Possible Projects for the Foundation

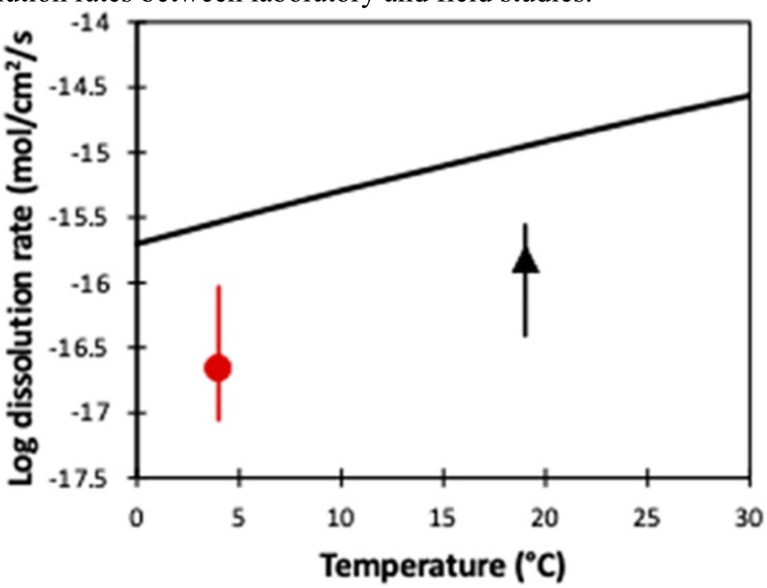
1. A 3-site Research Project

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 dryer temperate site.** 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.**

Pogge von Strandmann et al (2022) provided the following diagram illustrating the differences in dissolution rates between laboratory and field studies.



From Pogge von Strandmann et al, (2022). The top line represents dissolution rates of olivine at different temperatures based on laboratory studies. The black triangle represents the dissolution rate for field studies at about 19ºC while the red circle represents the slower field rate at 4ºC.

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 size 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 um 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** (mol/m^2/s) or (mol m^{-2}s^{-1}) is commonly defined by the relationship

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

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 7.0×10^{-14} mol/m^2/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 **B**runauer, Paul Hugh **E**mmett, and Edward **T**eller 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 20º and 80º and CuKα radiation (λ = 1.5406 Å) 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 and mafic 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 um, 10 um, 30 um and ≥ 100 um 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 would 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 m^2) 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. It 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 m^2, 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 m^2 (somewhat less since there will be a ½ meter path between the internal parts of the miniplots).

Each 64 m^2 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 size or 144 m^2.

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

Five different rock sizes: 0 (no rocks), 1 um, 10 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 x 5 x 4 x 1.5 = 150 macro-plots x 144 m^2 for a total of 21,600 m^2. We would double that to have land for solar panels and buildings (storage, test labs, administration and lodging. Thus, the total area = 43,200 m^2 = 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 plot (4 per 8 m plot) with a two-foot path between the internal boundaries. This makes it possible to answer several 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 CO_2? 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 CO_2. 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 CO_2.**

• **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 CO_2, 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.

This raises the possibility that we could fund independent research into the question - Is it possible to develop an inexpensive matrix that would dramatically increase the amount of pulverized olivine exposed to the air?

• **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. Suhrhoff (2022) listed a number of other plants that are Ni accumulators.

• **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-treatments, different types of grinding, different types of crops, etc. If these seem promising, in the following years they will also be performed at all sites.

• **Effect of Climate Rocks on Lawns.** This would involve planting grass in a miniplots and examining the progress of climate rock dissolution.

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.

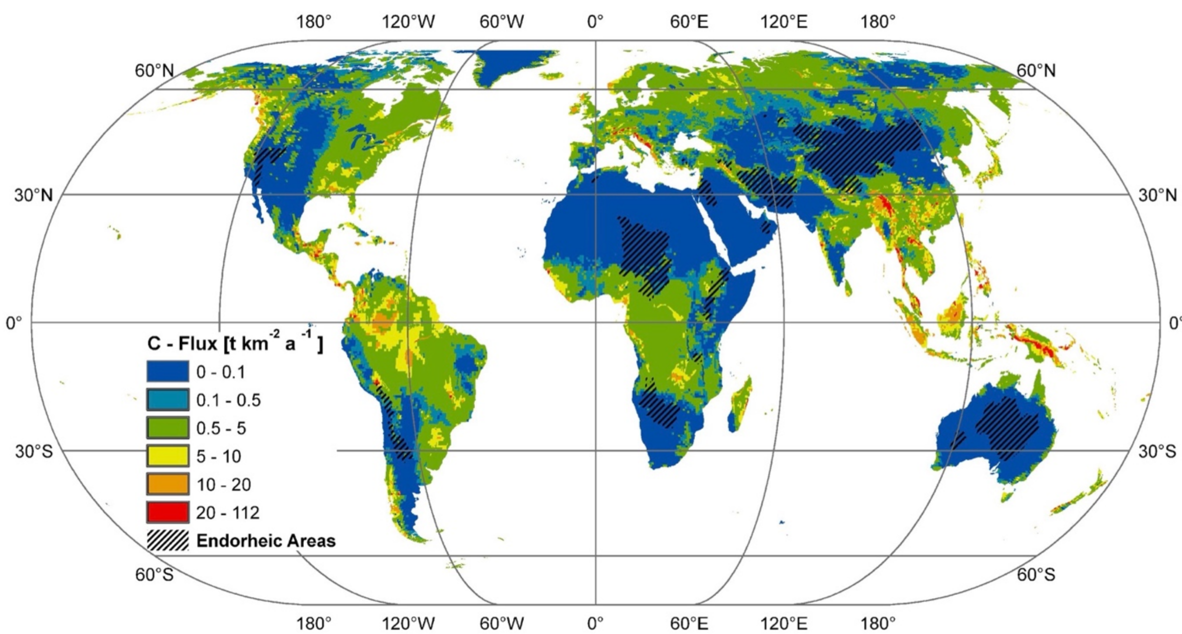
Goals The following are some of the questions and goals:

- 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 produces 29 times more rapid weathering than dry, temperate climates, and focusing on tropical "weathering hot spots" leads up to a further 5-10-fold increase in weathering (see above). This suggests that the exclusive use of hot spots would produce a weathering rate of 29 x 5 or 145 x that of temperate dry areas in the US. Clearly these would be the areas to use. This might dramatically change some of the above negative thoughts about EW. 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 PIs 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 CO_2 mineralization. **This would be just such a research program**. If the resources of the Comings Foundation are not adequate to cover these research expenditures, outside funds would be welcome.

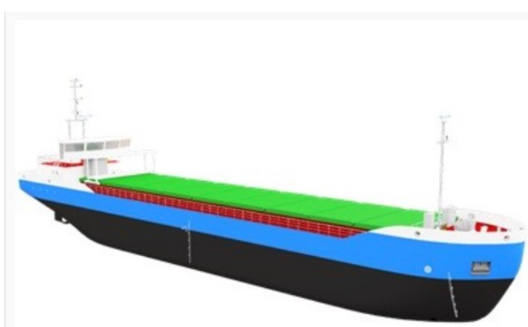
There are several advantages of funding such studies through a private foundation.

1. If the foundation develops a sizable endowment and runs on the return on 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, with an adequate endowment, we could 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 alkalinization of the oceans is to build a fleet of specialized OAE ships. To ensure they do not produce more CO_2 than they sequester they will be designed to run on carbon free electricity for both power and the electrochemistry for alkalinization. We will a contact a ship design firm, such as **Bay Engineering** (see Appendix E) 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-H_2 fuel cells? Standard O_2 H_2 fuel cells? Are these sources of electricity adequate to power a ship moving slowly as it lays down alkalinization 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 might 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 cconverts 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 an onboard grinding and pulverizing 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.

A ship with mesocosms. As descried above, Ulf Riebesell used mesocosms to test for the effects of nickel and other heavy metals in OAE experiments and to test for the effect of alkalinization on marine life. Similar mesocosms could be used for this purpose on the OAE ship which will need to be designed to easily allow for the use of mesocosms.

Adsorbing Nickel from Solutions The problem of contamination of the alkalinization fluids with heavy metals, such as nickel, can potentially 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 alkalinization projects on the ocean chemistry? This can be answered using mesocosms.

On-board chemistry laboratory Such a laboratory will be necessary to determine pH, salinity, alkalinity, temperature, pCO_2, pO_2, as well as all the members of the carbonate cycle Ω carbonate, CO_2, H_2CO_3, HCO_3^- and CO_3^{2-} for mesocosm and 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 and to follow the progress of the alkalinization?

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 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. The initial use of the OAE ship would need to basically be a research laboratory to satisfy various governance rules. If this shows that the benefits far outweigh any negatives, this will pave the way for large scale OAE. What departments in the US government handles that? NOAA? NOAA-OAP? The UN?

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. Lage 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 CO_2 output from the oil burning engines passed thru a slurry of pulverized olivine to adsorb the CO_2. She stated that "1 ton of olivine removes 1.25 tons of CO_2. To mine, pulverize & transport 1 ton olivine costs \$13 today equaling \$10.40/ton of CO_2 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 CO_2/day (90,000 ships release ≈ 1 billion tons of CO_2 & GHGs/year (ICCT, International Council on Clean Transportation, 2015). Cargo ships hold up to 21,413 TEUs (**T**wenty Foot **E**quivalent Shipping **U**nits). 1 TEU (the average container) holds up to 33.2 m^3, 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 CO_2. 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 CO_2 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 concerted to this approach, that would account for 1 gigaton of the needed C sequestration.

Electrochemical Extraction of CO_2 from Seawater Eisaman and colleagues (Eisaman et al, 2012; de Lannoy et al, 2018; Eisaman, 2020) described an electrochemical process of extracting CO_2 from seawater using a bipolar membrane electrodialysis system (BPMED). They demonstrated the ability to extract 59% of the total dissolved inorganic carbon from seawater as CO_2 gas with an electrochemical energy consumption of 242 kJ molÀ1 (CO_2). This was then converted into fuel. Eisaman and his team of researchers founded SEAMATE (Safe Elevation of Alkalinity for the Mitigation of Acidification Through Electrochemistry).

One configuration, termed the ‘base process’, added base to the seawater to shift the carbonate buffer system towards carbonate ions, which precipitated as $CaCO_3$. A closed loop cycle was achieved by returning this decarbonized and alkalinized brine to the ocean for additional CO_2 absorption from the air. With continued research they hoped to simplify the process and decrease costs. This may hold promise as an additional procedure that could be caried out on a OAE ship.

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, if our endowment is adequate, the Comings Foundation could step in and fund it.