

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

All of the premier organizations dedicated to combating climate change have concluded that in addition to reducing CO₂ emissions, it will be necessary to also remove CO₂ from the atmosphere to avoid an excessive rise in the earth's temperature. This is not meant to minimize the need to cut emissions. Both approaches are needed. The concepts involved are called NET's or Negative Emission Technologies and could remove up to 10 GtCO₂/y globally by midcentury and 20 GtCO₂/y globally by the century's end (NAS 2018b).

CCS, CCUS. One of the most common proposals is **Carbon Capture and Storage (CCS)**. This involves the capture of CO₂ produced in association with the burning of fossil fuels involved the production of electricity, especially coal-based power plants followed by the sequestration of the CO₂ into various underground storage sites. A modification of this approach is **CCUS (Carbon Capture Use and Storage)** where the captured CO₂ is put to a variety of uses and the excess sequestered. A major problem with these approaches is that there are serious concerns about the permanence and safety of the sequestered CO₂. Some sites may be ideal, but others may leak, resulting in the sudden release of massive amounts of CO₂ back into the atmosphere. This is reminiscent of the release of many tons of CO₂ from Lake Nyos in Cameroon in 1986 that killed 1200 people. This was possible because CO₂ is heavier than air and spreads over land like a carpet of death.

In addition, it is doubtful that there are sufficient geologically suitable sites to bury the billions of tons of CO₂ produced by coal burning power plants each year.

As pointed out by Mann (2020) a common place for sequestering the CO₂ is oil wells. The recovered oil, when burned, yields several times as much CO₂ as was sequestered in the first place.

Finally, this process is only about 90% effective in removing the CO₂ produced, leaving millions of tons still being released. (Mann, 2020).

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

First, the storage part has the same disadvantages as above, with CCS and CCUS, namely concerns about the safety and permanence of the CO₂ storage. Injection of CO₂ directly into mafic rocks (in situ sequestration) may be a way around this.

Second, these techniques are very expensive.

Finally, both **CCS**, **CCUS** and **DCCS** have the disadvantage that they do not address three other serious problems with climate change and greenhouse gases:

1. Ocean acidification.
2. Atmospheric NO₂
3. Atmospheric Methane

What the Ideal CO₂ removal technique should accomplish.

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

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

We believe that the NET that satisfies all of these conditions is: **Enhanced Weathering using Croplands and Oceans**

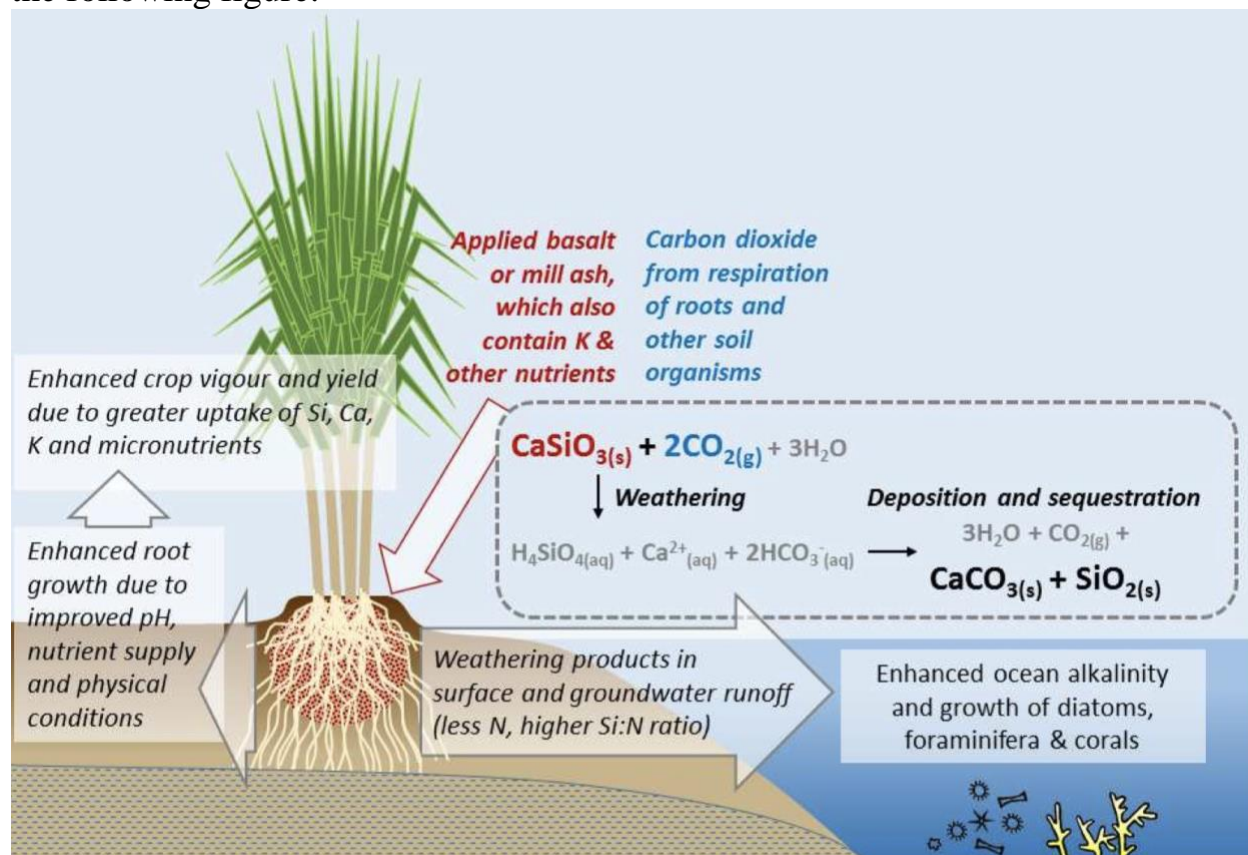
The following is a review of this technology as presented on our website – The Comings Foundation -> 3 Negative Emission Technology ->

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

While this technology is based on the work of many others, we are proposing to put it all different aspects together to start an actual working project in the Midwestern (for crops), at the coasts (for oceans) and possibly at other sites around the world.

Enhanced Weathering using Cropland

A form of accelerated weathering (EW) that improves its desirability as a NET is spreading ground-up mafic 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) and is outlined in the following figure.



Concept of farming with crops and rocks by Beerling et al (2018) especially using olivine $(\text{Mg,Fe})_2\text{SiO}_4$.

In soils, chemical breakdown of silicate rocks is accelerated during aqueous reactions with the elevated soil CO_2 environment, releasing base cations (Ca^{++} and Mg^{++}) and delivering bicarbonate (HCO_3^-) anions via runoff to surface waters and eventually the ocean. Enhanced weathering, therefore, also uses the oceans to store atmospheric CO_2 as these stable dissolved inorganic alkaline forms. Given the oceans worldwide store around 38,000 Pg* C (38,000 gigatons) >45 times the mass of C in the current atmosphere. The residence time of dissolved inorganic carbon in the global ocean is around 100,000 – 1,000,000 years, making it essentially a permanent C-storage reservoir on human timescales. The residence time for enhanced weathering using croplands is many, many years.

* Pg = pentagrams = 10^{15} grams = 10^9 tons or one gigaton.

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.

Is EW Sequestration of CO₂ on Croplands Possible in the United States?

The emphasis in the present review is on the potential role of Enhanced Weathering using Cropland and Oceans in the United States. The US Geological Survey published two important documents: USGS (2019) and Blondes et al, (2018). These documents reviewed other 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.
2. CO₂ Mineralization: Injection of CO₂ **into rock formations** deep underground for underground mineralization. This is termed *in situ* storage.
3. CO₂ Mineralization: Exposure of CO₂ to **broken or pulverized pieces of rock at the surface**, using leftovers from mining, called mine tailings.
4. CO₂ Mineralization: Spreading **pulverized mafic rocks onto croplands**.
5. CO₂ Mineralization: Spreading **pulverized mafic rocks onto the beaches or ocean**.

Because of the the potential danger of the escape of the CO₂ for #1, our emphasis will be on 4 and 5. The relevant questions are:

Where are the relevant mafic and ultramafic rock deposits in the US?

Are they close enough to the crops to be treated to be economically viable?

As a note: **Ma** = magnesium **fic** = ferric iron.

Mafic relates to a group of usually dark-colored minerals rich in magnesium and iron. They are dominated by **plagioclase** and **pyroxene**.

Plagioclase is the name of a group of feldspar minerals that form a solid solution series ranging from pure albite, $\text{Na(AlSi}_3\text{O}_8)$, to pure anorthite, $\text{Ca(Al}_2\text{Si}_2\text{O}_8)$.

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.

Common mafic rocks include **basalt**, **diabase** and **gabbro**.

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

Olivine

The most common ultramafic rocks are **olivine**, **dunite**, **periodite**, and **serpentine**. Dunite is best because it 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**.

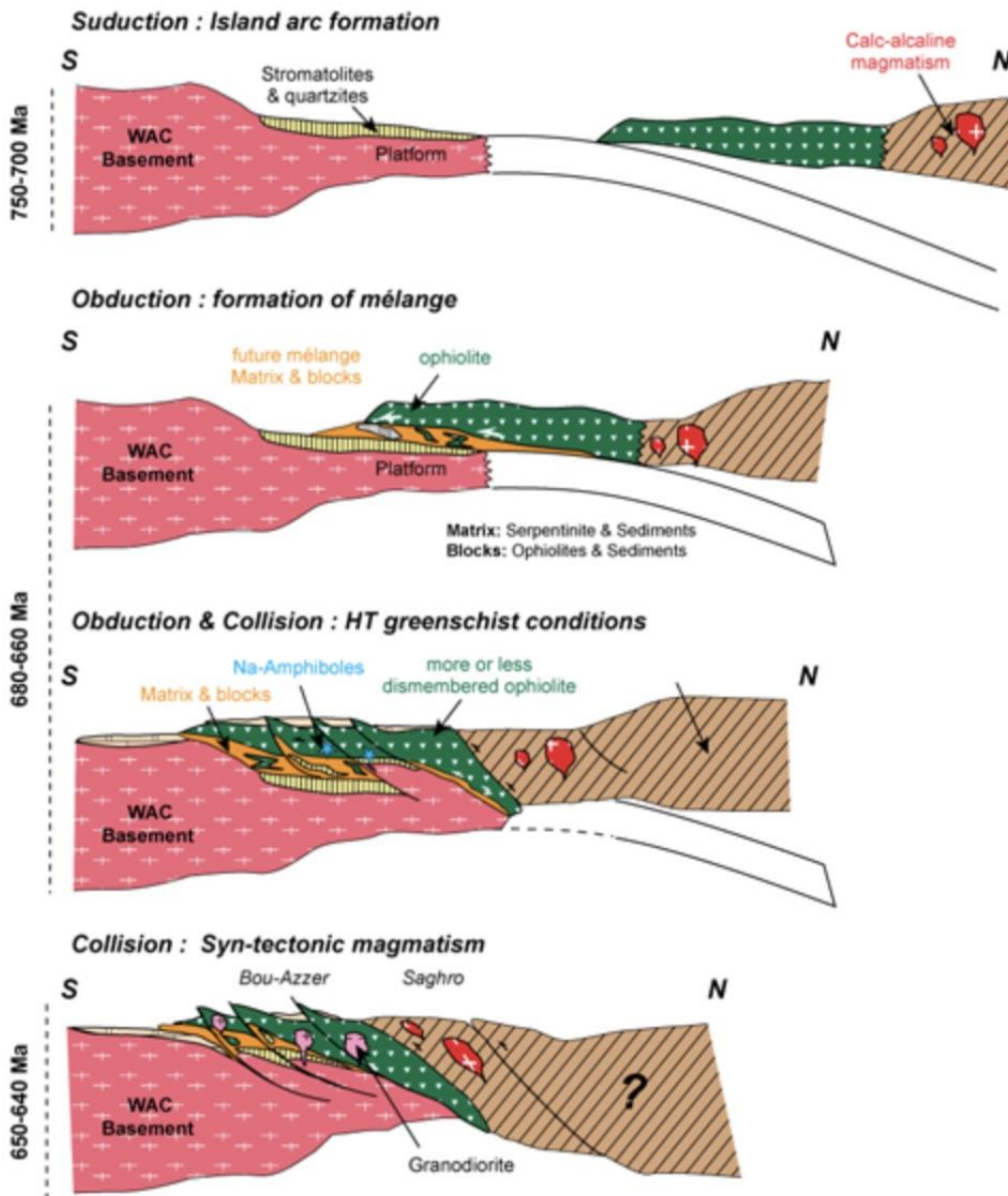
The following is a photo of my personal olivine-basalt that I purchased from a rock shop in Southern California.



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

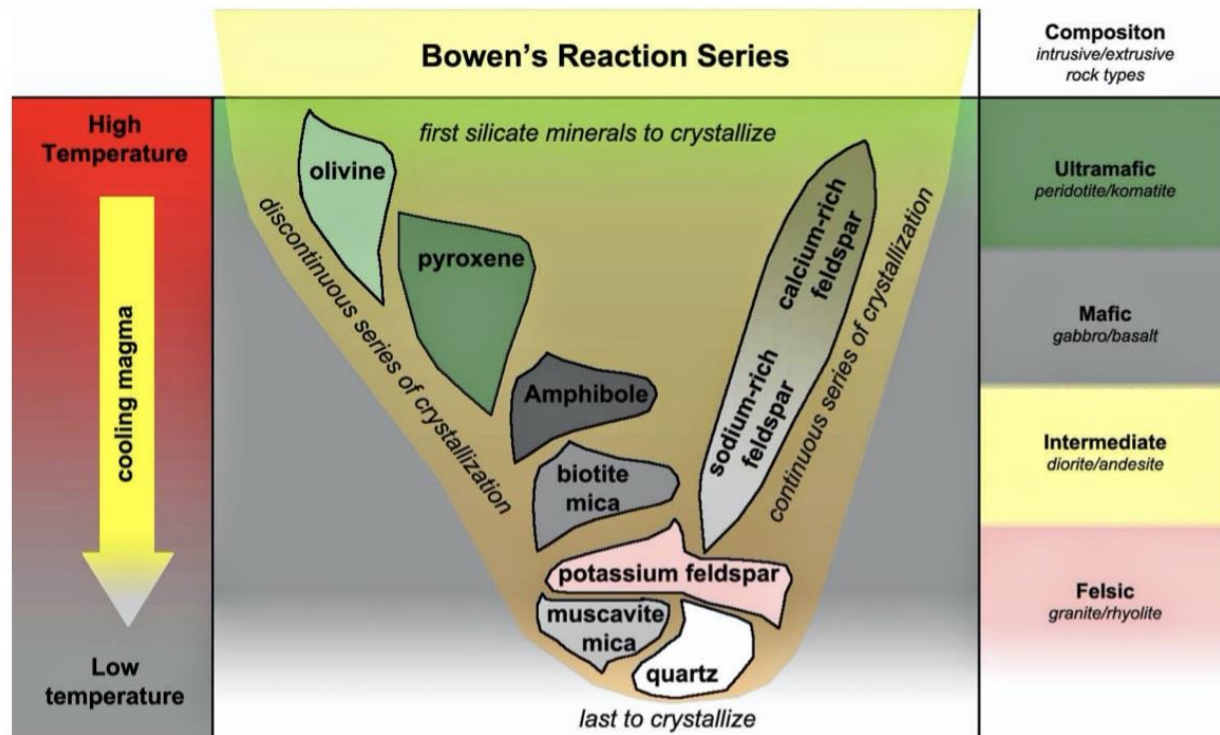
For those doing research on olivine reserves, if one searches for olivine, they will typically find only limited results. What to look for instead are the **ophiolites**. Ophiolites have an entire layer of olivine as the 90% pure form, dunite. And to further make it complicated to find olivine reserves,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

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



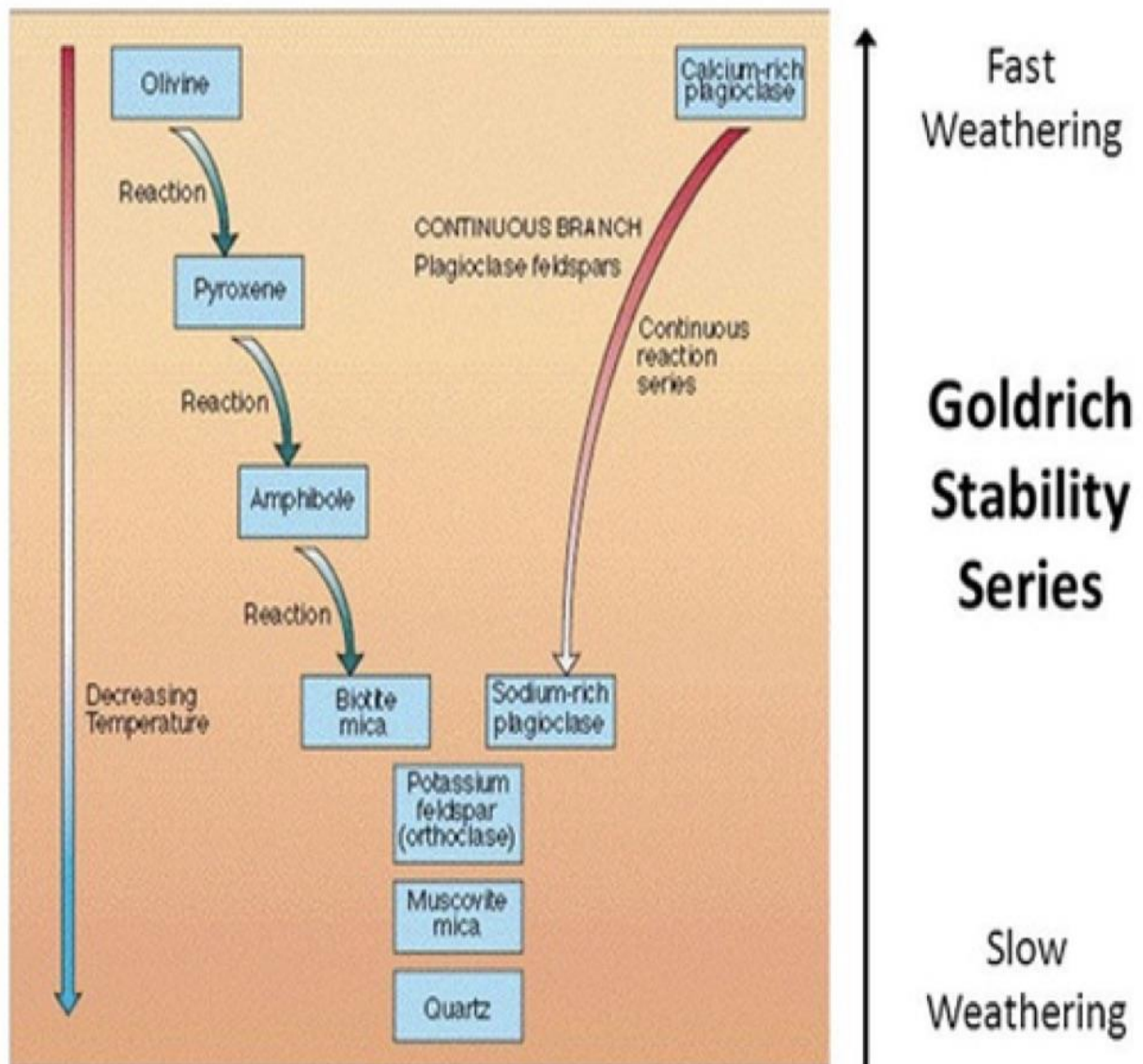
Model for the emplacement of the Bou-Azzer ophiolitic suite.

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



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

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



The relevant equation for sequestration of olivine is:

$$\text{Mg}_2\text{SiO}_4 + 4\text{CO}_2 + 4\text{H}_2\text{O} \Rightarrow 2\text{Mg}^{++} + 4\text{HCO}_3^- + \text{H}_4\text{SiO}_4$$
 Thus, one mole of olivine can sequester 4 moles of CO_2 .

Effect of pH on Olivine Weathering

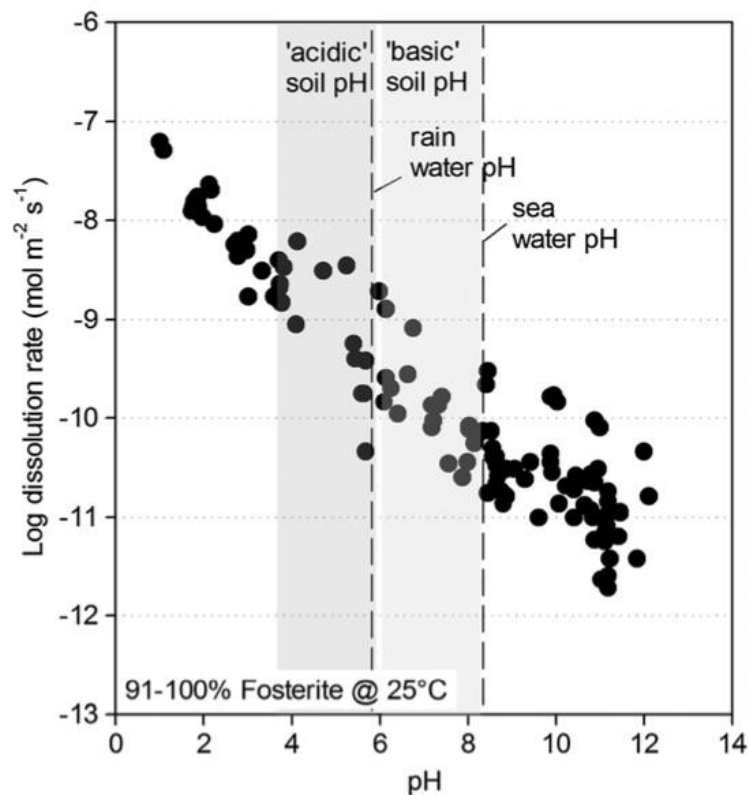
The following table shows the relative rate of weathering of olivine versus three other silicate minerals (basalt not included) at different pHs. Clearly olivine at pH 4 weathers very rapidly.

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 ($\text{mg m}^2/\text{day}$) obtained in the experiments of Franke & Teschner-Steinhardt (1994).

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

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

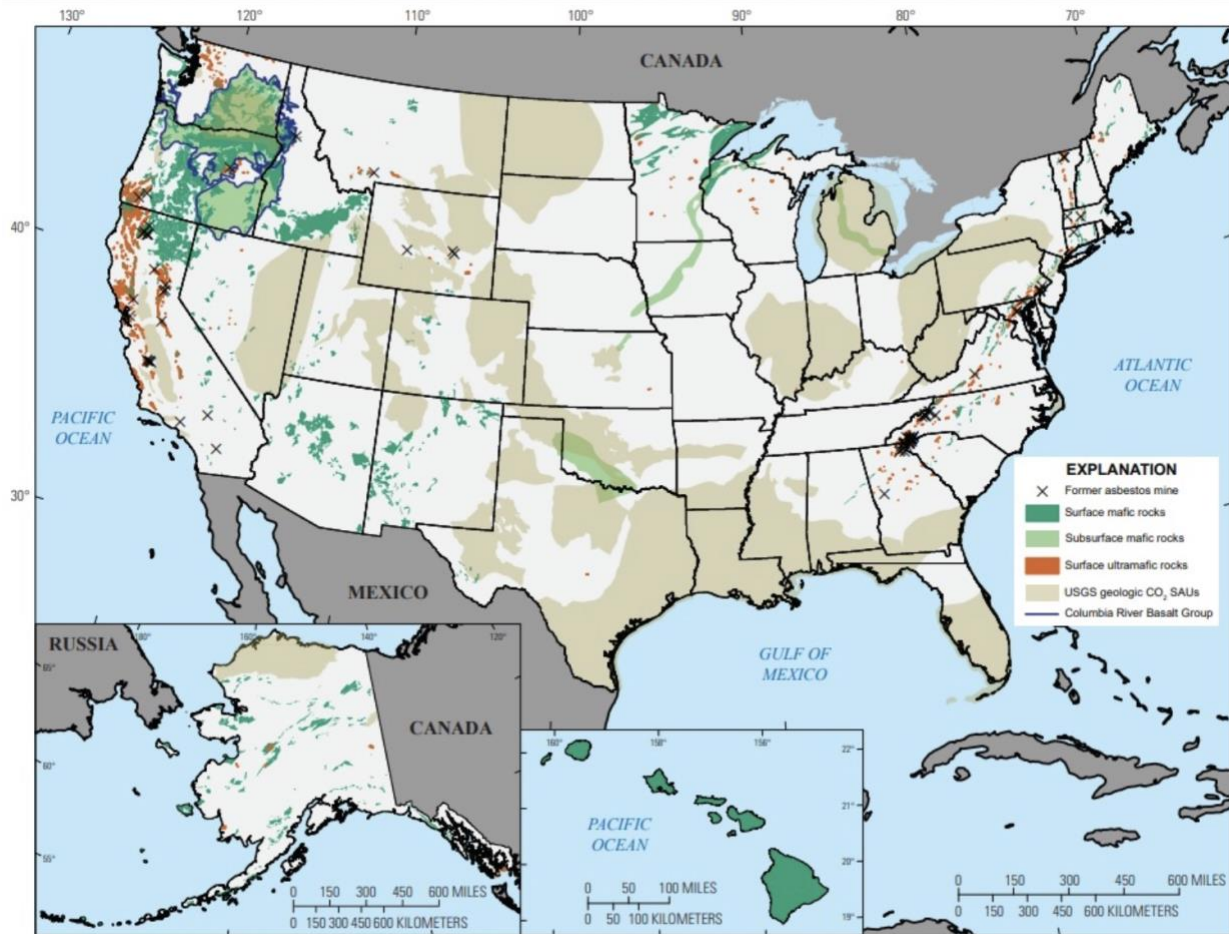


Dependence of olivine (fosterite) dissolution on pH
Figure from Hartman et al (2013)

The current average pH of ocean water is 8.1 while that of soil is 4 to 6. As can be seen, olivine dissociates ten to one hundred times faster at the pH of soil than the pH of seawater. Fosterite is a 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.



U.S. Geological Survey (USGS) geologic carbon dioxide (CO₂) storage assessment units (SAUs) were defined in the USGS national assessment of geologic CO₂ storage resources (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013) to estimate CO₂ storage potential in saline reservoirs within sedimentary basins.

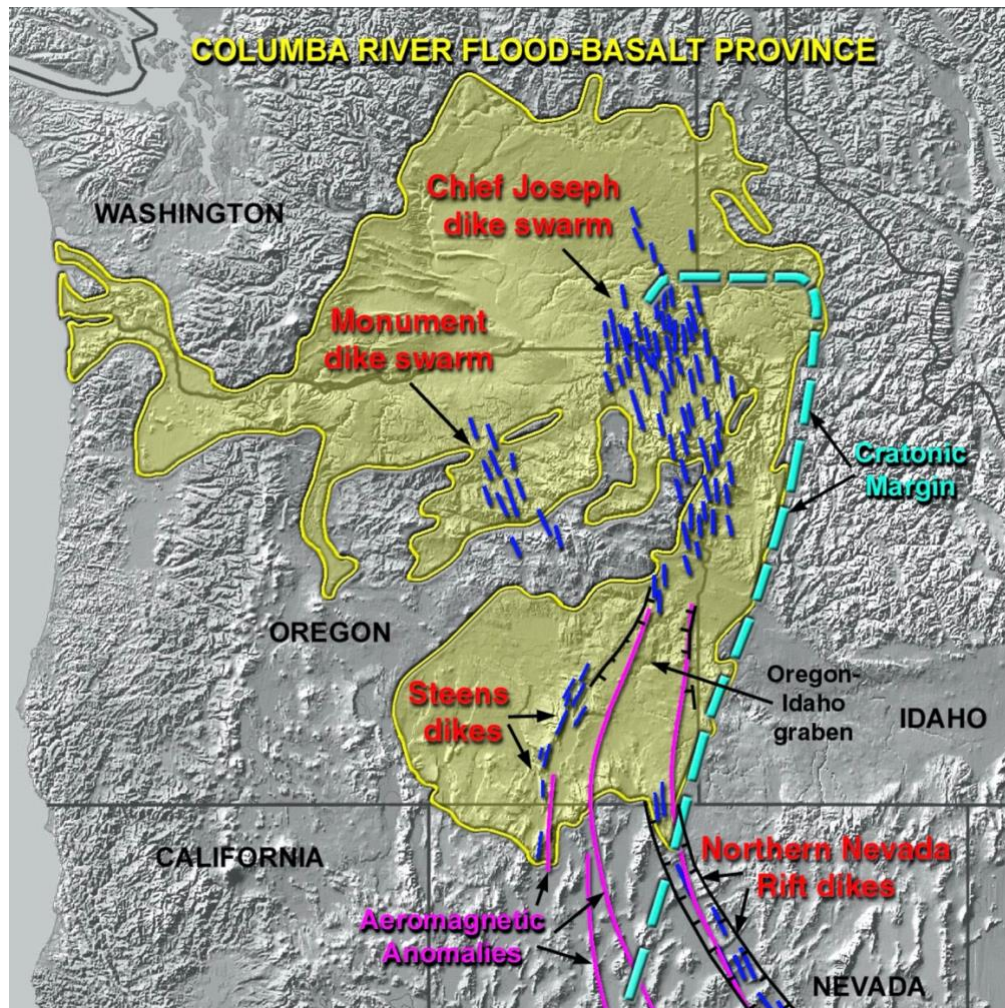
It is clear that the vast majority of the surface mafic and ultramafic rock deposits are in the Western US – Washington, Oregon and California and Hawaii. The sites in the Midwest (in light brown) are deep underground and presumably not economically viable for *ex situ* mineralization. All of Hawaii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

The following map is a clearer presentation of just the ultramafic (olivine) rocks in the U.S.



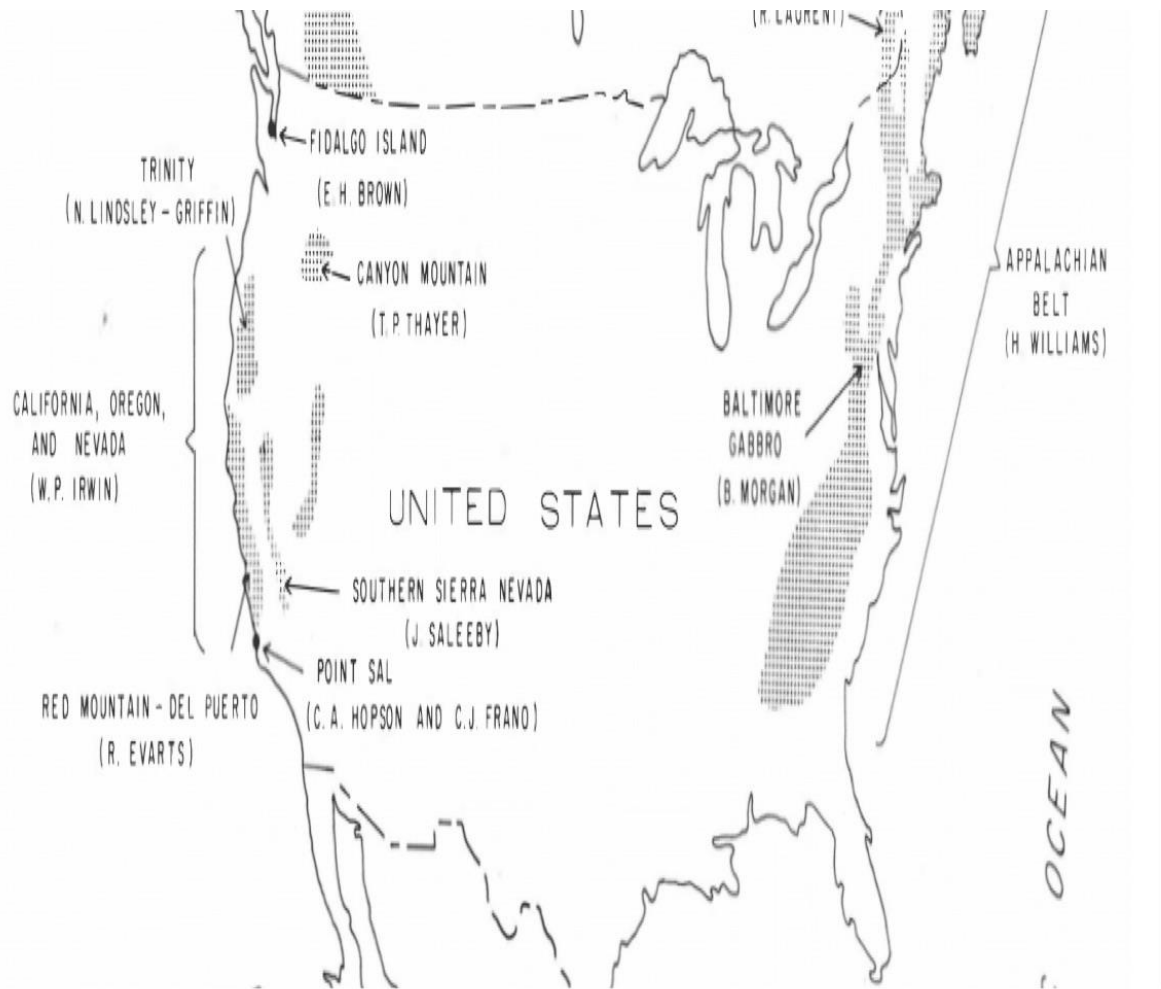
Ultramafic rock deposits in the U.S.

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



Columbia River Flood Basalt

Additional detail about olivine deposits is shown in the U.S is shown in following map (Project Vista).



This shows the olivine deposits on the west coast and the east coast. Goff et al (2000) 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.

These maps raise the question of whether the distance between olivine deposits in the U.S. and Midwest farmland are too great to allow for the economic application of enhanced weathering in most of the U.S.

Where are the Olivine Mines Worldwide?

The following map shows the location of olivine mines worldwide.



This is highly relevant to the fact that olivine weathers more rapidly in warm, humid weather.

Is the supply of olivine too limited for widespread EW?

A major sticking point for the use of olivine is “How much olivine is mined worldwide each year?” Total world production of dunite, serpentinite and olivine has been estimated to be over 8 Mt a year, of which about 4 Mt a year is estimated to be ‘pure olivine’ (Rudi 2001; O’Driscoll 2004). About 3.3 Mt of olivine is consumed annually in Europe. Most of this is supplied by Norway, which is the dominant producer. Other producers include Italy, Japan, Mexico, Pakistan, Spain and the USA.

If we need to remove up to 38 billion tons of CO₂ per year, 8 Mt/year of olivine would not be enough. This could be a major reason why basalt also needs to be used. The supply of basalt is huge. However, due to low current demand for olivine relative to the proven reserves, **many dunite reserves and ophiolites are currently not being mined**. Many areas are not even fully mapped. Olivine is one of the most abundant minerals on earth. It seems clear that a shortage of olivine will not be a limiting factor for EW.

Where to get Commercial Olivine or Basalt

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

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

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

The U.S. production of olivine in 1999 was 90 metric tons/yr. The production in Norway was 6,300 metric tons/yr. It was mainly used in foundries for slag conditioning and foundry sand. The two U.S. companies that produce olivine are **Unimin Corp** (North Carolina and Washington) and **Olivine Corp** (Washington). The **reserves in the Smokey Mountains, North Carolina are about 200,000 million metric tons**, while the **reserves in Washington** are about 17 million metric tons. The total world production of olivine was approximately **8 million metric tons in 1999**. An additional large olivine site is **Twin Peaks, OR** (Lackner, 2002). Huge deposits are in the Oman coastal range.

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

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

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

Weathering by Type of Land

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

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

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

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

This shows that there is indeed a significant increase in sequestration of CO₂ by location and type of land. **Sequestration is 29 times greater in tropical wetlands than in temperate dry lands**, and 2.4 times greater in the tropic wetlands than temperate wetlands.

Is this a project killer for efforts to institute EW in the Midwest? Not necessarily. Application of the dunite-olivine in the warm summer months could maximize sequestration.