – OAE approach is that it would not cost the US many billions of dollars and world-wide would save trillions of dollars in mitigation costs. If the CO₂ sequestration was spread among all countries of the world (#4 above) the US would only need to sequester the amount of CO₂ equal to its own emissions. Goff and Lackner (1998) pointed out we have more than enough ultramafic rocks in the U.S. to do that. Although we suggested that the Military set up a project to mine ultramafic rocks at Twin Sisters, WA, this could be done in tandem with a private company. Unimin Corporation which is currently mining at Twin Sisters. A support from the government to Unimin Corporation to significantly accelerate their mining and make it all available for EW and OAE, would utilize a skill that is already in place.

3. Fewer Environmentalists Objections

There have been a number of Direct Air Capture (DAC) initiatives and the Biden Infrastructure Bill has included several billion dollars toward four of these projects. However, not all is rosy with this approach. For example, Summit Carbon Solutions, a 4.5 \$billion enterprise, plans to capture 12 million tons of CO₂ annually in a program to make ethanol a carbon negative fuel. The CO₂ is then transported by pipeline from Iowa and Nebraska to South Dakota where it is to be pumped a mile underground under geologic formations, presumably basalt. This sounds great but a number of environmental groups are opposed. "CO₂ pipelines are a questionable attempt to prop up fossil fuels by taking advantage of government subsidies while providing a pretense that they are environmentally friendly," stated Ken Winston of the Nebraska Sierra Club. There have been a number of other objecting voices. Also, the potential problems of storing CO₂ under basalt domes was discussed above.

We believe that EW and OAE will generate far fewer objections because of the many advantages inherent in the process (see above) and the absence of potentially dangerous long

CO₂ pipelines and under basalt storage. Schuiling (2013) has discussed some of the ethical issues potentially involved with mining operations, especially in poor countries.

We emphasize that continuing to decrease emissions is a vitally important aspect of this approach. The level of commitment to sequestering CO₂ is pegged to the countries level of emissions. If they wished to reduce their level of mining, grinding and spreading, they would need to decrease their level of emission. This could be a strong incentive to reducing emissions.

Ethical Issues

Articles have been written about the ethics of geoengineering or climate engineering (Lin, 2013; Keller et al, 2014). The main category of climate engineering is solar geoengineering or solar radiation management, which involves reflecting some sunlight back to space to limit or reverse human-caused climate change.

Carbon dioxide removal (CDR) and NETs, the practice of deliberately reducing the amount of CO₂ in the atmosphere, is often mistakenly classified with solar geoengineering as a form of climate engineering and assumed to be intrinsically risky. In fact, CDR addresses the root cause of climate change and is part of strategies to reduce net emissions. The Intergovernmental Panel on Climate Change (IPCC) no longer refers to CDR as a subgroup of climate engineering but uses the terms solar radiation management and carbon dioxide removal separately (Wikipedia, 2021).

One of the major concerns about NETs is that they may loosen the pressure to cut emissions. As we have repeatedly pointed out, this does not apply to what we propose, since continued reduction in emissions is a critical part of our proposal.

4. Could quickly halt the rise in the earth temperatures despite continued emissions.

If all countries pledged to mine, process and use their ultramafic rocks to sequester the amount of CO₂ they are currently using, plus 30%, this would stop the rise in the earth's temperature before emissions were brought to zero and decrease the level of atmospheric CO₂

The final conclusion is that we urge the United States, and/or the UN to convene a new COP27, or involve each country individually, to getting all countries of the world to commit to a MINE, GRIND and SPREAD program to sequester 100 + 30% of their yearly CO₂ emissions. If they have to purchase the necessary rocks from other countries but cannot afford it, the billions of dollars in the Green Fund for mitigation of climate change could be used. The important issue is that **we must start now.**

Queen Elizabeth said, "They talk but don't do."

It is time to do.

The Questions Section

We have submitted the preliminary version of this document to 30 of the authors and researchers covered in this document for comments and to attempt to answer the following questions. We anticipate that in addition to their input, many of these questions will be answered by the [3-Site Research Proposal](#).

A. Questions about ultramafic rock weathering on cropland

The Comings Foundation is interested in activating the use of EW on croplands and non-croplands and OAE in the oceans. We feel that using these two approaches, by all countries in the world, will halt global warming. A rapid rate of dissolution of ultramafic rocks is critical to the success of this approach. Thus, we have some critical questions to ask.

1. Is grinding of ultramafic rocks, including serpentines, to a size of 1 um sufficient to allow the dissolution reaction to go to completion in only 1 to 3 years or quicker? and

2. Is a one acre field of solar panels or less sufficient to supply the energy necessary for such grinding? If pulverization alone is not sufficient for rapid dissolution, could such a field of solar panels also supply the energy necessary for concurrent grinding at 600°C temperature?

3. Would you be willing to serve as an advisor, in your area of expertise, to governmental and non-governmental entities?

4. Would you be willing to be listed as an advisor to the Comings Foundation?

Below is a list of some of the additional questions re:

- Do you find any errors of fact in this document. If so, send us a list of corrections.
- If you were setting the budget for the 3-site study what would you set per year for a 4 year study? We assume the first year would cost more since it would include the cost of buying the land.
- Is the section on understanding dissolution rates basically correct?
- 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 primarily emphasizing this NET in the hot, wet, temperate lands of the southern states or Central or South America make more sense?
- We could not find many articles on the use of serpentine rocks on cropland. Are you aware of some we have missed? Will it be necessary to pretreat serpentines with heat or other means for them to work on croplands? Will grinding alone be adequate? Will grinding + heat with concurrent grinding, be necessary?
- What are the governing (regulation) issues of EW on cropland or non-cropland, if any?
- What do you think 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 were it is used, or to do the final grinding onsite, again using clean energy?
- Can we elicit help from the U.S. Dept of Agriculture, Department of Interior, U.S. Geological Survey, FEMA, DOE, NOAA and the Biden Climate Group? Do you have a personal relationship or contact to any relevant government officials that would help?
- Do you agree that olivine is preferable to basalt for EW of crops in the U.S and elsewhere?

- As stated by Beerling et al (2020) national inventories of the location, availability and extent of mafic and ultramafic rocks as a resource are required world-wide to assess the potential contribution of this resource for EW. Appendix C is a start.
- 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, serpentine or basalt in the U.S? If so, where? We have suggested starting with the Twin Sister site in WA.
- 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 that still effectively sequesters CO₂? Is this known? Studies in Oman suggest this could be quite thick. If so, would spreading large amounts of ultramafic rocks on non-croplands be reasonable?
- In warm and humid areas, how thick can we 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 to prospects of EW as a solution to global warming.
- 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?
- **If you had to choose a EW weathering hot spot as part of the 3-site study, where would you choose?**
- What role can the U.S. Dept of Agriculture play in assisting with our EW efforts? Do you have any contacts there?
- What procedure would you recommend for testing the rate of dissolution of rocks in the field?
- As described above for the 3-site project, we could purchase 15 acres of land in a US Midwest state and Southern state and, a Central or South American country hot spot. Where would you place these sites?
- Do you have any recommendations on improving the 3-site study?
- If the suggestions under **Rapidly Stopping Global Warming** come to fruition, we suggested that the amount of CO₂ to be sequestered by each country each year should be equal to or greater than the amount of CO₂ they have emitted each year? It will probably be easiest to assign credits on the basis of how many tons of rocks have been used for EW each year.
- Estimates of the number of tons of ultramafic rocks needed per ton of CO₂ sequestered range from 1 to 5. What is your estimate?
- Since there are so many variables for the rate of sequestration such as temperature, rainfall, acidity of the soil, type of rock (olivine or serpentine), particle size and other, probably the best is to perform a preliminary study in each country to determine the sequestration rate for the soil and rocks used. What are your thoughts?

The Testing lab

- Samples from all three sites would be collected and sent to a central testing lab. What is the best procedure for collecting these samples? How deep should the test cores be? What is the best sampling tool?
- Are you aware of an existing academic soil testing lab that we could use? In addition to the usual parameters such as N, P, Ni, Cr, and other metals, we need to test for the products of ultramafic dissolution. What is the best technique for testing for rate of ultramafic rock

dissolution? Is mass spectroscopy the best technique to test soil samples for dissolution products?

- We would also test soil DNA for metagenomics. This would probably require a separate lab. Any suggestions?
- On site, we would test for soil pH, and perform daily tracking of temperature, rain, humidity and wind. Any others?

The Best Approach to Grinding

We would also consider offering grants to companies or appropriate university departments to research the best combination of grinders to attain a particle size of 1 um or less, and which techniques would require the least amounts of energy? Of water? Any suggestions about who to approach?

B. Questions about putting ultramafic rocks directly into the ocean and the use of 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? Since they do different things, we assume using both is most logical.
- 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.
- Harvey (2008) suggested that the outgassing of CO₂ from the ocean could be mitigated by the direct application of CaCO₃ from limestone. Would the products of electrolysis of olivine accomplish the same thing?
- In the same paper Harvey talks about time intervals of up to 200 years. We can't wait 200 years to solve global warming. What can be done to work in months to a few years? Will the electrolysis of ultramafic rocks accomplish this?
- Harvey (2008) investigated three possible boat sizes. It would seem that the largest, 250,000 tons, is reasonable. Agree?
- Limestone has a direct effect on the uptake of CO₂ by the following equation:
$$\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$$
 Is it a better choice than olivine?
- Harvey (2008) stated, "If this were done in regions where the saturation horizon is shallow and where strong upwelling (>50 m/a) occurs, water with restored CO₃²⁻ could be available to absorb more atmospheric CO₂ within as little as a few years after the addition of CaCO₃." Why after a few years. Why not immediately?
- Bach et al (2016) suggested there should be dedicated research to assess risks and co-benefits of mineral dissolution products on marine and other environments. How would you carry out such assessments?
- All things considered (availability, need for pretreatment or electrolysis, etc.) which would be best, spreading pulverized limestone or spreading products of hydrolysis of olivine on the ocean?
- Dissolution of olivine is slower at ocean pH than soil pH. Does this seriously impair the use of placing olivine directly in the ocean?

- It has been suggested that spreading olivine in the ocean requires that it be ground to 1 micron size. If this were done as a final step on a OAE ship which of the possible grinders listed in Appendix G, or others, would you use?
- 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 such as the Twin Sisters in Washington?
- Does the use of the OAE research ship in the Great Barrier reef area 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 dispersed 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 design an energy efficient OAE ship make sense? They were chosen because of their extensive use of computerized instruments and their wide range of services. See Appendix E. Any alternate ideas? If Bay engineering does not have the necessary expertise in solar panels, VAWTs, electrical engineering, or others, who would you recommend for assistance?
- Could NOAA or the Navy help? Do you have any contacts in NOAA or the Navy?
- 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 economically used for OAE? For EW on crops. Is it best to focus on the Twin Peaks site or both?
- 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. Would it help to gain the assistance of the military? If so, could they take over the largest olivine mining sites in the US by virtue of eminent domain for national security?
- The world's largest active olivine quarry is the 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 into the Atlantic ocean. Is this reasonable?
- An alternative mentioned above is loading Norwegian olivine on a OAE ship, doing the final grinding on board, and distributing some in the ocean on the way to other ports. Is this reasonable?
- 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?
- As noted above, in contrast to the land-based approach described by Rau et al (2018), in the ship-based approach where all the energy produced in the form of H₂ could be utilized onboard to provide locomotion and energy for electrolysis. Is this feasible? 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?

- Can electrolysis be used to remove nickel and chromium from the slurry before releasing it to the ocean?
- Finally, and most importantly, can the utilization of different electrolysis techniques significantly reduce the claim of Kohler et al (2013) that 300 large ships would be required to place enough olivine in the ocean. Can the use of various forms of electrolysis reduce that 5 fold to 60 ships? Would the use of highly energy efficient OAE ships, and focusing on outgassing regions, reduce that further?
- Also important, can on-board electrolysis also be used in parallel or sequentially to remove Ni and other heavy metals before dumping the mix into the ocean?
- Do you think that having a Ken Burns type documentary on EW and OAE to hopefully develop public enthusiasm, would be a good idea? Would you be willing to be interviewed?

C. Questions Relating to the Grand Plan and New Caledonia

- 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 studied this area such as Pierre Gautier? Is this essentially a task for the U.S. government?
- While there has been some turmoil about independence, the New Caledonians have recently voted to remain with France.
- We believe involving many different countries in providing a source for mafic and ultramafic rocks is the only viable way forward for EW technology. Is this reasonable?
- Can we enlist the aid and possibly funding, through involvement of the Department of Agriculture? The Biden Climate Team? The President? NOAA? Other? Who would you recommend contacting? Do you have any contacts in these areas?
- To make such a plan work we would need to have it headed by someone with gravitas in the field. Who would you recommend? If this is in your field, would you be willing?

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. The following are types of peridotite (Wikipedia).

- **Dunite**: more than 90% olivine, typically with Mg/Fe ratio of about 9:1.
- **Wehrlite**: mostly composed of olivine plus clinopyroxene.
- **Harzburgite**: mostly composed of olivine plus orthopyroxene, and relatively low proportions of basaltic ingredients (because garnet and clinopyroxene are minor).
- **Lherzolite**: most common form of peridotite, mostly composed of olivine, orthopyroxene (commonly enstatite), and clinopyroxene (**diopside**) and have relatively high proportions of basaltic ingredients (garnet and clinopyroxene). Partial fusion of lherzolite and extraction of the melt fraction can leave a solid residue of harzburgite.

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.

Antigorite is a lamellated mineral in the phyllosilicate serpentine with the ideal chemical formula of $(\text{Mg,Fe}^{2+})_3\text{Si}_2\text{O}_5(\text{OH})_4$.

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 $\text{MgCaSi}_2\text{O}_6$. 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 ($\text{NaAlSi}_3\text{O}_8$), and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$).

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

Harzburgite is an ultramafic variety of peridotite consisting mostly of the two minerals olivine and low-calcium pyroxene enstatite MgSiO_3 ferrosilite FeSiO_3 .

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 $\text{NaAlSi}_2\text{O}_6$ or $\text{Na}(\text{Al},\text{Fe}^{3+})\text{Si}_2\text{O}_6$

Lherzolite is a ultramafic rock. It is a coarse-grained rock consisting of 40 to 90% olivine along with significant orthopyroxene and lesser amounts of calcic chromium-rich clinopyroxene.

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.

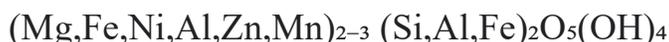
Iizardite ideal formula is $\text{Ni}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$, but most specimens contain some magnesium, and $\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$ is more realistic.

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, $\text{Na}(\text{AlSi}_3\text{O}_8)$, to pure anorthite, $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$.

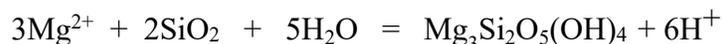
Serpentinization occurs when ultramafic rocks, enriched in the minerals **olivine** and orthopyroxene, **react with water** at high temperature and are converted to rocks containing a suite of minerals dominated by serpentine. A significant by-product of the reaction is H_2 .

Serpentinization encompasses **a series of hydration reactions** that occur when ultramafic rocks are exposed to circulating aqueous fluids at temperatures lower than 400°C , leading to the formation of serpentine phases. The combined formula for serpentines is:

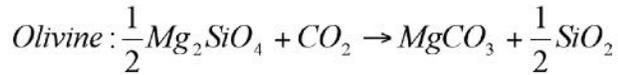
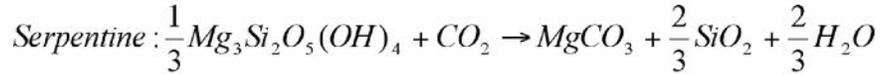


Serpentine is a soft ductile mineral and its presence in the mantle wedge lubricates subduction of the oceanic plate. Production of serpentine in the oceanic crust produces hydrothermal fluids and releases gaseous methane and hydrogen, as observed along mid-ocean ridges. The pH of the hydrothermal fluids is generally low but under some conditions, notably at low temperature, may be high enough to be favorable to life.

The following formula shows the serpentinization for a single mineral outcome.



The following formulas show how serpentine and olivine interact with CO_2 .



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. Worldwide Ultramafic Mining Sites and Companies

A. Companies that Provide Information on the Olivine Industry

There are several companies that provide financial analysis of the olivine industry – at a cost of thousands of dollars. Two of these are as follows.

Markets and Research.biz Global Olivine Powder and Olivine Sand Market 2021 by Manufacturers, Regions, Type and Application, Forecast to 2026 – \$3,500 Single User, \$5,250 Multi-User, \$7,000 Corporate User. This would be a source of a listing of the relevant companies. What follows is research we have done ourselves.

Global Olivine Market Research Report has In-Depth Collective analysis of different factors that analyze the Industry growth, Olivine Market Size, Share, Value, Volume. It constitutes trends, restraints, and drivers that transform the market in positive manner. The segmental analysis of Olivine Market focuses on sales, revenue and forecast by region (country), this report also states import/export consumption, supply and demand Figures, cost, price, revenue and gross margins. To get a Sample PDF of report go to: <https://www.marketreportsworld.com/enquiry/request-sample/17332983>

B. World-wide Olivine and other Ultramafics Sites by Country

The following is a list from Taylor et al (2016). It was also presented above.

Estimated Global Dunite Reserves Taylor et al, (2016)

Only the largest sites are included. For entire list see reference.

Country	Location	Potential Reserves*
Australia	Owendale complex	3.7
	Tout complex	11.6
	Avondale	1.5
Canada	British Columbia	45.0
China	Songshugou massif	33.2
	Unmeasured ultramafics	66.0
	Ophiolites	11.5
Greenland	Greenland	8.2
Japan	Horoman Hill	10.5
New Zealand	Almklovdalen	7.8
Russia	Galeomean complex	17.2
	Kondyor massif	33.5
Sweden	Arutats	1.8
USA	Twin Sisters	256
	Alaska	43.9
	North Carolina & Georgia	1.6
Turkey	Ophiolites	48.0
Oman	Ophiolites	1,650

Totals	USA & Canada	346.5
	Total – Oman	601.0
	Total + Oman	2,251

* Pg (pentagrams) or Gt (gigatons)
See Taylor et al (2016) for references.

Taylor, L.L. et al (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nature Climate Change **Supplemental Information**.

DOI: 10.1038/NCLIMATE2882

When harzburgite (olivine + enstatite FeSiO_3) instead of dunite was examined the reserves in Pg were much greater.

Supplementary Table S8. Major known resources of harzburgite.

Ophiolite resources	Area (km ²)	Depth (km)	% Olivine	Est. Pg *
Cyprus				
Olympus ultramafic complex	40 ^a	2 ^b	61 ^c	266
Samail ophiolite, Oman	14,000 ^d	5 ^d	40 ^e	64,323
Papuan Ultramafic Belt	6,000 ^f	4 ^f	71 ^f	41,763

*Resources estimated using estimated areas, depths and mineralogies and specific gravities of: olivine = 3.32, orthopyroxene = 3.5, clinopyroxene = 3.3, serpentine = 2.55, spinel = 3.8¹⁷.

^aAssuming 2/3 of the 60 km² area of the Olympus ultramafic complex is harzburgite¹¹⁵.

^bDerived from Figure 3, Dilek and Eddy¹¹⁶.

^cMineralogy 61% olivine, 27.2% orthopyroxene, 4.5% clinopyroxene, 1.5% spinel, 5.4% serpentine. This is the mineralogy used by the weathering model (excluding spinel)¹¹⁷.

^dAfter Kelemen and Matter¹⁰⁴.

^eMineralogy 40% unserpentinised olivine, 40% serpentine, 10-15% orthopyroxene, 5% spinel¹⁸.

^fMineralogy 71% olivine, 21% orthopyroxene, 6% clinopyroxene, 1% spinel, partly serpentinised¹¹⁸.

Note the large deposits in New Guinea.

United States

Eastern U.S. The extractable ultramafic rocks are located in **Vermont**, and the **Pennsylvania-Maryland-District-of-Columbia (PA-MD-DC) region**, western North **Carolina** southwestern **Puerto Rico**. The ultramafic rocks consist of variably serpentinized dunite, harzburgite, and minor lherzolite generally containing antigorite and/or lizardite as the major serpentine minor phases.

Larger deposits in Vermont and most deposits in North Carolina contain a core of dunite. Individual ultramafic bodies in the Appalachian Mountains areas great as 7 km³ although typically they are <= 1 km³. The total volume of all deposits in the eastern United States is conservatively estimated at 30 km³. In contrast, ultramafic deposits in southwestern **Puerto Rico** have an estimated volume of roughly 150 km³. **The data show that the ultramafic deposits of the eastern United States and southwestern**

Puerto Rico could potentially sequester many years of annual U.S. CO₂ emissions if favorable geotechnical, engineering, and environmental conditions prevail. The ultramafic bodies they described all belong to ophiolite sequences, the most voluminous and widespread of all ultramafic deposits. Magnetic and gravity surveys are probably excellent methods to make a first-cut determination of deposit dimensions because of the relatively high magnetic properties and high density of many ultramafic deposits. Ultramafic rocks containing significant secondary carbonate minerals should be avoided because the sequestration potential of these rocks has already been tapped by natural processes.

Environmental restrictions in heavily populated areas of the Maryland-Pennsylvania region may impede exploitation of some serpentinite deposits. Descriptions of individual quarry sites follow.

Hunter (1941) previously calculated the mass of commercial dunite deposits in western **North Carolina and adjacent Georgia**. He determined a total mass of **208 x 10⁶ metric tons of relatively unaltered olivine** containing more than 45 wt % MgO and a mass of **908 x 10⁶ metric tons of partly serpentinized dunite** composed.

The **Belvidere Mountain** ultramafic body in Vermont, having an estimated volume of roughly 2.75 km³, is capable of handling the equivalent of 200 years of CO₂ emissions for a United States population center of 1 million people. Belvidere Mountain in northern Vermont is the site of one of the oldest and one of the largest asbestos producing mines in the United States. The asbestos at Belvidere, which is chrysotile, was first discovered in 1896, and the site saw intermittent production until the 1920s.

Tailings at the mine consist of three main tailings piles, corresponding to the Eden, Lowell, and C-Area quarries (see below).



C-Area tailings pile at Belvidere Mountain, Vt. Photograph taken by Krevor et.al (2009). It is estimated that more than 29–30 million tons of serpentine tailings are located at the site.

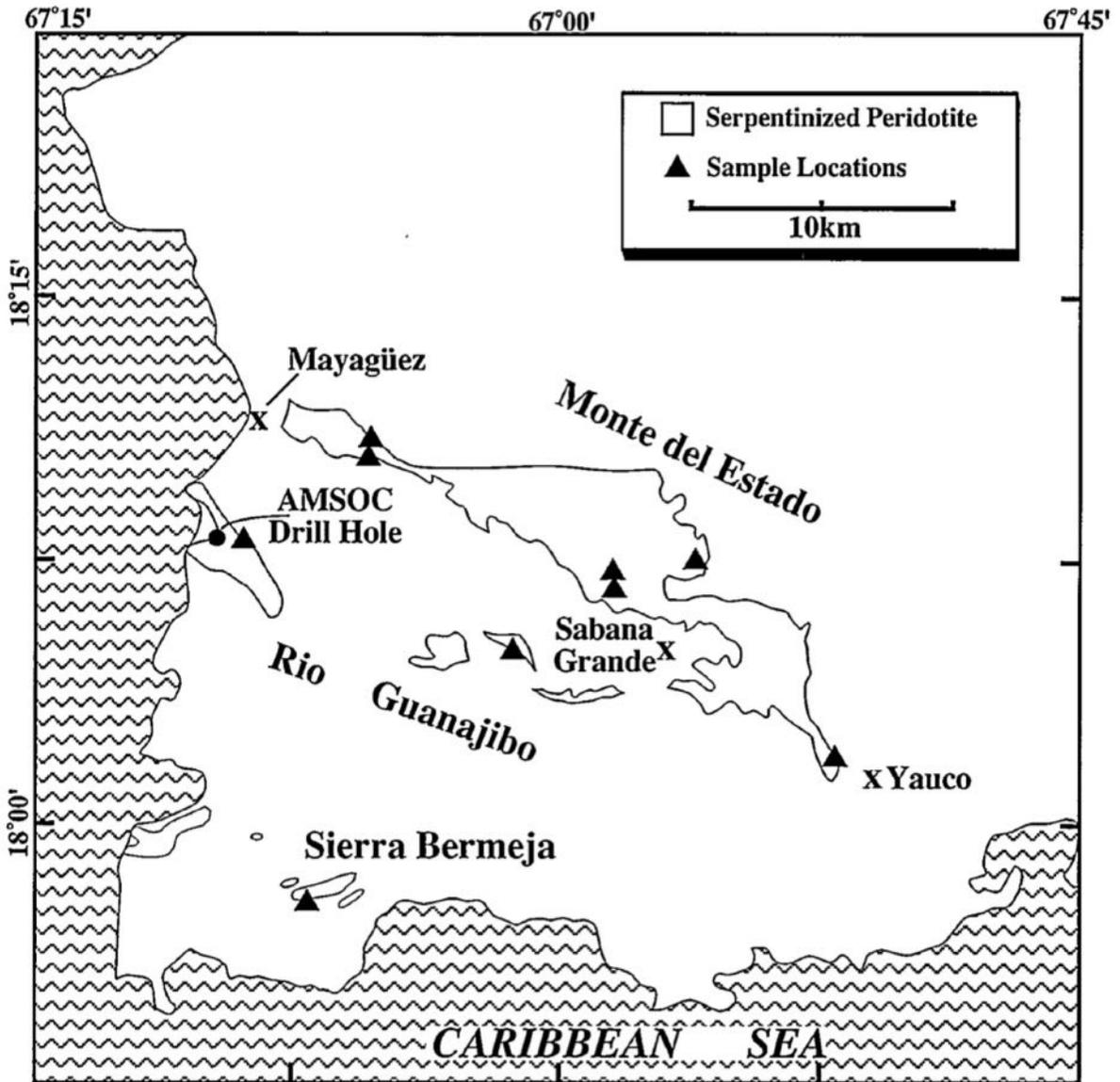
The volumes of serpentinite in the PA-MD-DC region (roughly 30 km³) could sequester the CO₂ emissions of an equivalent population center for 1,600 years.

The high-purity dunite from bodies in Vermont and western North Carolina and the low-grade serpentinites of Puerto Rico (below) are more desirable than the metamorphosed serpentinites that occur throughout most of the Appalachians.

North Carolina Olivine occurs as isolated dunite bodies, or alpine-type peridotites, in the Blue Ridge. Two main districts, the **Webster-Balsam district** in Jackson County and the **Spruce Pine district** in Yancey and Mitchell counties, have produced most of the olivine. The deposits contain 50 to 90 percent olivine. Vermiculite and anthophyllite asbestos also occur in the same rocks as the olivine and have been mined in the past. North Carolina leads the nation in olivine production, although production is presently limited to the **Daybrook Mine near Burnsville** in Yancey County. Olivine production has declined in recent years because of a decline in steel production and because of increased competition from olivine imports.

Maine The **Boil Mountain ophiolite complex** is located to the west of Hurricane Mountain, north of Augusta Maine (Van Vleck and Beane, 2001). The ultramafic units consists chiefly of pyroxenite. It is not rich in olivine.

Puerto Rico Serpentinized mantle peridotite occurs in three belts restricted to the southwest part of Puerto Rico.

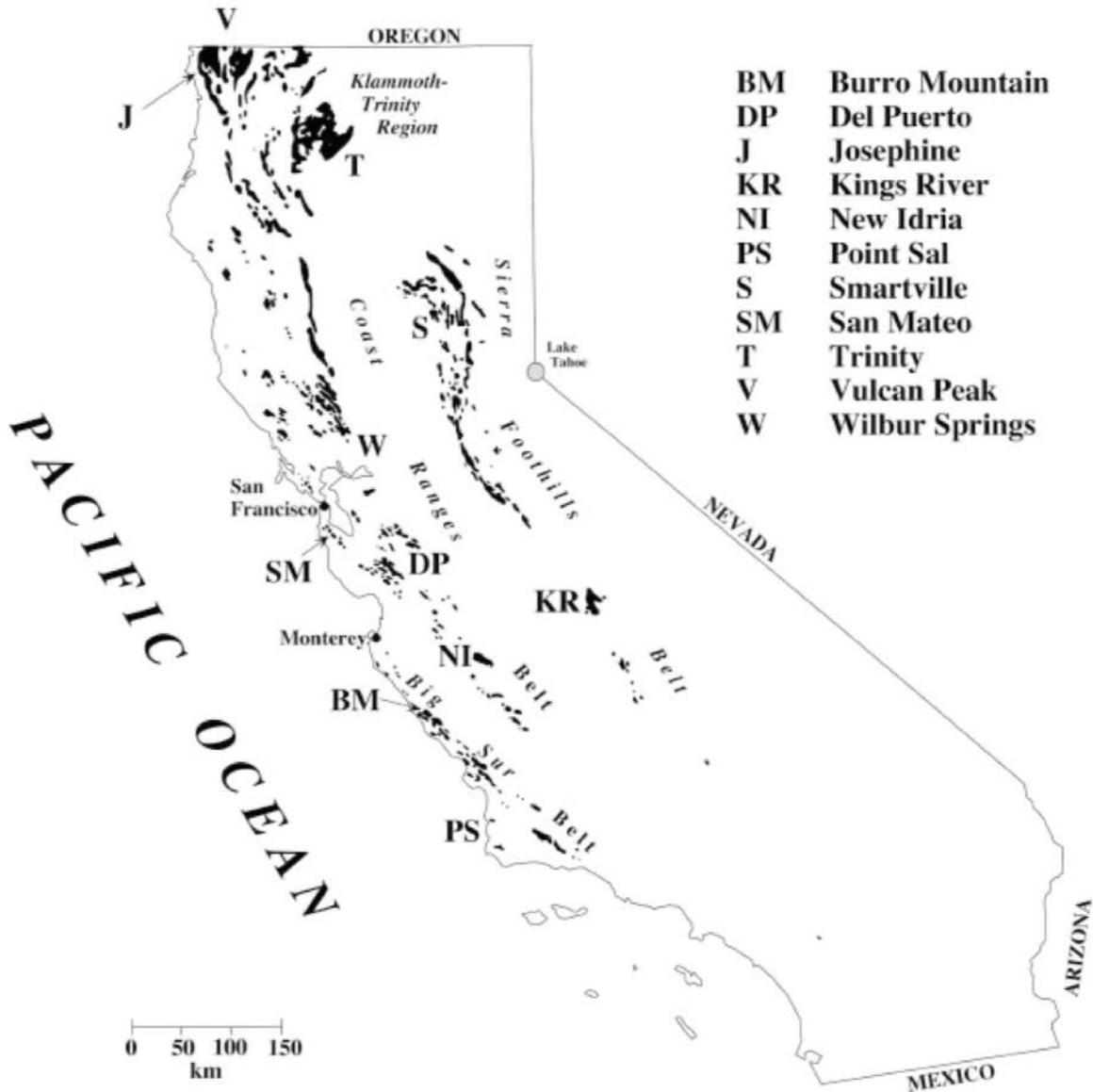


Map of the serpentinized peridotite in Puerto Rico.

Ultramafic deposits in southwestern Puerto Rico consist of serpentinized dunite and harzburgite. Because the population of Puerto Rico is about 4 million, this body could sequester the waste CO₂ of the island for more than 1,900 years. The Monte del Estado serpentinite could dispose of the CO₂ emissions produced by a million people consuming energy at current U.S. rates for 7,300 years, if such a thick body could be totally exploited. Samples from Puerto Rico and California are comparable in general appearance to each other but look quite different from the serpentinites of the PA-MD-DC region.

Western U.S. (Goff et al, 2000; Golf and Lackner, 1998; Golf et al, 1997).
California (Golf and Lackner, 1998)

The following figure shows the location of ultramafic rocks in California.



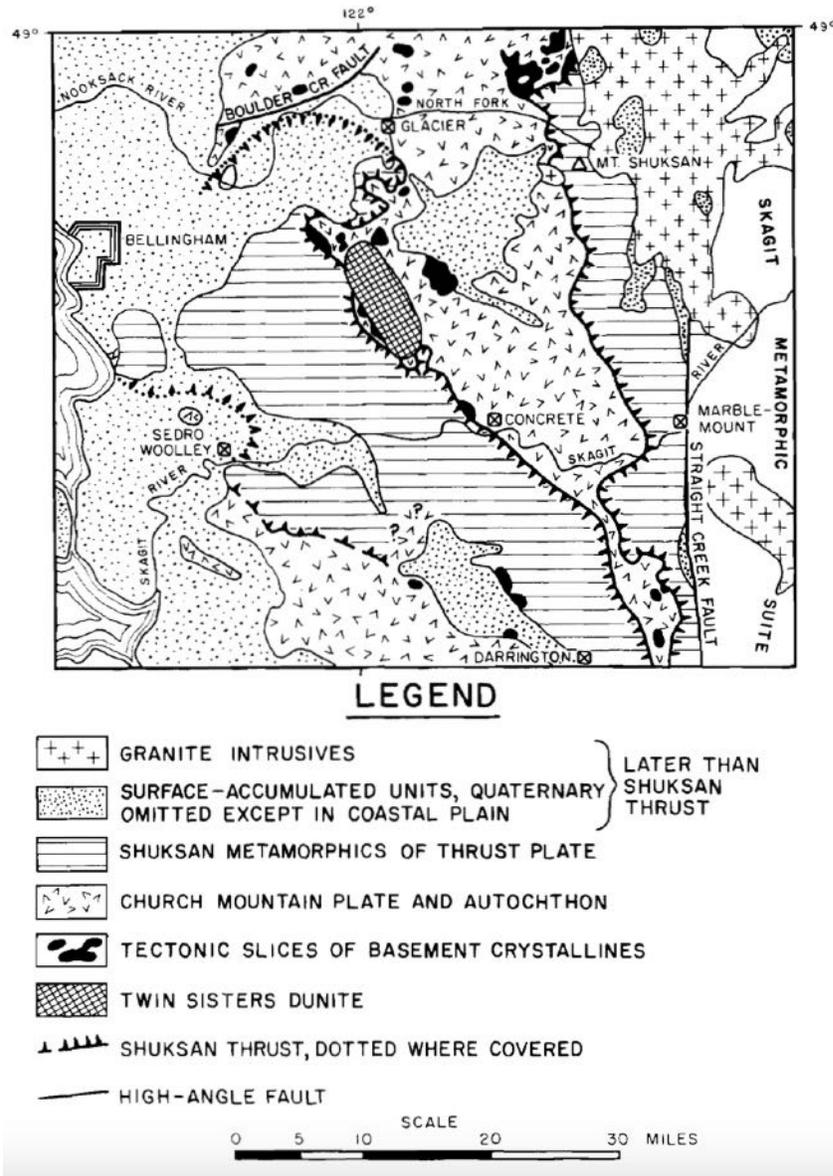
Map of California showing locations of ultramafic provinces. The Vulcan Peak peridotite in extreme southern Oregon is actually part of **the greater Josephine ophiolite, the largest in North America.**

Del Puerto The Del Puerto ultramafic body lies 60 km due east of San Jose in the California Coast Ranges. The body is part of an elongate slab of ophiolite whose ultramafic part (**up to 300 m thick and about 40 km²**) is variably serpentinized. The magnesite has been largely mined out. The serpentinite is the preserved base of an extensive, north-trending sheet of ophiolite that is about 50 km long and averages 2 to 6 km wide. The thickness of the deposit varies from a few tens of meters on the west to several hundred

meters on the east. Historic and dilapidated mining infrastructure is visible over all of the Del Puerto body.

Wilbur Springs Serpentine Wilbur Springs serpentinite mass is located about 200 km NNE of San Francisco on the eastern side of the Coast Ranges. The serpentinite is the preserved base of an extensive, north-trending sheet of ophiolite that is about 50 km long and averages 2 to 6 km wide. The thickness of the deposit varies from a few tens of meters on the west to several hundred meters on the east. Wilbur Springs proper is a small but thriving hot spring resort first developed before the turn of the century. The resort now caters to people who seek quiet, natural surroundings. Most of the land occupied by the serpentinite belongs to the U.S. Bureau of Land Management or to a few cattle ranches.

Twin Sisters. The Twin Sisters dunite, Washington, is **one of the largest fresh olivine deposits in the world** and is the **site of the largest olivine production operations in the United States** (Ragan, 1963; Harben and Smith, 2006). Estimates have put **remaining reserves of unaltered olivine at 200 gigatons** (Harben and Smith, 2006). **Unimin** and the **Olivine Corporation** are the main producers of olivine from the Twin Sisters ultramafic body, with a combined production of around 100,000 short tons per year. This dunite body covers about **90 km²** and is presently mined by **open-pit** methods for refractory (foundry) sand.



Twin Sisters area after Christensen, 1971

Partially serpentinized peridotite and dunite in large masses (20 to 80% serpentine) are more common. Examples include the Belvidere Mountain prospect in Vermont, the **Canyon Mountain and Vulcan Peak** deposits in Oregon, the **Del Puerto and Burro Mountain** bodies of California and most peridotite in the **Stillwater Complex**. The Belvidere, Vulcan Peak, Del Puerto, and Stillwater bodies contain small zones ($\geq 4 \text{ km}^2$) of relatively unaltered dunite.

Josephine Ophiolite Perhaps the largest body of continuous serpentinite outcrop in the United States occurs at the **Josephine Ophiolite** of northwest California and Oregon, which extends over $\geq 800 \text{ km}^2$ (Harper, 1984). These deposits, although

some are huge, are mostly serpentinized harzburgite and are not as desirable as the unaltered dunites.

The following table compares the CO₂-sequestering potential of some U.S. ultramafic bodies.

	Twin Sisters, WA	Vulcan Peak, OR	Del Puerto, CA	Belvidere Mtn., VT	Wilbur Springs, CA	Baltimore Complex, MD	San Mateo, CA	Stillwater, MT
Volume-Density								
Area (km ²)	91	16	40	2.3	200	100	4?	26
Depth (km)	0.6	0.5	0.3	≤1	≥0.2	0.3	0.25	0.5
Est. Vol. (km ³)	54	8	12	2	40	30	1	13
Density (g/cm ³)	3.3	3.2	2.8	2.9	2.65	2.7	2.6	3.1
Wt-% Mg								
Peridotite	29.9	27.4	27.2	29.1	—	—	—	17.5
Serpentinite	— ^a	—	20.9	23.1	21.8	21.2	19.9	—
Combined	29	27	23	26	21	21	20	17
Sequestering Properties								
R(CO ₂) ^b	1.91	2.05	2.40	2.13	2.63	2.61	2.76	3.25
Mg (10 ⁹ tons)	52.0	6.91	7.73	1.5	22.3	17.0	0.5	6.85
CO ₂ (10 ⁹ tons)	94.1	12.5	14.0	2.7	40.3	30.8	0.9	12.4
USA (yr) ^c	18.8	2.50	2.80	0.55	8.05	6.15	0.18	2.48
World (yr) ^c	4.95	0.66	0.74	0.14	2.12	1.62	0.048	0.65

R(CO₂) R = mass ratio of rock processed to CO₂ sequestered. For example, at a deposit such as the Del Puerto ultramafic body, California, a ton of sequestered CO₂ would require on average mining, crushing, and dissolving 2.4 tons of ultramafic rock.

USA (yr) Percent of USA CO₂ emissions that could be sequestered by these rocks.

World (yr) Same as for USA (yr) but for the world's CO₂.

The sequestering potential of small ultramafic bodies is considerable. For example, the Belvidere Mountain ultramafic body, having an estimated volume of about 2 km³, is capable of handling the equivalent of 0.5 year of present total U.S. CO₂ emissions (about 5 gigatons/yr).

Compared with a typical coal mine, the Del Puerto deposit is quite large. By itself, the Del Puerto deposit could dispose of all of the CO₂ emissions associated with a population of 10 million people for about 70 years. Thus, it would suffice for the local region. However, to absorb the CO₂ output of the United States, **many more such mines would be needed.**

Large-scale Open-Pit Mining Open-pit mining on the scale envisioned would have profound economic and environmental impact. Precedents for open-pit mining of serpentinite presently exist at New Idria and at other mines in the California Coast Ranges (Coleman, 1996).

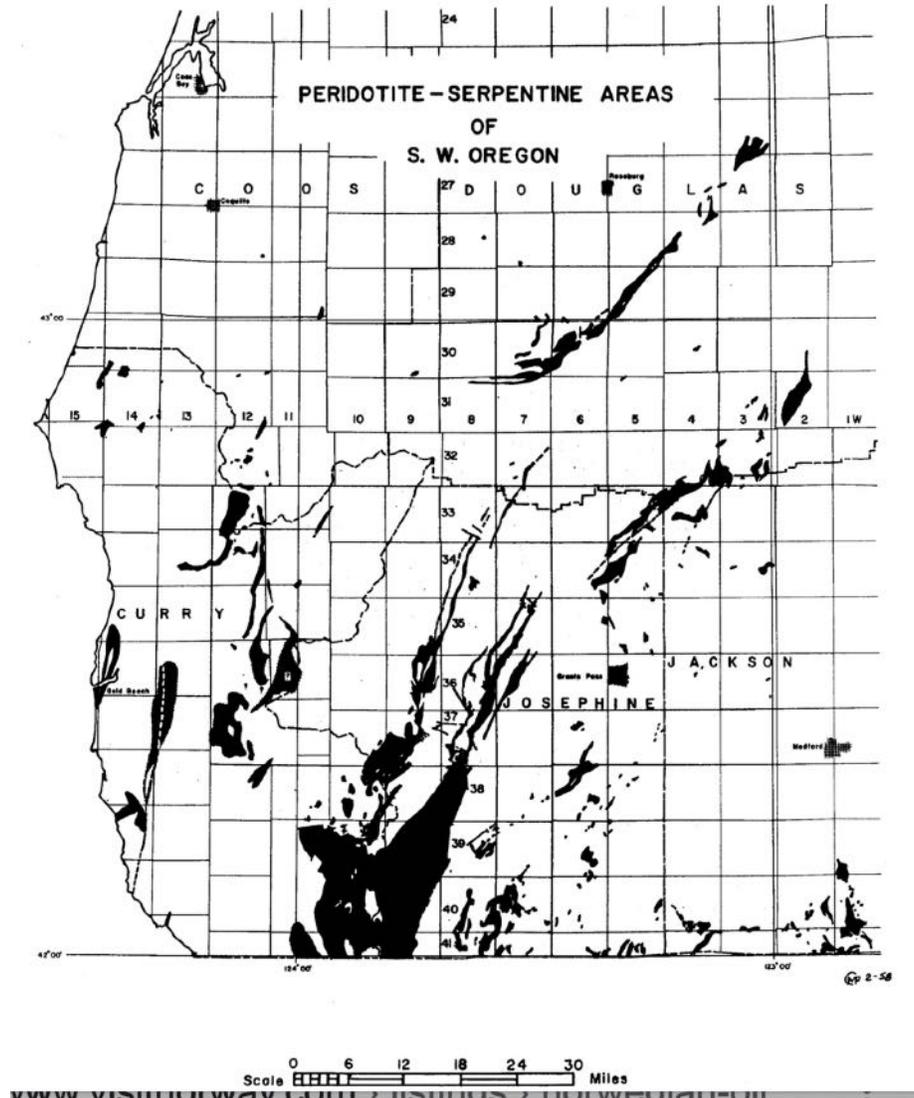
From another perspective, the abundance of Mg in the Earth's crust (0.035 mol-%;) it is not surprising that there should be more than enough Mg in ultramafic deposits to sequester global CO₂ emissions.

Other States: USGS article Geologic units containing Peridotite lists the US other with ultramafic rocks – i.e., California - Kentucky - Massachusetts - Maryland - Michigan - Minnesota - New York - Oregon - Pennsylvania - Tennessee - Virginia - Vermont - Washington - Wisconsin – Wyoming. Some of these are reviewed above. Others are left to the interested reader.

Also: **Geologic units containing Ultramafic intrusive rock.** Alabama - Connecticut - Georgia - Massachusetts - Maine - Michigan - Montana - North Carolina - New Hampshire - South Carolina - Vermont - Washington - Wisconsin

Oregon (Wagner, N.S. and Ramp, L.,1958)

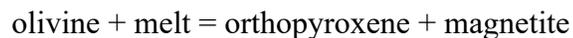
The following map shows the location of ultramafic deposits in Oregon.



Hawaii Though not a major emitter of CO₂, Hawaii is endowed with significant volumes of potential reservoir rocks that could be utilized to mitigate local CO₂ emissions.

Alaska Mafic and ultramafic rocks are widely distributed in the islands of the southern part of Alaska. A discontinuous, elongate zone of mafic and ultramafic plutonic rock crops out in south-central Alaska for a **distance of more than 1000 km.**

Blashke Islands are between Juneau and Kechican. Himmelberg et al, 1986 and Himmelberg and Loney, 1995, reported on the presence of a ultramafic complex on these islands. The peridotite-gabbro suite at the Blashke Islands is one of more than **30 Alaskan-type ultramafic complexes** exposed along a linear trend in southeastern Alaska. The center of the intrusion is dunite, with wehrlite, **olivine** clinopyroxenite, and gabbro occurring progressively outward. Serpentinization of the olivine-rich rocks ranges from about 25 to 75 percent. Dunite, approximately 2 km in diameter, makes up the core of the peridotite-gabbro suite and is the most abundant rock type exposed. The gabbro unit is as much as 300 m wide and forms the outermost part of the peridotite-gabbro suite. Orthopyroxene + magnetite which are commonly associated with olivine, are probably a result of a late stage magmatic reaction:



Red Bluff Bay, south east of Sitka, on the southeast coast of the Baranof Island, has fine-grained dunite-wehrlite and clinopyroxenite form a **body 3 km by 6 km**.

Duke Island south of Kechican, has dunite, peridotite, clinopyroxenite, and hornblendite and are locally serpentinized. The dunite and peridotite in these ultramafic rocks contain small amounts of chromite, asbestos, and platinum group metals, and the clinopyroxenite locally contains accumulations of titaniferous magnetite.

This is a sampling of the ultramafic deposits in the southern part of Alaska. Himmelberg and Loney (1995) 18 sites, mostly islands, with ultramafic deposits.

So, what are Alaskan-type ultramafic complexes? Many of the igneous intrusions (plutons) are concentrically zoned, an unusual characteristic that has led to their classification as 'Alaska-type,' or 'Alaskan,' complexes (Taylor, 1986).

Are there enough ultramafic rocks in the U.S. and Puerto Rico to allow the sequestration of significant amounts of CO₂?

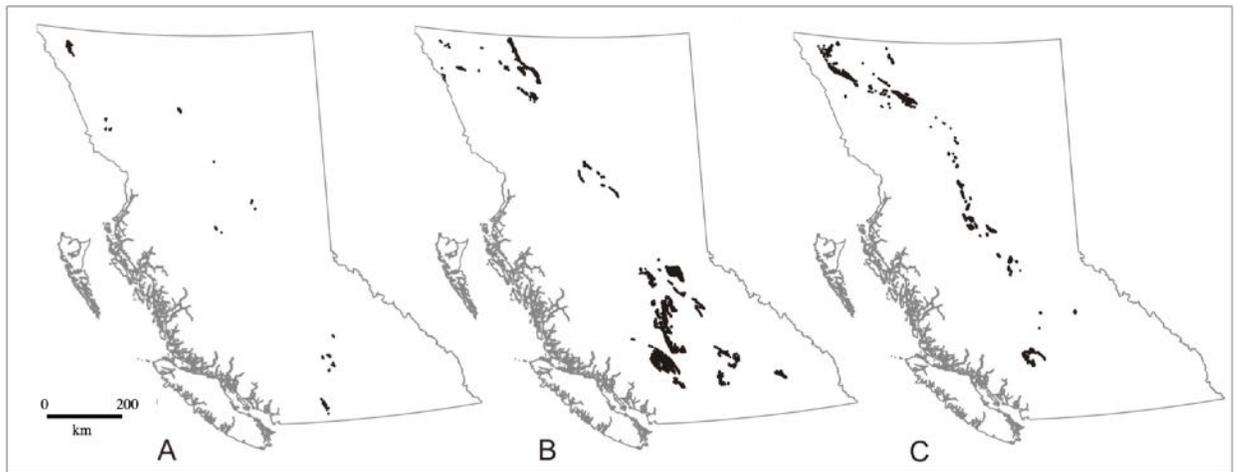
Goff & Lackner (1998) stated that small ultramafic bodies of about 1 km³, can potentially sequester about 1 gigatons of CO₂. A single large deposit of dunite (about 30 km³) could dispose of nearly 20 years of 1998 U.S. CO₂ emissions. Are there enough ultramafic deposits in the U.S. to sequester the U.S. and world contribution to global warming?

Canada

Olivine Mountain (a goldmine) consists of 3,021-hectares and covers part of the **Tulameen Ultramafic Complex**, a large slab of magnesium and iron-rich rock that ascended from near the base of the earth's crust to its current position during continental collision and the emplacement of the Cache Creek terrane in southwestern British Columbia. Dunite, olivine and hornblende clinopyroxenite are the principle ultramafic rocks (Hancock, 1991).

The Olivine Mountain Project is located in the Interior Plateau area of South-Central British Columbia, 25 kilometers northwest of Princeton near producing mines & recent major discoveries: A major recent discovery is ~50km Southeast of Westhaven Ventures (TSXV:WHN) Shovelnose Project & Kodiak Copper's (TSXV:KDK) MPD Project. **GSP Resource Corp** optioned a 60% Interest in Olivine Mountain Project to **Full Metal Minerals Ltd.** GSP Resource is located at #1610-777 Dunsmuir St., Vancouver, BC.V7Y 1K4 info@gspresource.com

Other BC Ultramafic Deposits British Columbia has favorable geology and excellent exploration potential to host the raw materials suitable for CO₂ mineral carbonation, one of the methods considered for lowering greenhouse gas levels. The following map shows the olivine and serpentinite deposits separately and together.



Separating out the dunite and serpentinite zones associated with ultramafic rocks: A. Areas where ultramafic rocks are reported to contain dunite only. B. Serpentinite only. C. Dunite and serpentinite are reported together. (Voormeij and Simandl, 2004).

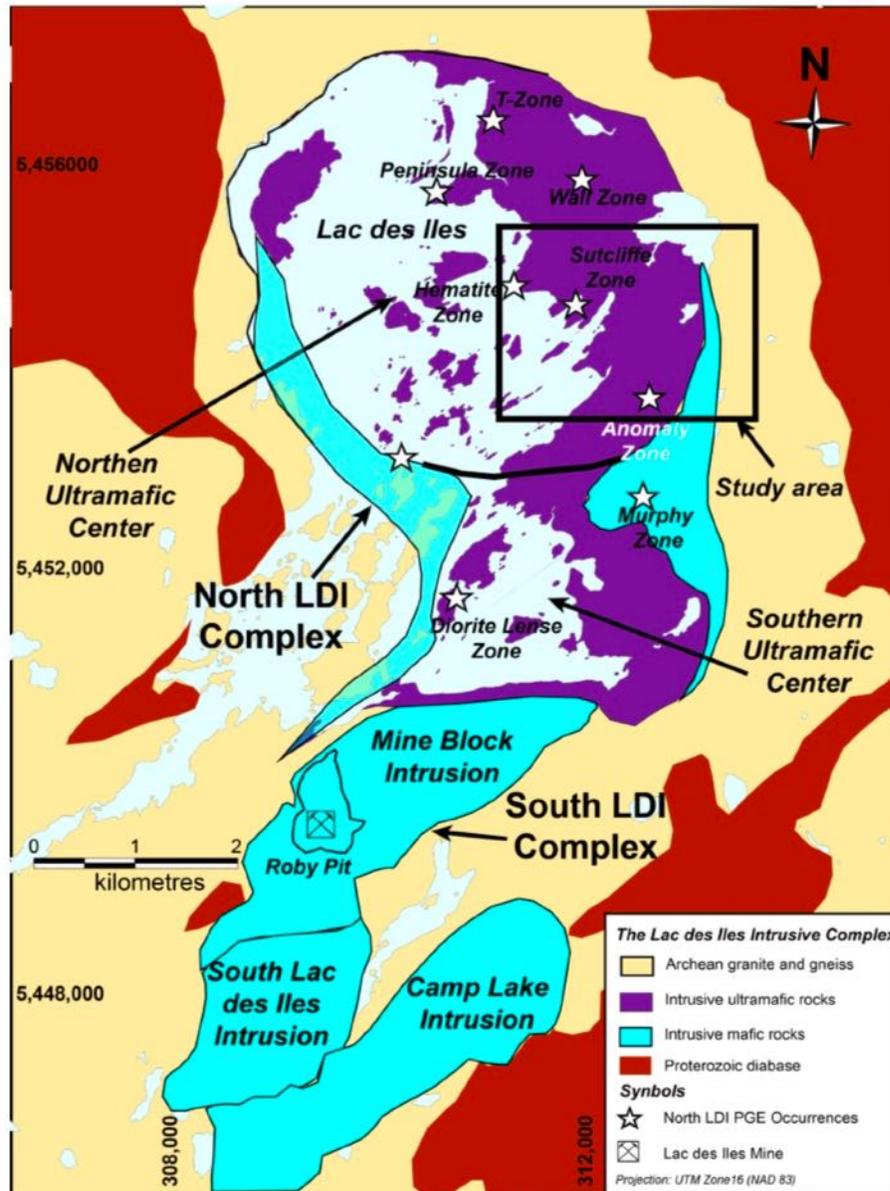
Abitibi Area is way north of Ottawa, immediately north of Amos. A study has been made of a **30-mile segment** of a belt of ultramafic-gabbroic igneous bodies extending past the south side of Lake Abitibi, Ontario. It is composed of peridotite and **dunite** (MacRae 1969).

Timmins Gold Mines Since the discovery of Gold in the Timmins Area, North of Toronto in Ontario, 30 different mines have produced a total of 50 million ounces of gold. Ultramafic rocks are often in close association with gold deposits. Now it is not the gold but the ultramafic rocks that is of interest. These areas deserve attention for the amount of ultramafic rocks they could produce. (Pyke, 1975).

The largest differentiated layered sill (flat intrusion of igneous rock) known in Manitoba is the **Fox River sill** This body appears to be continuous over a **length of 155 miles**. This sill has a surface area of approximately 200 square miles. Serpentinized dunite and peridotite are estimated to make up approximately 78 percent of the exposed portion of the body. The lithologic variation ranges, from serpentinized dunite to gabbro, and the

ratio of mafic to ultramafic rocks is approximately 1:10. **This represents a massive amount of ultramafic rock.**

Lac de Iles. The following figures shows the ultramafic deposits in the Lac des Iles complex in northern Ontario (Djon, 2017).



Simplified local geology map of the Lac des Iles Complex (Modified from Lavigne and Michaud, 2001)

Mining Companies in the U.S. and Canada

Cova (formerly Unimin) Corp 3 Summit Park Drive, Suite 700, Independence, OH 44131 Covia's facilities span North America with a **vast, convenient distribution network** in close proximity to our customers. See map on website.

Our main role is to provide a broad array of high-quality minerals and material solutions for the industrial and energy markets and a comprehensive and accessible distribution network.

When you need materials in the smallest possible size, our experts can get it done. Covia's micronization services reduce minerals to the proper level to work best for your application. Whether you require large volume units or small custom packages, our individual product packaging options include a variety of bags, pails, boxes, and drums. Our high-volume bagging capabilities enable us to deliver bulk material in supersacks and totes. Covia hosts an extensive terminal network, ensuring our products are there when you need them, every time. Getting your product to you when you need it is the final step. We keep it simple.

Cova (Unimin) Corporation is a wholly owned subsidiary of global 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. Executive offices are located in New Canaan, Connecticut with technology, analytical and sales service centers situated throughout North America. Unimin has over 2,400 employees located in 19 states in the U.S., Canada and Mexico. Industrial Customer Service 800-243-9004 Sales@CoviaCorp.com

Olivine Corporation is a magnesite mine located in Skagit county, Washington. It is located in Bellingham, WA, United States and is part of the Other General Purpose Machinery Manufacturing Industry. Office: 928 Thomas Rd, Bellingham , WA, 98226-9044. Phone (360) 733-3332 It is much smaller than the Cova, Corp.

Olivine Corp is located in Bellingham, Washington. This organization primarily operates in the Incinerators, Metal: Domestic or Commercial business / industry within the Industrial and Commercial Machinery and Computer Equipment sector. This organization has been operating for approximately 58 years. Olivine Corp is estimated to generate \$280,000 in annual revenues and employs approximately 2 people at this single location. The Olivine Corporation Mine is part of the San Juan Wilderness. **The Olivine Corporation Mine was closed at the time of data entry with no known plans to re-open.**

The **Swen Larsen Quarry** sits at the **base of the Twin Sisters Mountain and is a key site where olivine is mined. This quarry is one of a few places in the United States known to have access to olivine** (Kogel, 2006). The quarry has been in operation since 1953. **Twin Sisters Olivine** (formerly known as United Western Supply) has owned this site and **Olivine Corporation** has consulted on operations since January 27, 2012 to present time. The olivine from this site is mainly used for **molding sand in metals casting**, a component in refractory lining of combustion chambers, and for artistic use in the community. Current mining operations include excavation of material, crushing and screening on-site, and the hauling of material off-site for further processing and sale to market. The active season is 1 to 2 months a year.

GSP Resource Corp. (TSX-V: GSPR) is a mineral exploration & development company focused on projects located in Southwestern British Columbia. The Company has

an option to acquire a 100% interest and title to the **Alwin Mine Copper-Gold-Silver Property** in the Kamloops Mining Division, as well as an option to acquire 100% interest and title to the Olivine Mountain Property in the Similkameen Mining Division. For more information, please contact:

Simon Dyakowski, Chief Executive Officer & Director Tel: (604) 619-7469

Email: simon@gspresource.com

Full Metal Minerals Ltd. (TSX-V: FMM) was incorporated in 2003 as a public company. It is a Canada-based mineral exploration company. The company is engaged in the acquisition, exploration, and development of resource properties. 409 Granville Street, Suite 1500, Vancouver, British Columbia V6C 1T2, Canada.

www.fullmetalm minerals.com Full Metal Minerals Proceeding with Option Agreement to Earn 60% Interest in **Olivine Mountain Project** with GSP Resources.

Contact Information - For more information, please contact:

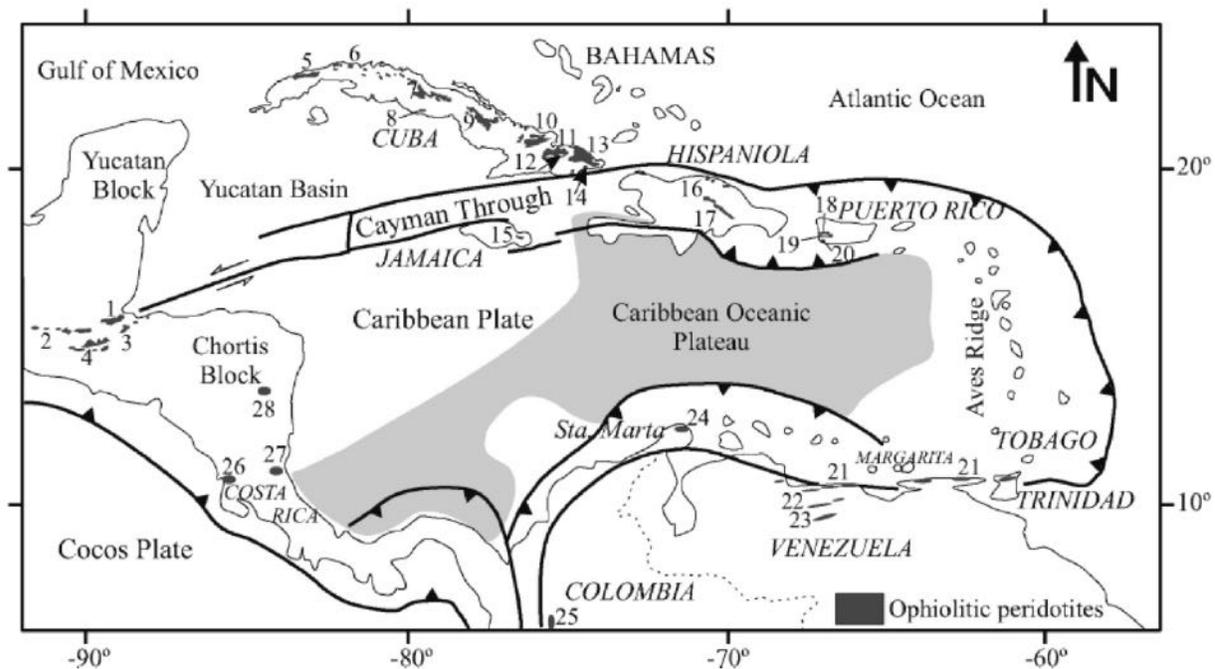
Simon Dyakowski, Chief Executive Officer & Director Tel: (604) 619-7469

Email: simon@gspresource.com

Noble Mineral Exploration, Inc. Toronto, Ontario August 11, 2021 is pleased to announce that it has closed agreements with a number of parties (the “Parties”) to option or acquire 321 mining claims (the “Claims”) in **Mann, Hanna, Duff, and Reaume Townships**, covering an area totaling approximately 6,539 hectares. As reported by the Company on May 31, 2021, the Company has also staked an additional 256 mining claims in Mann, Hanna, Duff and Reaume Townships totaling approximately 5,453 hectares. There are over **20 km of mapped ultramafic rocks in Mann Township**. The ultramafics consist mainly of mafic sheets, sills and dikes that have intruded into and differentiated within volcanogenic sediments. The differentiated intrusions are composed of basal peridotite, usually serpentinized with a transition to pyroxenite, and then gabbro. The peridotite, and the better mineralized dunite, are the host rocks for the nickel-cobalt sulphide

Caribbean Area

As shown in the following map, there are numerous deposits of ultramafic rocks in the Caribbean area (Lewis et al, 2006). (See this article for more references.) All the ultramafic rocks around the Caribbean have been serpentinized to at least some degree. There are three main serpentine minerals, antigorite, lizardite and chrysotile.



Distribution of **ophiolite-related ultramafic rocks** around the margins of the Caribbean Plate: 1: Sierra de Santa Cruz; 2: Baja Verapaz Unit; 3 Juan de Paz; 4: El Tambor Group (South Motagua and North Motagua); 5: Cajálbana; 6: Habana-Matanza; 7: Villa Clara; 8: Escambray; 9: Cam-agüey; 10: Holguín; 11: Mayarí-Cristal; 12: Alto de La Corea; 13: Moa-Baracoa; 14: Sierra del Convento; 15: Arntully; 16: North Coast Belt; 17: Loma Caribe; 18: Monte del Estado; 19: Río Guanajibo; 20: Bermeja; 21: La Franja Costera; 22: Loma de Hiero; 23: Villa de Cura; 24: Guajira Peninsula (serpentinites of Cabo de la Vela); 25: “Dunita de Medellín” (Aburrá ophiolite); 26: Santa Elena; 27: Rio San Juan; 28: Siuna. Main localities are numbered in italics.

Guatemala Ophiolitic rocks exposed along the Motagua Fault Zone in Guatemala include some large bodies of harzburgite such as the Sierra de Santa Cruz and La Gloria massifs. Recently have recognized four main ophiolite units containing peridotites (1) Sierra de Santa Cruz, (2) Baja Verapaz, (3) Juan de Paz, and (4) El Tambor group (South Motagua and North Motagua).

Cuba In Cuba, the largest bodies of ophiolite-related ultramafic rocks (serpentinized peridotites and serpentinites) crop out to the north of the island, along the so-called “northern ophiolite belt”. The ophiolites of northern Cuba occur as seven separate “massifs” (ophiolite blocks) or suites exposed along the entire length of the island, from west to east: 5. Cajálbana, 6. Habana-Matanza, 7. Villa Clara, 8. Escambray 9. Camagüey, 10 Holguín, 11. Mayarí-Cristal, 12: Alto de La Corea; 13: Moa-Baracoa; 14: Sierra del Convento. All ophiolite massifs contain massive chromitite bodies, a characteristic feature of SSZ ophiolites.

Jamaica A small faulted block of serpentinitized peridotite (~0.25 km² in area) known as the 15 **Arntully serpentinite** is located in the southern edge of the Blue Mountains along the Plantain Garden Fault in eastern Jamaica. This body is considered to be related to the Bath Dunrobin complex of basalts and gabbros which would make this an ophiolite association. The Arntully body is composed mainly of serpentinite with a core of partly serpentinitized harzburgite, Iherzolite, dunite and abundant blocks of rodingite.

Hispaniola Serpentinitized peridotites of apparent ophiolitic affinity occur in two belts across Hispaniola, namely the 16. North Coast belt and the Median Belt in the Cordillera Central. In both belts there is evidence that these originated separately as parts of ophiolite associations that are now highly dismembered and most of the original features have been destroyed. The north coast serpentinites are small (only the Punta Gorda body exceeds 5 km across) and there is little soil developed on these. The main serpentinite belt, the 17. Loma Caribe peridotite, in central Hispaniola in the Median Belt is about **4-5 km wide** and extends for 95 km from La Vega to Cerro Prieta north of Santo Domingo.

Puerto Rico in southwestern Puerto Rico there are three relatively small serpentinitized peridotite bodies, namely 18. Monte del Estado, 19. Rio Guanajibo and the 20. Bermeja in the south. (see also above).

Venezuela 21. La Franja Costera with peridotites, 22. Loma de Hierro with peridotites with dunite, 23. Villa de Cura with harzburgites, 24. Guajira Peninsula (serpentinites of Cabo de la Vela).

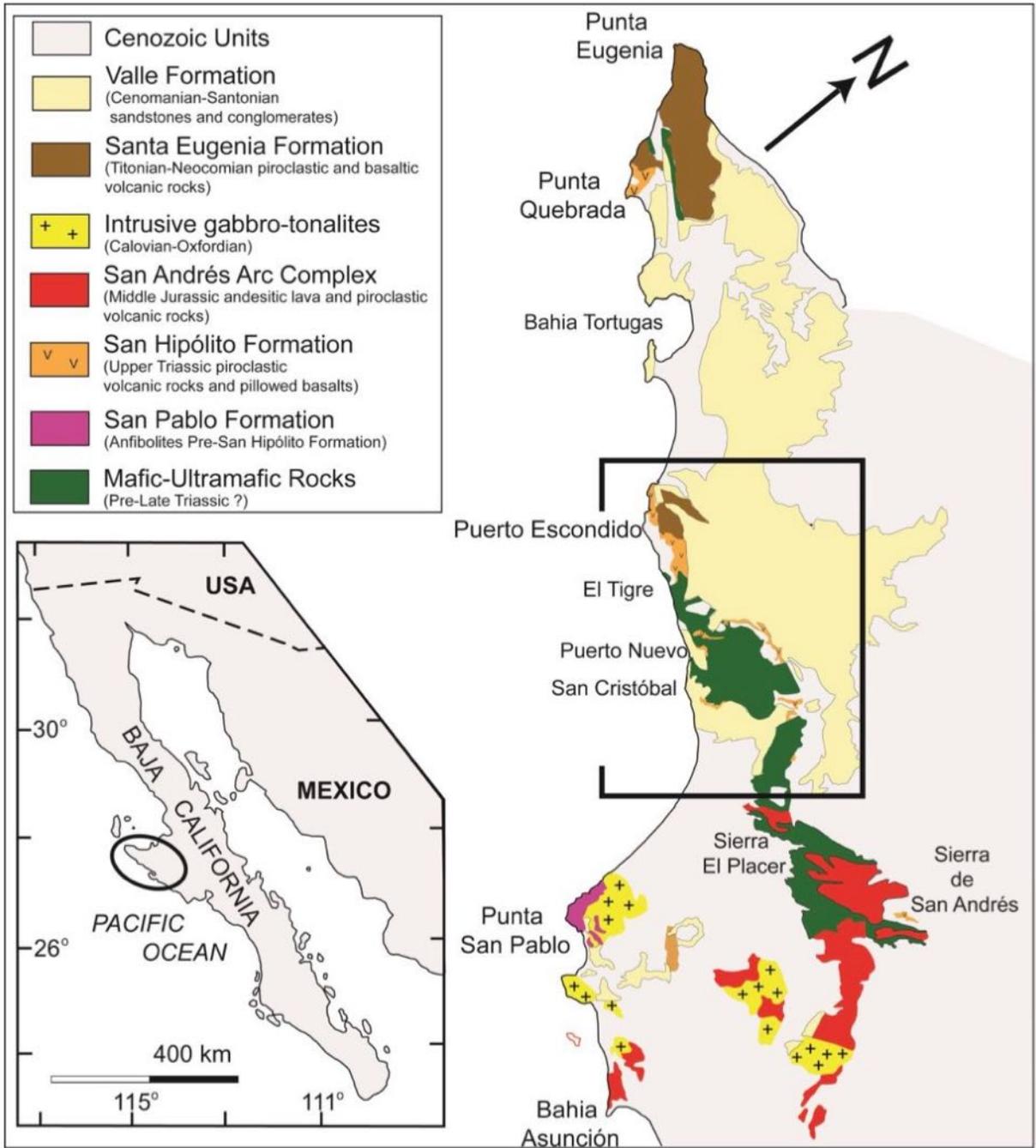
Columbia 25: “Dunite de Medellín” with Aburrá ophiolites.

Costa Rica 26: Santa Elena with harzburgite and dunite. 27. Rio San Juan with serpentinite and Iherzolite.

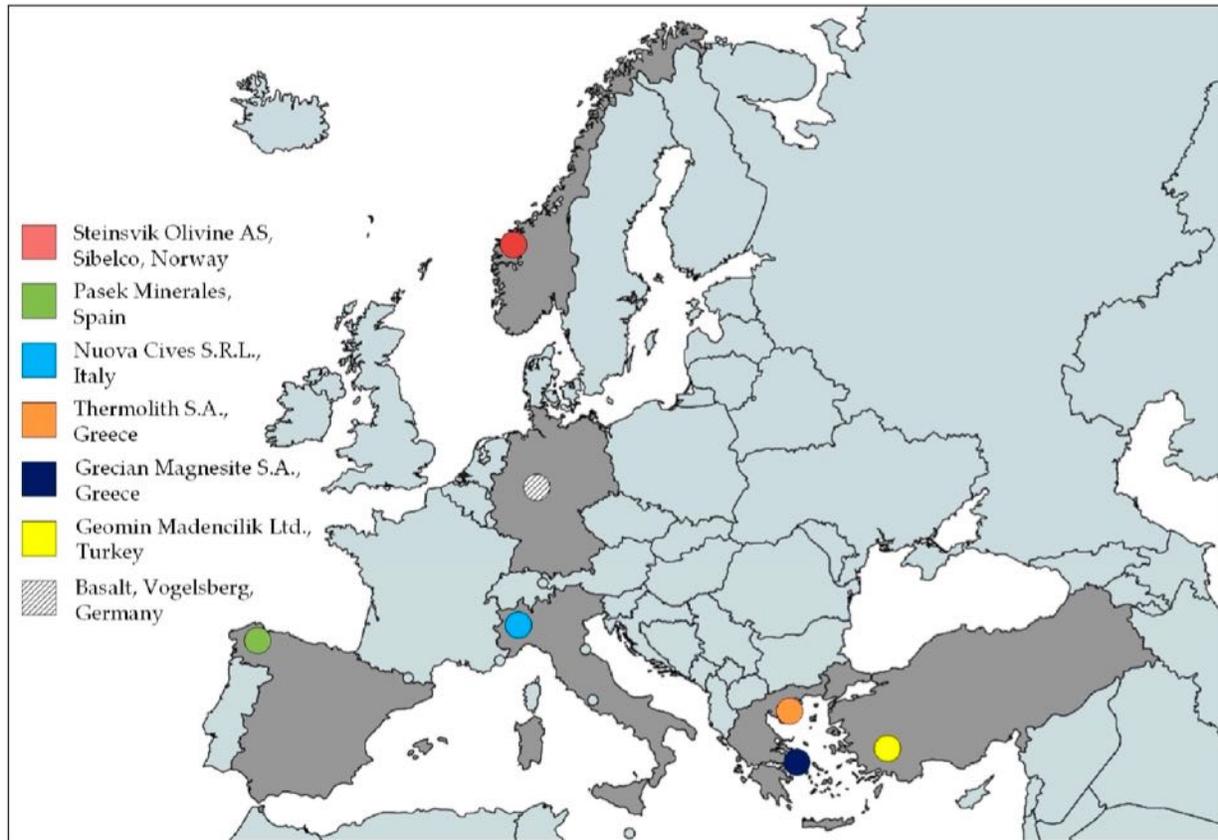
Nicaragua 27. Rio San Juan and 28. Siuna with serpentinite and peridotite.

Mexico The Loma Baya deposit the ultramafic–mafic complexes in coastal Guerrero (Las Ollas, Camalotito, El Tamarindo, and Loma Baya, are associated with the Zihuatanejo terrane by the southernmost border of the Guerrero composite terrane.

There are many other locations in Mexico. One example is shown in the map of Baja below.



European Mining Sites and Companies (especially see Kremer et al, 2019)



Norway, Spain, Greece, Italy, and Turkey are major olivine producing countries in Europe, with a total amount of between **4,200 to 5,00 kilo tons/yr**, which represents more than 50% of the global olivine production. For details see the above reference.

The companies on this map are presented by their country below.

Norway

Norway is the main source of olivine in Europe, particularly in an area stretching from Åheim to Taffjord, 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. Production is between 2,525 and 3,500 ktpa. Many deposits in the Gusdal Mine (mainly mined from Sibelco, but also from Steinsvik) is sufficient for the market.

Around 57 olivine mining sites are available in Norway (Norwegian Geological Survey, 2020), personal communication to . The biggest production comes from the Åheim district, and the mine is located close to a deep-water harbor. This site has around 92% olivine containing dunite rocks, and the purity of rock is consistent (Evans, 1997). The average composition in Gusdal mine is summarized in the table below.

Norway Gusdal Olivine Pit (Åheim Olivine Pit), Almklovdalen, Vanylven, Møre og Romsdal, This site provides detailed maps to Norwegian Olivine Mining sites.
 Norwegian Olivine mine, North Cape Minerals, Sibelco, AS Olivin, Raudbergvika Olivine Mine, Norddal, Møre og Romsdal, **Norway**

Content	Composition in olivine (%w.t)
MgO	47
SiO ₂	41.45
Fe ₂ O ₃	9.2
Cr ₂ O ₃	0.565
Al ₂ O ₃	0.31
NiO	0.3
MnO	0.115
CaO	0.12
K ₂ O	0.01
Na ₂ O	0.015
LOI	1.555

Average composition of olivine in Gusdal open miningpit, Norway. Personal communication from Norwegian Geological Survey to Vinita, R.(2020)

Steinsvik Olivine AS Velsvikvegen 729, 6133 Lauvstad, **Norway**
welsvik@online.no

Turkey Dunite rocks and harzburgites are the main sources of olivine in Turkey. There are many deposits with a **significant amount of olivine** bearing rocks, but only a few deposits are mined to date, due to economic and location aspects.

Dudolp Mining Mimar Sinan Üsküdar-İstanbul, **Turkey** +90 850 303 3930
info@dudolpmine.com, <http://www.dudolpmine.com/> Dudolp Mining is a world wholesale mining supplier company specialized in natural mineral mining including olivine

Oresan Mining is your reliable partner for export finance, facility investment, marketing and product development in metals, minerals and mining industries. Levent Cd. Şener Sk. No:5 Beşiktaş / İstanbul, Turkey +90 212 573 55 49 info@oresan.com

Olivine mining is considered rather new when compared with other minerals. Olivine mine has become quite important mineral in terms of its physical characteristics and in iron and steel and casting sectors of Europe's and world's developed countries for the past 20-25 years.

Eryas Mining Company – Green Sand Founded in 2008 and carrying on the activities in industrial minerals, specifically **olivine** and olivine based refractories with the mine and the plant in Iskenderun. Ehlibeyt Mah. Ceyhun Atuf Kansu Cad. 1271.Sk., Ankara, Ankara, **Turkey** Forsterite Mg_2SiO_4 95% Fayalite 5% Fe_2SiO_4
Website: www.eryas.com

Ore-Met Olivine Sands Pazaraşığı Mah. Sena Sok. No:11/10 Yalvaç / ISPARTA / Turkey +90 (246) 441 26 27
info@ore-met.com

Ore-met Mining, which was established as a family company in the region of Isparta Yalvaç in the 1970s, started its first mining experiments in 2003 with the entrepreneurial spirit of investors and administrators for institutionalization. The company, which started with barite mining, was followed by magnesite, chrome, bauxite and **ultimately olivine**, and it was established as a family partnership and today it has become a giant corporation that produces and markets mining and industrial minerals.

Produces many different types of olivine sand.

Dakduklu Minerals Established in 1982 in Isparta, Turkey Pazarasagi Mah Sena, Sok No. 11/10 Valvac, Isparta, **Turkey**
info@yalvacolivin.com Multiple types of olivine sands

Geomin Madencilik Sanayi ve Ticaret Limited Geomin R&D Office Pamukkale University Technology Development Zone Denizli / **Turkey**
E-Mail: info@geomin.com.tr Telephone: +90 258 215 50 30. Geomin Madencilik is a mining company working on all stages of sourcing industrial minerals for local and global markets. We supply olivine, diatomite, bentonite, bauxite, chromoium and other industrial minerals.

Egamin mining owns Rich reserves of olivine in the Denizli and Muğla regions in the southwest of Turkey. The Köyceğiz Deposit, located in Mugla, has an estimated reserve of 1,200m tons. Mimar Sinan Mahallesi, Isilar Saygin Sokak,Sevilen Apt No1/D3 Alsancak Izmir, Tyrkey

LTC Minerals Olivine gets its name from typical green olives. The aluminum foundry industry uses olivine sand to cast objects in aluminum. Olivine sand requires less water than silica sands while still holding the mold together during handling and pouring of the metal. Less water means less gas (steam) to vent from the mold as metal is poured into the mold. We supply Olivine in various sizes and specs. Please contact us for details...
1690 Sok, No: 5, D: 301 Karsiyaka – Izmir – Turkey www.ltc.com.tr +902323642462

Belgium

Euromines European Association of Mining Industries, Metal Ores & Industrial Minerals
Avenue de Tervueren, 168, box 15 1150 Brussels-**Belgium**

Sibelco A global material solutions company. Our company sources, transforms and distributes specialty industrial minerals – particularly silica, clays, and **olivine**. Founded back in 1872, we have grown into a multinational business with operations in around 30 countries and an extensive multi-mineral portfolio.

SCR-Sibelco N.V. Plantin en Moretuslei 1A

B-2018 Antwerp, **Belgium**

Tel: +32 3 223 6611 **Email:** info@sibelco.com **Website:** sibelco.com

Location map ([pdf 833KB](#))

North America

3426 Toringdon Way, Suite 106, Charlotte, NC 28277

United States of America **Tel:** +1-704-625-2122

Email: customersupport.us@sibelco.com

Web: sibelco.com/northamerica

Asia

Level 19, Singapore Land Tower, 50 Raffles Place, Singapore 048623

Tel: +65 6538 0355 **Email:** customersupport.sg@sibelco.com

Web: sibelco.com/asia

Australia & New Zealand

PO Box 47 Dunwich QLD 4183 Australia **Tel:** +61 7 3409 6800

Email: info@sibelco.com

Web: sibelco.com/australia-new-zealand

South America

Estrada Municipal Alcides Tofanin, s/n – Km 1,1, Jarinu, SP, 13240-000, Brazil

Tel: +55 11 2398-1200 **Email:** customersupport.br@sibelco.com

Web: sibelco.com/south-america

Europe, Middle East & Africa

Plantin en Moretuslei 1A, B-2018 Antwerp, Belgium

Tel: +32 3 223 6611 **Email:** <https://www.sibelco.com/europe-africa-contacts/>

Web: sibelco.com/emea

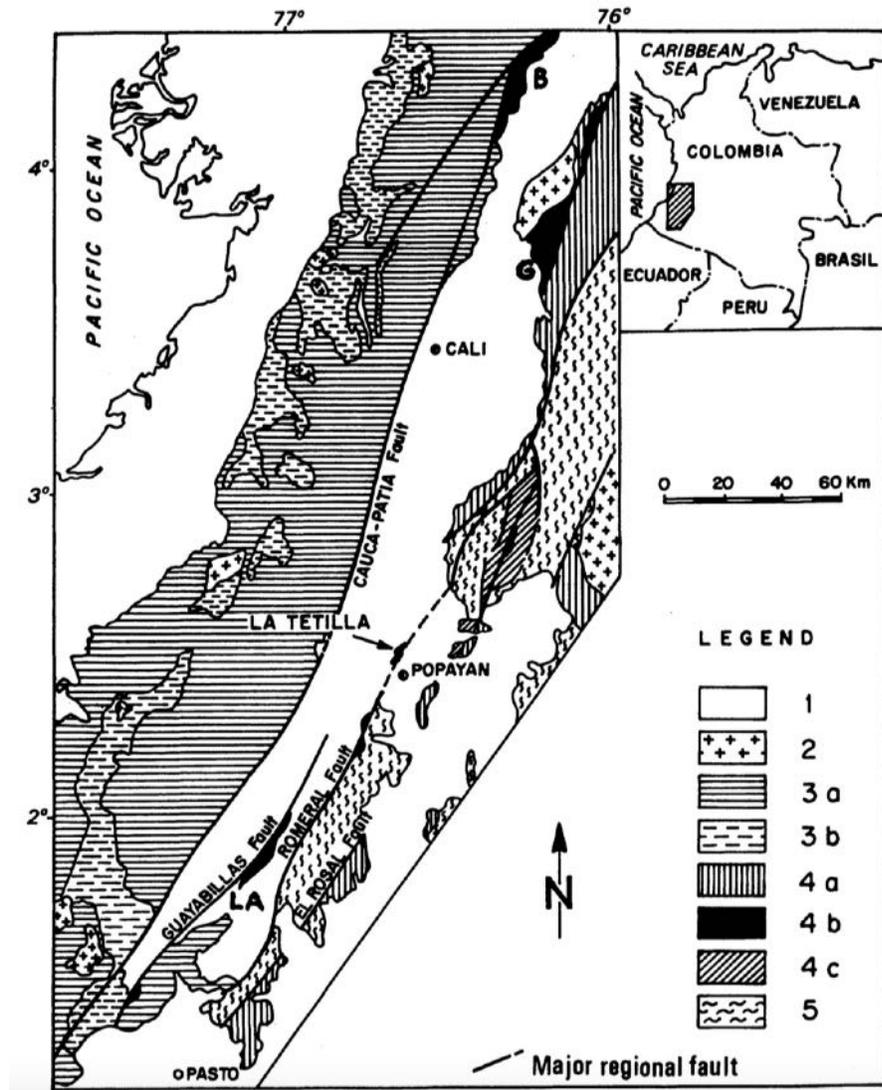
Spain

Pasek Minerales Mina Dunita Landoy, 15360 Carino, La Corna, **Spain**
pasek@pasek.group Produces Dunites - Magnesium silicate – 37% MgO. 1,000,000 million tons/yr (This is probably an error. Should read 1,000,000 tons/yr)

Columbia

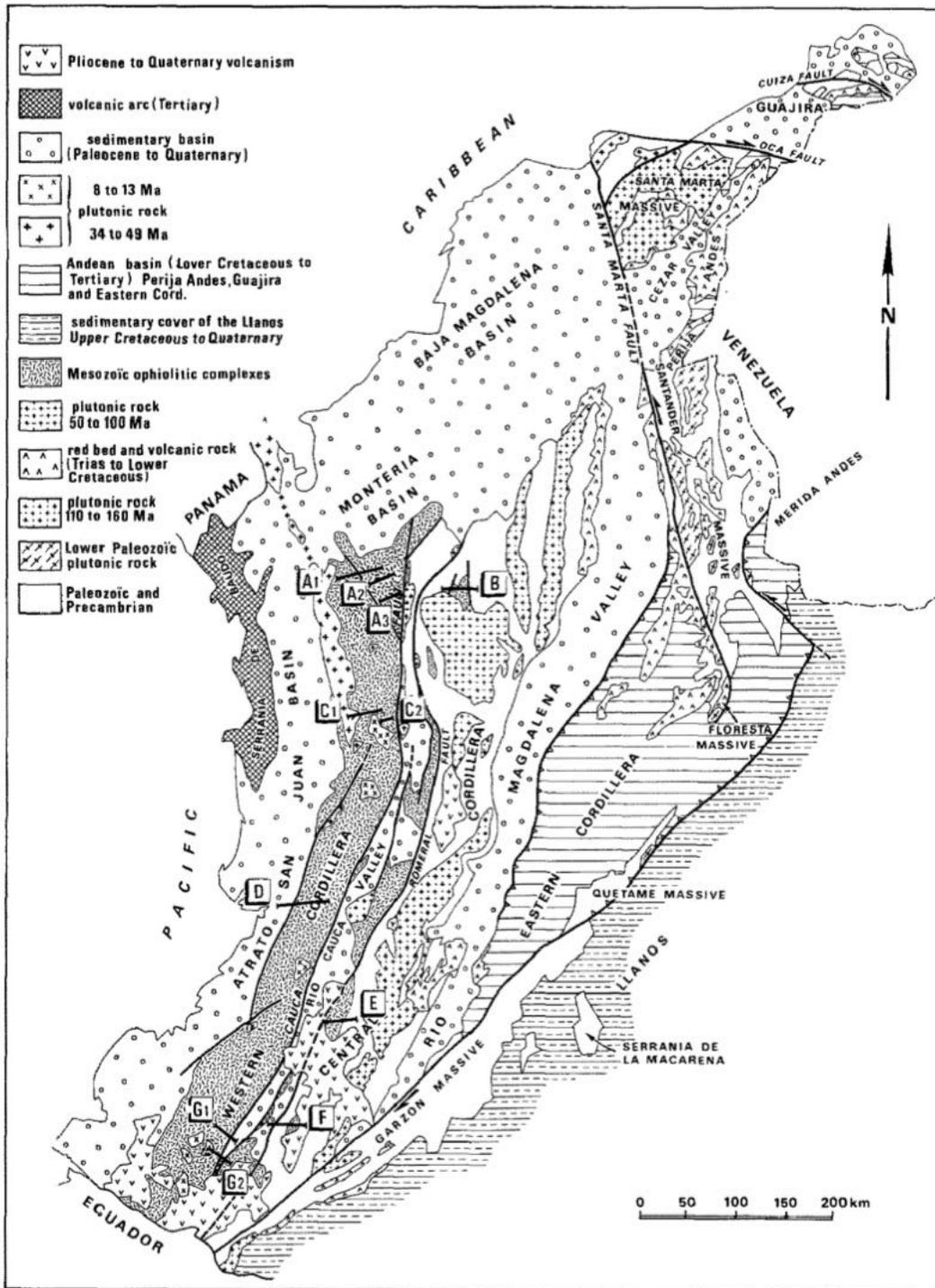
The following are two geological maps of ophiolite deposits in Columbia, both showing areas close to the Pacific. For orientation, the first shows regions just north of Cali (see above map). The first is from Spadea, P. et al.(1987) Ophiolite Complex from La Tetilla, Southwestern Colombia. The following 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-ultramafics:** (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.

Germany

Basalt Vogelsberg Active basalt quarry operated by the Vogelsberger Hartstein Industrie GMBH & Co KG of the Süd Hessische Asphalt-Mischwerke GmbH. Vogelsberg Basaltworks, Rinderbügen, Büdingen, Wetteraukreis, Darmstadt, Hesse, Germany Vogelsberg is a large volcanic mountain range in the German Central Uplands in the state of Hesse, separated from the Rhön Mountains by the Fulda river valley. Emerging approximately 19 million years ago, the Vogelsberg is **Central Europe's largest basalt formation**, consisting of a multitude of layers that descend from their peak in ring-shaped terraces to the base.

Italy

Nuova Cives SRL Olivine Minerals Localita Cross, 10080 Vidracco, **Italy** 39-0125 789078 An experience matured in over 50 years of activity in exploitation, processing and trading fields of industrial minerals that allowed to improve a specific know-how for the production of a wide range of **Olivine products**. The extracted and mined ores come mainly by national deposits –in exclusive concessions – placed in Piedmont with different mineralogical compositions and different chemical-physical characteristics.

“Bric Carlevà” Mine, mining concession covers 125 hectares and exploitable resource for more than 300 million tons of mineral.

“Finero” Mine, with an extension of more than 150 hectares and reserves for more than 250 million tons.

The mine plantation is an **open-pit** one and the mineral mined by means of explosives. The working stages are made in the modern plant of Vidracco, where it takes place the primary and secondary crushing, separation of waste materials, enrichment, tertiary and quaternary crushing, defillerization, classification. Separated and dedicated lines are presents for the production and storage of products coming from the different mines. This deposit's expected reserves contain about 100 Mt of dunites, with grades of 95% to 97% of olivine.

Olivine/dunite is mined from a deposit in the north near Turin in the municipalities of Castellamonte, Vidracco and Baldissero Canavese. This deposit's expected reserves contain about 100 Mt of dunites, with grades of 95% to 97% of olivine. The mafic-ultramafic Ivrea-Verbano Zone in Northwest Italy bears several peridotite massifs, namely Finero, Balmuccia, and Baldissero. Additionally, there are two open-pit mines currently producing: “Bric Carleva” with ~300 Mt resources and “Finero” with ~250 Mt reserves (stated by Nuova Cives SRL).

Greece

Exploration of a new Olivine Deposit in Northern Greece One of the minerals that have been exploited during the last decade in Greece is **olivine**. Today the main identified deposits of olivine in Greece are in the Vourino Mountain range in Western Macedonia, in Northern Euboea and in the central mainland. The new deposit that Grecian Magnesite intends to exploit is near the village of Chromio in Western Macedonia. The area of the deposit is about 400 x 250 meters. The deposit has a volume of 8,3 million cubic meters which corresponds to possible resources of **23.3 million tons of olivine**. Based on a systematic sampling campaign the quality is characterized as

healthy olivine. The presence of chromites adds value to olivine due to its refractory properties. A representative chemical analysis of the deposit is of the following chemistry.
SiO₂ 46-48%, MgO 45-49%, CaO 1%, FeO₂ 8%, Cr₂O₃ 0.2 – 1.8%.

Thermolith, S.A. P.O. Box 59, 63100 Polygyrou, Kalyves, 63100 Poligiros, Greece
Telephone +30 237 1054137 Fax +30 237 1054278 info@thermolith.vionet.gr
www.thermolith.gr

The activities of the company are the production and trade of high refractory mixes and industrial minerals (Olivine) for use in the steel production industries (steel plants). The company has very good penetration perspectives in the Balkans. Thermolith S.A. exploits important deposits of olivine, a refractory mineral used in steelmaking as slag conditioner and EBT filler sand, as well as in the manufacturing of shaped and unshaped basic refractory products. Thermolith S.A. produces a wide range of olivine-based products for steel plants. They also produce olivine in various grain sizes for the refractory industry. It is a small but dedicated company.

Rachoni Magnesite Mine, Gerakini (Chalkidiki, Northern Greece) the ultramafic rocks of the area have not only all been subjected to serpentinization, but these rocks have also undergone carbonation, silification and clay alteration (Tzamos, et al, 2020).

Grecian Magnesite, S.A. 45, Michalacopoulou str., GR 115 28 Athens, Greece +30 210 7240446 -7 Email: info@grecianmagnesite.com As the magnesite specialists we proudly are, we offer a wide range of application-specific grades of Caustic Calcined Magnesia, Deadburned (Sintered) Magnesia, Magnesium Carbonate (Raw Magnesite) & Basic Monolithic Refractories for a host-lot of industries; from iron & steel, mining & metallurgy to manufacturing, construction, and the environment.

With more than a million tpa capacity, our Dunite production tops the global competition both in numbers and in quality. This carbon neutral and highly versatile rock is valuable in an array of applications; from blast furnace flux, foundry sand and refractories to blast cleaning, mineral wool and the environment.

Our 40-45% rich in MgO Dunite is also far less costly than any other material nearly matching its properties: dolomite, quartz sand, metallurgical slag and others. For the last several years, we have invested heavily in new Dunite based products, with large scale industrial trials both in-house and at customers sites. We are now proud to offer various Dunite products with a long list of advantages.

Today the main identified deposits of olivine in Greece are in the Vourino Mountain range in Western Macedonia, in Northern Euboea and in the central mainland. The new deposit that Grecian Magnesite intends to exploit is near the village of Chromio in Western Macedonia. The area of the deposit is about 400 x 250 meters. The deposit has a volume of 8.3 million cubic meters which corresponds to **possible resources of 23.3 million tons of olivine.**

Vitruvit S.A. Industrial Minerals Thessaloniki – Verona, 14th km Old National Road, GR 570 11, Greece

Branches in Kalives and Skoumtsa

Thermo Tap hole with optimized grain size distributions

Thermo Tap hole is produced from selected mineral olivine, a refractory mineral with high percentage of Fosterite content and high refractoriness. As a result of long experience and cooperation with the steel making industry, we offer optimized grain size distributions that guarantee free and easy opening of the EBT in Electric Arc Furnaces. Standard production of EBT filler sand is 1-6mm, 2-6mm and 3-8mm.

Slag Conditioner with excellent artificial foamy slag

In electric arc furnace (EAF) applications, olivine when applied as a slag conditioner promotes the development of excellent artificial foamy slag and successfully balances viscosity and volume for efficient Sulphur removal and electrode protection. Olivine is more consistent in quality and aggregate size than calcined materials and shows uniform dissolution during a heat. Standard production of Thermo slag conditioner is 10-40mm.

Olivine Sand as Foundry Sand Olivine is a valuable raw material for use in Foundries as Foundry sand for mold construction in both ferrous and non-ferrous metal casting. Foundry sand from Olivine has an uniform low thermal expansion (0,8% at 1300 °C) resulting in better casting accuracy and smoother surface. Its high heat absorption and conductivity, along with its grain-shape that leads to optimal porosity, help degassing during casting. Olivine is compatible with non-organic binders such as Bentonite, demands small quantity of water and is suitable for use in alkaline resin-bonded system. Furthermore, olivine not containing free silica, contributes to provide a high standard work environment for the workers and a high health and safety performance for the foundry.

Sandblasting Sand Particularly suitable for wet-blasting abrasive systems.

Olivine is a dynamic natural mineral with high abrasion index. Having a hardness between 6.5 and 7.0 Mohs, it is suitable for restoring aluminum, fiberglass, marble/stone facades and wood as well as cleaning and providing a medium profile on steel. It is particularly suitable for wet-blasting abrasive systems, creating an enhanced and high economy slurry blast mixture that leads to advanced performance. Olivine also has the advantage of reduced disposal concerns in some cases.

Summary of Olivine Production and Potential in Part of Europe

Vinita (2020) provided the following list of olivine production and potential in three European countries, Spain, Italy and Norway.

Quarry location	Olivine production	Reserve size/amount	% Olivine content
Spain	0.7 Mt/y	n/a	25-35
Italy	0.25 Mt/y	100 Mt	90-95
Norway	2 Mt/y	6 km ³ ; 25-30 km ³ ; 48 km ² ; 250 million tons (Gusdal mine)	90-95

India

Keala, Kakkaponu Distric, India Unusual dunite: High in Mg, low in Ni

Olivine India Group 1st Floor, NM Arcade, Opp.ARRS Multiplex, Meyyanur, Salem 636009. Tamilnadu, **India**. Phone : +91-427- +91-8489913915/25 (Board Line)
Email :info@olivineindia.com. Olivine Sand has been the Core Product of Olivine India Group as the name itself suggests. We host India's largest state of art manufacturing facility with **5000 Tons a month** manufacturing capacity. Olivine India is undisputed leader in Indian Market with Olivine Sand supplies to Foundries, Steel Mills, Refractory Industries and Multiple Industries for various applications.

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Japan

Japan is the second-largest producer of peridotites for comparison of European olivine sources with worldwide deposits. The sample comes from the Horoman Mine in the Hidaka Province in Hokkaido.

Hokkaido In the Kamuikotan Tectonic Zone, ultrabasic rocks are found as sporadic masses in a long region of about 300 km from northern Toikanbetsu, Teshio Province in southern Mitsuishi, Hidaka province. the zone is characterized by the association of numerous large bodies of ultrabasic intrusives

Hamada A melilite–olivine nephelinite lava flow occurring in Hamada, SW Japan

(Tatsumi et al, 1999). The nephelinite melt is multiply saturated with olivine and clinopyroxene

Shikoku the Murotomisaki Gabbroic Complex is a sill – like layered intrusion of up to 220 m in thickness and is located at Cape Muroto, Kochi Prefecture, Japan. There are several olivine – rich zones within the intrusion, which may have been formed through accumulation of olivine crystals. (Hoshide, T. et al, 2006).

China

Ophiolites are widespread and abundant in China, where they lie along suture zones delineating major tectonic blocks. They are typically tectonically disrupted mélanges composed of isolated blocks of peridotite, gabbro and basalt.

A rapidly expanding database of high-precision age dates and detailed geochemical analyses on Chinese ophiolites is providing new insight into the nature and timing of the tectonic events that shaped this part of Asia.

Oman

Semail Ophiolite, Oman 1.4×10^5 gigatons Deposit Lifetime 1,056 yrs.

New Zealand

Red Hill, New Zealand 871 gigatons olivine est. Deposit lifetime 6.6 yr
The Red Hills ultramafic massif, the South Island, New Zealand, contains a suite of cm-scale shear zones that are composed of dunite, pyroxenite, and olivine websterite.

Dun Mountain is composed of dunite, orthopyroxene peridotite, and serpentinite. Dun Mountain is composed of dunite, orthopyroxene peridotite, and serpentinite. Dun Mountain is a mountain in the Richmond Range near the city of Nelson in the Tasman District of New Zealand's South Island. The mountain is named for its brown (Dun) color. The color is caused by the ultramafic rock which forms the mountain.

Red Mountain area includes a portion of the Dun Mountain Ophiolite Belt, a linear feature which is exposed for at least 170 km in the southern part of South Island New Zealand. The Dun Mountain belt occurs as a series of melanges and tectonic slices with complex structural relationships between mafic and ultramafic lithologies. In contrast, the Red Mountain area comprises a relatively coherent ophiolite sequence in fault contact with surrounding metasedimentary and metavolcanic units.

Russia

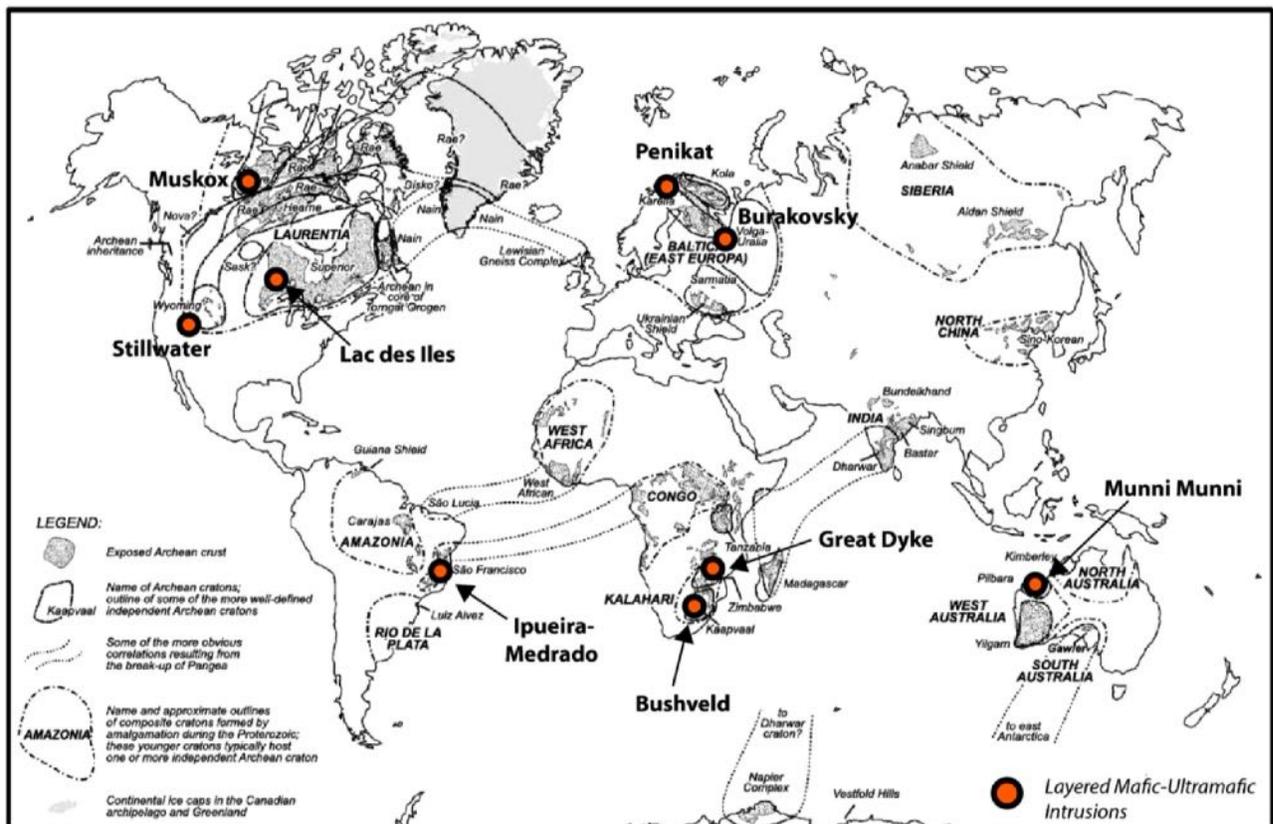
JSC North Urals Dunites is planning to mine dunite as a source of olivine from the Iovinsky deposit in Russia's Ural Mountains, which promises to be the world's second largest project of its kind. Vladislav Vorotnikov, IM Correspondent, discovers how the company is dealing with environmental opposition and the challenge of finding new markets. Mount Konzhak, the site of NUD's proposed Iovinsky dunite mine, is located in the Sverdlovsk region of Russia's Ural Mountains and is a popular recreation spot – a fact which has sparked conflicts over the mine's development.

South Africa

The **Bushveld Igneous Complex (BIC)** is the largest layered igneous intrusion within the Earth's crust. It is approximately 2 billion years old and is divided into four different limbs: the northern, southern, eastern, and western limbs. The Bushveld Complex comprises the Rustenburg Layered suite, the Lebowa Granites and the Rooiberg Felsics, that are overlain by the Karoo sediments. The site was first discovered around 1897 by Gustaaf Molengraaff. Located in South Africa, the BIC **contains some of the richest ore deposits on Earth.** The Complex includes **layered mafic intrusions** (the Rustenburg Layered Suite) and a felsic phase.

Layered Mafic-Ultramafic Intrusions

Djon (2017) referred to the Lac de Iles deposits as **Layered Mafic-Ultramafic Intrusions** and provided the following map of other similar sites throughout the world.

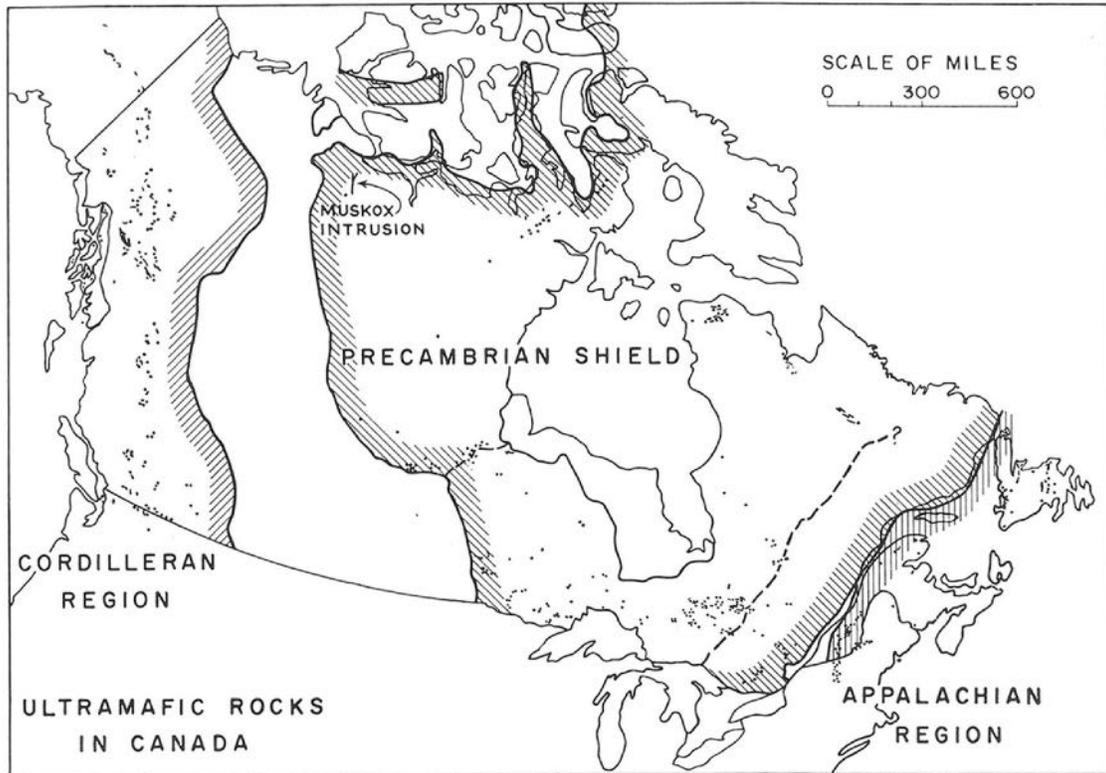


We will take this as a opportunity to include these regions in this listing. Lac des Iles and Stillwater were covered above.

Muskox Intrusion outcrops are in the north- western corner of the Canadian Shield. The intrusion is a Precambrian layered basic pluton, **74 miles in length**. The central layered series is **8500 feet thick** and contains 38 main layers of dunite, peridotite,

pyroxenites and gabbros which vary in thickness from 10 to 1800 feet. The Muskox intrusion has a higher olivine content than would normally be expected (Smith and Kapp, 1963).

31

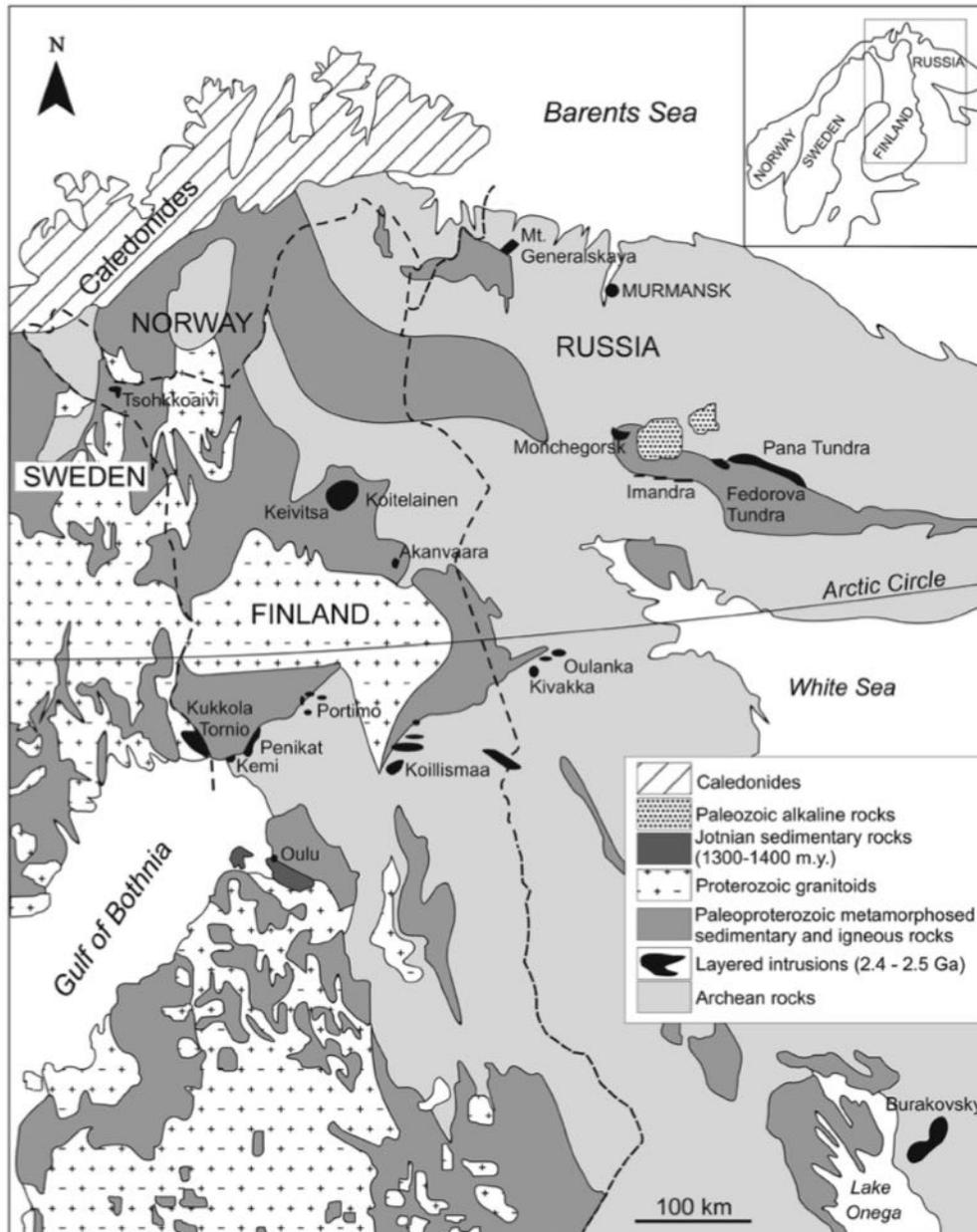


The Muskox Intrusion is in the northwestern corner of the Precambrian Shield

The **Stillwater igneous complex** is one of the world's great layered mafic intrusions, distinguished not so much by its size as by the fact that it is tilted on its side, and **erosion has exposed the layering to ready access**. It is a large layered mafic intrusion located in southern Montana in Stillwater, Sweet Grass and Park Counties. The complex is exposed across **30 miles** of the north flank of the Beartooth Mountain Range. The complex has extensive reserves of chromium ore and has a history of being mined for chromium. More recent mining activity has produced palladium and other platinum group elements. The Basal zone is composed of a variety of rocks, including: Cumulates, principally orthopyroxene cumulates but with minor amounts of one- and two-phase cumulates **dominated by olivine**, orthopyroxene, clinopyroxene, inverted pigeonite, and plagioclase.

The **Penikat** layered ultramafic-mafic intrusion in Northern Finland is one of the most richly mineralized layered intrusions on Earth.

The **Burakovsky layered complex**, consisting of 2,430 Ma, is located in Karelia, Russia, is one of the largest layered Fennoscandian intrusions. It consists, from the base to the top, of a thick ultramafic part **dominated by dunite and peridotite** overlain by a layered mafic part that consists of alternating layers of pyroxenite, wehrlite and gabbro (Transitional Banded Zone, TBZ), and a thick sequence of gabbroic rocks [Gabbronite Zone (GNZ), Pigeonite Gabbronorite Zone (PGNZ), Magnetite Gabbronorite–Diorite zone (MGDZ), which predominates (Bailey et al, 2011).



Schematic geological map showing the location of the main Paleoproterozoic layered intrusions in the Fennoscandian Shield (after Alapieti & Lahtinen 2002).

The **Great Dyke** is a linear geological feature that trends nearly north-south through the centre of Zimbabwe passing just to the west of the capital, Harare. It consists of a band of short, narrow ridges and hills spanning for approximately 340 mi. The range is host to vast ore deposits, including gold, silver, chromium, platinum, nickel and asbestos. The Great Dyke of Zimbabwe is unique within the family of large-layered intrusions by virtue of its highly elongate form.



NASA Image

It is rich in chromite which is enclosed in cumulus olivine high in Fe^{2+} .

The Bushveld Complex is the world's largest layered intrusion, and because of its unique character most other layered intrusions are compared with it. The Bushveld Complex, as exposed at current levels of erosion, consists of eastern, western and northern limbs, and is some seven to nine kilometres thick. Despite its **size the amount of olivine is limited**.

The **Munni Complex** is a layered sequence of clinopyroxenite, peridotite, and gabbro within the Archean Pilbara Block, Western Australia. The intrusion has been tilted, exposing some 2000 m of layered ultramafic rocks overlain by over 3500 m of gabbroic rocks.

Ophiolite Sites around the World from Wikipedia

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.

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]

Mexico and the Caribbean

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

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

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

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]

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(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)

For Appendices D to H see

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Appendix D see the Musk Prize page

Appendices E-H page

Appendix E Bay Engineering Inc

Appendix F Vertical Axis Wind Turbines (VAWT)

Commercial VAWT's with 5 kW+

Appendix G Final Stage Grinders

Appendix H Photovoltaics on Floats

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