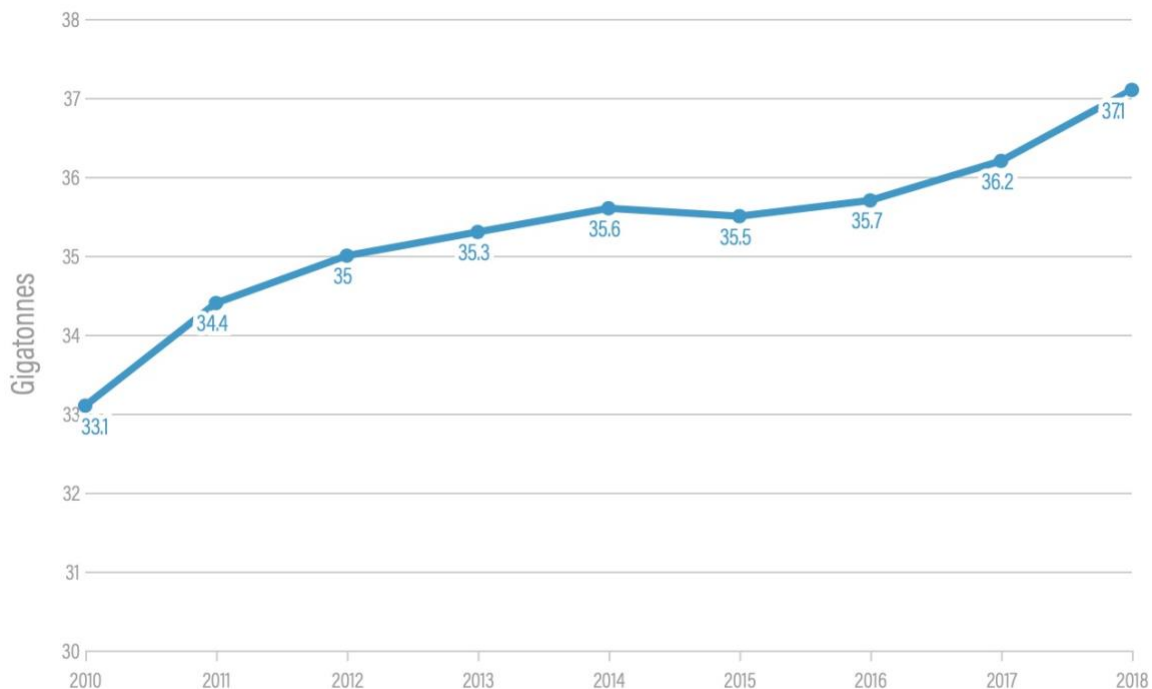


How much of the Problem of Removing CO₂ from the Atmosphere can be solved by Enhanced Weathering?

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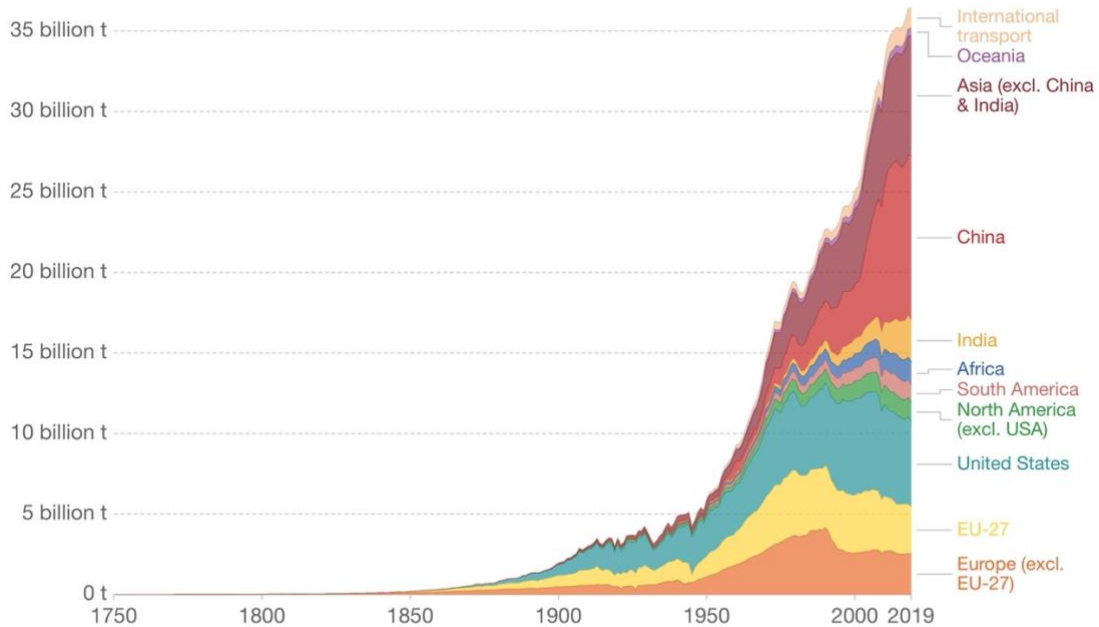
The rate of emissions appeared to be leveling off from 2014 to 2016, but then increased significantly from 2016 to 2018. The levels in 2019 were **36.8 gigatons**. They were anticipated to drop by at least 7% in 2020 due to the pandemic.

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.

The following figure shows the contribution of each major country.

Annual total CO₂ emissions, by world region

This measures CO₂ emissions from fossil fuels and cement production only – land use change is not included.



Source: Our World in Data based on the Global Carbon Project OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY
 Note: 'Statistical differences' included in the GCP dataset is not included here.

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

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

So, how much is a PgCO₂?

As shown below, we often see a statement like “could perhaps extract 0.5–4 PgCO₂/yr, by 2100.” It is not immediately obvious how much a PgCO₂ is. Did the P stand for pentagram (10^{15}) or picogram (10^{12})? The table above indicates that the symbol for a pentagram is P, while the symbol for 10^{12} is T. The definitive answer came from Canadell and Schulze (2013). They stated that:

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

So how much is a ton of C?

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

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

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⁻¹/yr to 70×10^6 ha of the annual crops corn/soy in the corn belt of North America could sequester 0.2–1.1 PgCO₂, 0.2 or 1.1 gigatons up to 13% of the global annual agricultural emissions, in the long run.

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

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

c) Strefler et al (2018). Our results show that enhanced weathering is an option for carbon dioxide removal that could be competitive already at 60 US \$/t CO₂ removed for dunite, but only at 200 US \$/t CO₂ removed for basalt. The

potential carbon removal on cropland areas could be as large as **95 Gt CO₂/year for dunite** and 4.9 Gt CO₂/year for basalt. The best suited locations are warm and humid areas, particularly in India, Brazil, South-East Asia and China, where almost 75% of the global potential can be realized.

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

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

Some Approaches to EW Short of Massive Spreading of Rocks on Soils

The above review shows that the approach to EW that involves spreading rocks of cropland is a massive undertaking. This raises the question: Are there some approaches to EW that are not as difficult? Two possibilities come to mind—attempting to save the great barrier reefs and improving yields of rice farms.

A. Addressing the Problem of the Destruction of the Great Barrier Reef in Australia. Because of the distances involved, this problem would be best addressed by placing olivine into the waters near the Great Barrier Reef. To do this, we will need to get the olivine from Australia. Researching this was not easy. The following is why.

1. The first search response was: **Mortlake is one of the world's hotspots for olivine and Australia's olivine capital.** The olivine of Mortlake formed around 70 - 80 kilometers below the ground and was brought to the surface during volcanic eruptions. Much of the olivine around Mortlake is contained in what are called 'bombs' which look like tear drop shaped lumps of rock. These 'bombs' range in size from something as small as a pigeon's egg to ones as big as a car. When searching for olivine it's merely a matter of finding a 'bomb' and then cracking it open with a hammer. About 90 per cent of olivine is an olive-green color.

2. A second search response was: The only known olivine occurrence in New South Wales is the **Doonba deposit near Barraba**. This body was identified during regional exploration for chrysotile asbestos as one of numerous discrete bodies of relatively un-serpentinised harzburgite within an extensive zone of serpentinised harzburgite. Later, Breyley (1990) identified the rock type as dunite. Consequently, additional fresh, commercially acceptable olivine deposits could occur in this or other ultramafic belts, even among bodies mapped as harzburgite.

3. A third possibility was referenced in NAS (2018) showing the following figure and where the source is mine tailings.

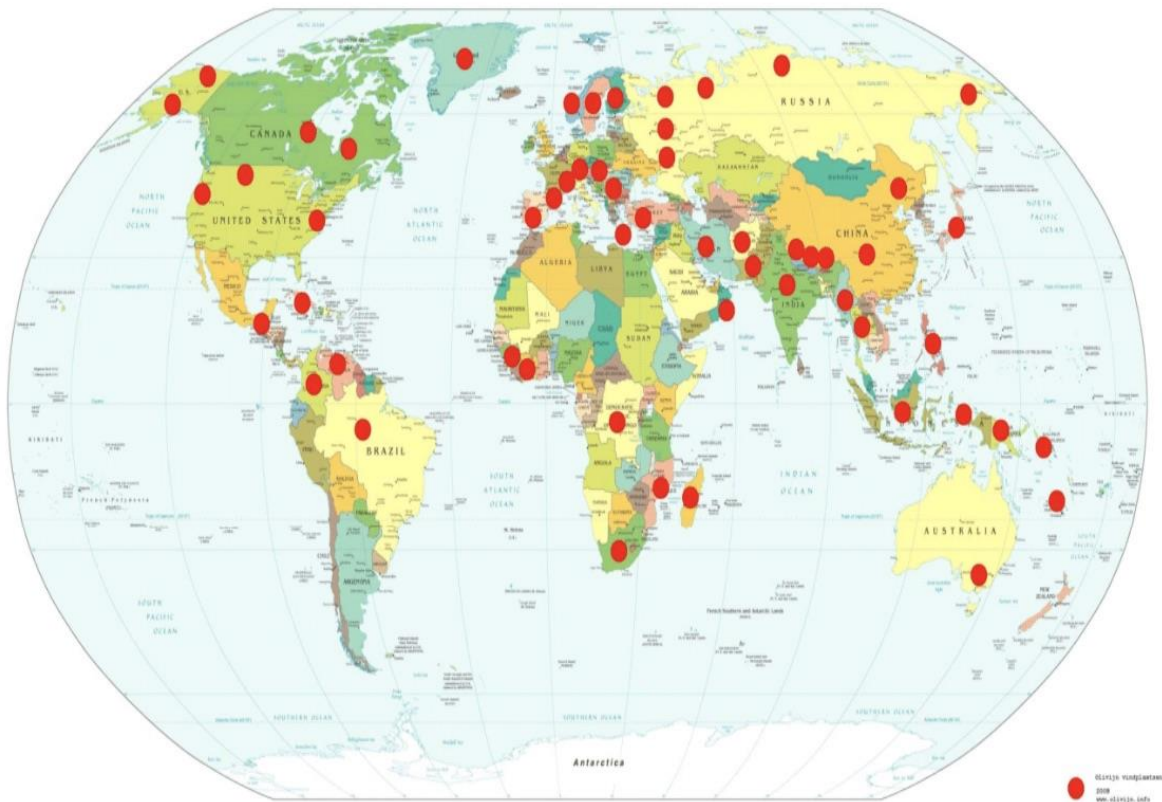


Cementation of tailings originally deposited as water-sand slurry. LOCATION: Mt. Keith Nickel Mine, WA, Australia.
Greg Dipple

4. A fourth search response was: The **Doonba** dunite deposit, north of Tamworth, is the only known New South Wales olivine deposit of commercial potential. This belt is dominated by harzburgite that is variably sheared and extensively to completely serpentized. The Doonba mass is important in being more olivine-rich and significantly less-serpentized than is typical of ultramafic rocks elsewhere in that belt. The economic potential of the Doonba deposit was recognized during the Manilla–Narrabri Metallogenic Map project (Brown et al. 1992). The resource is currently being explored and tested for various refractory applications in the steel industry and for use in agriculture.

So, what is the problem? Although both are north of Sydney, Barraba and Tamworth are an hour apart. When I search under “commercial mining of dunite or olivine in Australia” I get response #2 above. When I search under commercial mining in Australia, many different minerals are listed but not olivine or dunite. It looks like there is not much in the way of mineable olivine or dunite in Australia.

However, if the supply of olivine is too limited in Australia to combat ocean acidification what about the surrounding areas? The following is a map showing the worldwide distribution of olivine.



Dunite Massifs around the world. Dunite is a formation of greater than 90% olivine

It is clear that there are a number of olivine deposits immediately north of Australia that could be used for this purpose.

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

since production increases will, come from yield increases because of lack of available land.

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

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

Who can do the research and answer the questions listed below?

Three of the co-authors of the Beerling et al paper, Stephen P. Long, Evan DeLucia and Ilsa Kantola were from the Carl R. Woese Institute for Genomic Biology and/or the Department of Plant Biology, both at the University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. (which happens to be where I took my undergraduate work) We could use grant funds to enlist them to study the above questions. The more long-term goal is to implement the widespread use of finely ground basalt or olivine on large tracts of cropland in the United States Midwest.

An additional person to contact would be Joshua West, second author on the Hartman et al (2013) paper. He is located just around the corner from the Comings Foundation at the Department of Earth Sciences, University of Southern California, Los Angeles, California, USA.

Questions that need to be Answered about weathering on cropland

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

1. How can a modest sized foundation, currently with \$1 to \$5 million to distribute each year, and possibly \$25 million later, best contribute to getting enhanced weathering of either crops or the ocean, started in the United States?

2. If our consultants had these funds what are the initial and subsequent steps they would take?

To begin this process, we propose to provide grant funds or funds for consultants, to answer the above questions, and many more below. Beerling et al (2020) stated - there is an urgent need to address unanswered technical and social questions and develop rigorous audited testing in the field where the full elemental cycles can be closed, efficacy of CO₂ capture quantified, and the risks, benefits, socioeconomics, techno-economics, and ethics assessed. This is what we would like to assist with.

Below is a list of some of the additional questions.

- Which is better to use, olivine or basalt, in EW of crops in the U.S.?
- Where are stockpiles of aggregate waste mafic rocks that can be used?
- As stated by Beerling et al (2020) national inventories of the location, availability and extent of this resource are required to assess the potential contribution of this resource for ERW. We need to develop a US inventory.
- Where in the US can olivine be obtained? The above provided only a partial answer.
- Would it be cheaper to purchase commercially available olivine in the United State or Norway?
- How much would cost per ton CO₂ be if solar or wind energy, or other renewable, was used for grinding?
- Should there be a centralized facility for mining and processing olivine or basalt? If so, where?
- Could carbon free sources of energy (solar, wind) be made available in these areas?
- How to get farmers to switch from lime to basalt?
- 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?
- What are the governing (regulation) issues, if any?
- If non-cropland is used, what is the thickness of the spread olivine or basalt that still effectively sequesters CO₂?
- Once we answer some of these questions, what are the prospects of spreading this technology to other countries?
- Some countries have better supplies of olivine. Would it be better to start in those countries?
- Hartman et al (2013) proposed that EW takes place much more rapidly in humid tropical countries. This would require setting up a lot of new infrastructure in humid lands. What are the implications of this for doing EW in the U.S.?
- As described below, one source of power to grind the rock could come from a Solar Chimney Power Plant (SCPP). This also has the potential of combining this

with a Photo-Catalytic Reactor (PCR) to also remove methane. Question: Can we engage an engineering company to build and test SCPPs. Will they work in the Midwest? Will using PCR really remove methane? If so, how much?

- The map on page 16 shows the worldwide distribution of olivine mines. Given that olivine weathers much rapidly in warm humid weather would it be possible to pick areas that a) mine olivine and b) are located in regions with warm humid weather to focus on EW of crops or non-croplands?
- In warm and humid areas, how thick can one coat non-croplands with olivine and still have efficient weathering? If the answer is a significant multiplier of the amount spread on cropland, this could dramatically enhance the prospects of EW as a solution to global warming. If carbon credits are in place, that could pay for using noncroplands.
- What role can cooperative working with the U.S. Dept of Agriculture play in assisting with EW?

Questions about Putting Mafic rocks directly into the ocean.

- 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?
- A second important question who can we support to help us with a project of putting mafic rocks directly into the ocean? Can the University of Illinois group help us with that?
 - The ocean approach has the advantage of directly combating ocean acidification and of by-passing the potential problems of obtaining the cooperation of farmers and spreading the rocks over large areas of cropland. Of course, both approaches can be used.
 - Dissolution of olivine is 10 to 100 times slower at ocean pH than soil pH. Does this seriously impair the use of placing olivine directly in the ocean, or does it simply take longer?
 - Hartman et al (2013) emphasized the need for infrastructure to transport basalt or olivine over distances and the carbon cost of this. Isn't this a good reason to emphasize direct spreading pulverized olivine in the ocean?
 - If olivine was ground up and spread in the ocean off the west coast of the U.S. how long would it take for the decrease in acidification to spread to, for example, the Great Barrier Reef?
- 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. Is this conclusion valid? Does that rule out using basalt?

- 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 these be used?
- Since the largest deposits of olivine in the U.S. are on the West and East coast of the U.S. would these be better sites to begin our ocean projects?
- Can one or both of the U.S. olivine companies be of assistance? Utilizing these companies could solve the problem of where to get the olivine for enhanced weathering using the ocean or croplands.
- An overriding major question is: How much CO₂ can be sequestered per year combining the use of cropland and non-cropland in the US, India and China, and other countries, plus the oceans? Beerling et al (2020) hopes to achieve an average global goal of 0.5 to 2 gigatons of carbon dioxide (CO₂) per year by Enhanced Weathering of Croplands worldwide. Worldwide 38 gigatons of CO₂ were released in 2019. (Bill Gates says the figure is 51 gigatons). Thus, EW using croplands would account for only about 4% to 6% of the needed CO₂ sequestration. How much more can be sequestered by using the oceans? Or, by using non-croplands.
- The world’s largest active olivine quarry is the Gusdal Pit in Norway (see above). No chemicals are needed to extract the rock, nothing is underground, the process is not mining, it is surface extraction. This raises the possibility of purchasing olivine on site, ensuring it is finely ground, and immediately distributing it into the ocean. Is this reasonable?
- One of the most pressing reasons to place olivine directly into the ocean is to combat ocean acidification and, among others, save the Great Barrier Reefs off Australia. Would it make more sense to disperse the olivine near the Great Barrier Reef itself? If so, are there adequate olivine deposits in or near Australia to accomplish this?

A Short Course in Mineralogy

Because of the wide number of minerals mentioned 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. Common mafic rocks include basalt, diabase and gabbro.

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

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

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

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

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

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

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

Aragonite is a carbonate mineral, one of the three most common naturally occurring **crystal forms of calcium carbonate**, $CaCO_3$ (the other forms being the

minerals **calcite and vaterite**). It is formed by biological and physical processes, including precipitation from marine and freshwater environments.

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

Diopside is a rock-forming pyroxene mineral with a chemical composition of $\text{MgCaSi}_2\text{O}_6$. 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.

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

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 $\text{Na}(\text{Al},\text{Fe}^{3+})\text{Si}_2\text{O}_6$

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

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

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

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.

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, $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$.

References

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

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

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

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

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

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

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

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

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

Blondes, M.S., Merrill, M.D., Anderson, S.T., and DeVera, C.A., 2019, Carbon dioxide mineralization feasibility in the United States: U.S. Geological Survey Scientific Investigations Report 2018–5079, 29 p., <https://doi.org/10.3133/sir20185079>.

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

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

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

Co2.earth (2014). <https://www.co2.earth/global-co2-emissions>

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

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

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

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

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

Goff F, Guthrie G, Lipin B, Fite M, Chipera S, et al. (2000). Evaluation of Ultramafic Deposits in the Eastern United States and Puerto Rico as Sources of Magnesium for Carbon Dioxide Sequestration. Rep. LA13694-MS. Los Alamos Natl. Lab., Los Alamos, NM

Griffioen, J., (2017). Enhanced weathering of olivine in seawater: The efficiency as revealed by thermodynamic scenario analysis. *Sci. Total Environ.* 575, 536-544.

Guntzer, F. et al (2012) Benefits of plant silicon for crops: a review. *Agron. Sustainable Devel.* 32, 201-213.

Hangx, S. J. T.; Spiers, C. J. (2009) Coastal spreading of olivine to control atmospheric CO₂ concentrations: A critical analysis of viability. *Int. J. Greenhouse Gas Control* 3:757–767.

Hartmann, J. et al (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* 51, 113–149.

Hartmann, J., and S. Kempe (2008), What is the maximum potential for CO₂ sequestration by “stimulated” weathering on the global scale?, *Naturwissenschaften*, 95, 1159–1164. doi:10.1007/s00114008-0434-4.

Hartmann J et al (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification *Rev. Geophys.* 51 113–49

Hartmann, J., and N. Moosdorf (2012), The new global lithological map database GLiM: A representation of rock properties at the Earth surface, *Geochem. Geophys. Geosyst.*, 13, Q12004. doi:10.1029/2012GC004370.

Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr, and J. Scheffran (2013), Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification, *Rev. Geophys.*, 51, 113–149, doi:10.1002/rog.20004

Hinsinger, P. et al. (2001) Plant-induced weathering of basaltic rock: experimental evidence. *Geochim. Cosmochim. Acta* 65:137-152.

Jenkyns, H.C., (2010) Geochemistry of oceanic anoxic events: *Geochemistry, Geophysic, Geosystems* 11:Q03004. doi:10.1029/2009GC002788.

Kantola, I.B. et al (2017) Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biol. Letts.* 13:20160714.

Kantola, I.B., et al (2016). Climate change mitigation through enhanced weathering in bioenergy crops. American Geophysical Union, Fall General Assembly, abstract #H13B-1358.

Kheshgi HS. (1995). Sequestering atmospheric carbon-dioxide by increasing ocean alkalinity. *Energy* 20:915–22

Kohler, P., Hartman, J. & Wolf-Gladrow, D.A. (2010) Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci. USA* 107:20228-20233.

Köhler, P. et al (2013) Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology. *Environ. Res. Lett.* 8 014009

Kramer, D.A. (2020) Current mining of olivine and serpentine. USGS, Reston, VA.

Lackner, K.S. (2002) Carbonate Chemistry for Sequestering Fossil Carbon. *Annual. Rev. Energy Environ.* 27:193–232. doi:10.1146/annurev energy.27.122001.083433

Lark, T.J. et al. (2020) Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications* | 11:4295 1-11. <https://doi.org/10.1038/s41467-020-18045-z>.

Lehmann, J. and Possinger, A. (2020) Atmospheric CO₂ removed by rock weathering. *Nature* 583:204-205.

Lenzi, D. et al (2018) Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561:304-305.

Lewis, J.F. et al (2006). Ophiolite-related ultramafic rocks (serpentinites) in the Caribbean Region: a review of their occurrence, composition, origin, emplacement and Ni-laterite soil formation. *Geol. Acta* 4, 237–263.

Louvat, P., Allègre, C.J., 1997. Present denudation rates on the island of Réunion determined by river geochemistry: basalt weathering and mass budget between chemical and mechanical erosions. *Geochim. Cosmochim. Acta* 61, 3645–3669.

Marion, G.M., Millero, F.J., Camoes, M.F., Spitzer, P., Feistel, R., Chen, C.-T.A., (2011). pH of seawater. *Mar. Chem.* 126, 89-96.

McGrail, B. P., et al (2006), Potential for carbon dioxide sequestration in flood basalts, *J. Geophys. Res.*, 111, B12201, doi:10.1029/2005JB004169.

Makowski, D. (2019) N₂O increasing faster than expected. *Nature Climate Change* 9:907–910.

Meysman FJR, Montserrat F. (2017) Negative CO₂ emissions via enhanced silicate weathering in coastal environments. *Biol. Lett.* 13: 20160905. <http://dx.doi.org/10.1098/rsbl.2016.0905>

Montserrat, F. et al (2017) Olivine Dissolution in Seawater: Implications for CO₂ Sequestration through Enhanced Weathering in Coastal Environments. *Environ. Sci. Technol.* 51: 3960–3972

Moosdorf, Nils, Renforth, Phil and Hartmann, Jens (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science and Technology* 48 (9) , pp. 4809-4816. 10.1021/es4052022 file

National Academies of Sciences, Engineering, and Medicine (2018). *Direct Air Capture and Mineral Carbonation Approaches for Carbon Dioxide Removal and Reliable Sequestration: Proceedings of a Workshop in Brief*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25132>.

National Academies of Sciences, Engineering, and Medicine (2018b). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Stephen Pacala (Chair). The National Academies Press.

O'Connor WK, Dahlin DC, Nilsen DN, Walters RP, Turner PC. (2000). Carbon dioxide sequestration by direct mineral carbonation with carbonic acid. *Proc. 25th Int. Tech. Conf. Coal Util. Fuel Syst.*, Mar. 6–9, pp. 153–64. Clearwater, FL

Oelkers, E. H. (2001) An experimental study of forsterite dissolution rates as a function of temperature and aqueous Mg and Si concentrations. *Chem. Geol.* 175: 485–494.

Oelkers, E.H. et al.(2018) Olivine dissolution rates: A critical review. *Chemical Geology* 500: 1-19

Olsen AA (2007) *Forsterite Dissolution Kinetics Applications and implications for chemical weathering*, Dissertation Virginia Polytechnic Institute. Available: <http://scholar.lib.vt.edu/theses/available/etd-07052007-135551>.

Percival, L.M.E., et al. (2016) Osmium isotope evidence for two pulses of increased continental weathering linked to Early Jurassic volcanism and climate change. *Geology* 44:759–762.

Philip A.E. et al (2021) The lithium and magnesium isotope signature of olivine dissolution in soil experiments. *Chemical Geology* 560:120008. <https://doi.org/10.1016/j.chemgeo.2020.120008>

Project Vista. Olivine and Dunite Reserves and their position in ophiolites. <https://legacy.projectvesta.org/wiki/olivine-and-dunite-reserves-and-their-position-in-ophiolites>

Pokrovsky, O. S.; Schott, J. Kinetics and mechanism of forsterite dissolution at 25°C and pH from 1 to 12. *Geochim. Cosmochim. Acta* 2000, 64 (19), 3313–3325.

Rau GH, Caldeira K. (1999). Enhanced carbonate dissolution: a means of sequestering waste CO₂ as ocean bicarbonate. *Energy Convers. Manag.* 40:1803–13

Rau, G.H. (2011) CO₂ mitigation via capture and chemical conversion in seawater. *Environ. Sci. Technol.* 45, 1088–1092.

Renforth, P. (2012) The potential of enhanced weathering in the UK. *Int. J. Greenhouse Gas Control* 10, 229–243.

Renforth, P., Kruger, T., (2013) Coupling mineral carbonation and ocean liming. *Energy Fuel.* 27, 4199–4207.

Renforth, P., Jenkins, B.G., Kruger, T. (2013) Engineering challenges of ocean liming. *Energy* 60, 442–452.

Renforth, P. et al (2015) The dissolution of olivine added to soil: Implications for enhanced weathering. *Applied Geochemistry* 61: 109–118

Renforth, P. & Henderson, G. (2017) The negative emission potential of alkaline materials *Rev. Geophys.* 55:636–674.

Rigopoulos, I., Petalidou, K.C., Vasiliades, M.A., Delimitis, A., Ioannou, I., Efstathiou, A.M., Kyratsi, Th., 2015. Carbon dioxide storage in olivine basalts: effect of ball milling process. *Powder Technol.* 273, 220-229.

Rigopoulos, I., Vasiliades, M.A., Ioannou, I., Efstathiou, A.M., Godelitsas, A., Kyratsi, Th., 2016. Enhancing the rate of ex situ mineral carbonation in dunites. *Adv. Powder Technol.* 27, 360-371.

Rigopoulos, I., Harrison, A.L., Delimitis, A., Ioannou, I., Efstathiou, A.M., Kyratsi, T., Oelkers, E.H., (2017). Carbon sequestration via enhanced weathering of peridotites and basalts in seawater, *Applied Geochemistry* (2017), doi: 10.1016/j.apgeochem.2017.11.001.

Rockstrom, J. et al. (2017) A roadmap for rapid decarbonization. *Science* 355, 1269-1271.

Rosso, J. J.; Rimstidt, D. J. A high-resolution study of forsterite dissolution rates. *Geochim. Cosmochim. Acta* 2000, 64 (5), 797–811.

Schuilng, R. D. (2006). Mineral sequestration of CO₂ and recovery of the heat of reaction, in: *Macro-engineering: a challenge for the future*. In V. Badescu et al. (eds.), *Macro-Engineering: A Challenge for the Future*, p 21-29. Springer.

Schuilng, R. D. and Krijgsman, P. (2006). Enhanced weathering: an effective and cheap tool to sequester CO₂. *Clim. Change* 74:349-354.

Schuilng, R.D., de Boer, P.L. (2010). Coastal spreading of olivine to control atmospheric CO₂ concentrations: a critical analysis of viability. Comment: nature and laboratory models are different. *Int. J. Greenhouse Gas Control* 4, 855–856.

Schuilng, O. (2018) *Olivine The Philosopher's Stone*. Elmar Publishers.

Sodal, J. (2015) *Silicate weathering in soils: A solution for soil pH management?* Master of Science Thesis Department of Earth Science University of Bergen.

Smith, et al. (2016) Biophysical and economic limits to negative CO₂ emissions. *Nat. Clim. Change* 6:42-50.

Spawn, S.A. et al (2019) Carbon emissions from cropland expansion in the United States. *Environ. Res. Lett.* 14: 045009.

Strefler, J. et al (2018) Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* 13.

Taylor, L.L. et al. (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Change* 6:402-406.

Taylor, et al (2017) Simulating carbon capture by enhanced weathering with croplands: an overview of key processes highlighting areas of future model development. *Biol. Lett.* 13: 20160868.

Thompson, R. L. et al. (201) Acceleration of global N₂O emissions seen from two decades of atmospheric inversion. *Nature Climate Change* 9:993-998.

TNO (2008) TNO-U-R-0776/B Desk study on the feasibility of CO₂ sequestration by mineral carbonation. <http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/kamerstukken/2009/01/26/reactie-opbrief-van-hr-schuilings-over-olivijn-rapport/k12009006101aolivijnrapport.pdf>

Tubana, B.S., et al (2016) A review of silicon in soils and plants and its role in US agriculture: history and future perspectives. *Soil Sci.* 181:393–411.

USGS (2019) Making Minerals-How Growing Rocks Can Help Reduce Carbon Emissions.

von Uexküll, H. R. & Mutert, E. (1995) Global extent, development and economic impact of acid. *Plant Soil* 171, 1–15.

Wignall, P. B. (2015) *The Worst of Times. How Life on Earth Survived Eighty Million Years of Extinctions.* Princeton Oxford University Press.

Wilson, M.J., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. *Clay Miner.* 39:233–266.

Wogelius, R. A.; Walther, J. V. Olivine dissolution at 25°C: Effects of pH, CO₂, and organic acids. *Geochim. Cosmochim. Acta* 1991, 55 (4), 943–954.

Wolff-Boenisch, D., Wenau, S., Gislason, S.R., Oelkers, E.H., 2011. Dissolution of basalts and peridotite in seawater, in the presence of ligands, and CO₂ : Implications for mineral sequestration of carbon dioxide. *Geochim. Cosmochim. Acta* 75, 5510-5525.

Wood, S., Sebastian, K. & Scherr, S. J. (2000) *Pilot Analysis of Global Ecosystems: Agroecosystems* (world Resources Inst).

Zhang Q, Sugiyama K, Saito F. 1997. Enhancement of acid extraction of magnesium and silicon from serpentine by mechano-chemical treatment. *Hydrometallurgy* 45:323–31