

# Finding the perfect rock: Choosing the best source material for Enhanced Weathering

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Whitepaper



**ZeroEx**

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# Introduction

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Every enhanced rock weathering (ERW) project begins with the same step: finding the right rock, or feedstock. As the ERW industry expands and matures, finding the right feedstock will become even more critical to a project's success. Companies will increasingly find themselves stuck between pressure to maximize weathering rates and legal restrictions on contaminants in some feedstock. As a result, anyone interested in nature-based carbon removal can benefit from understanding why specific materials are chosen for use in ERW. This white paper briefly discusses some of the considerations involved, what issues most often crop up, and steps to address them.



# Selecting rocks and minerals

Choosing weathering material, or feedstock, is one of the most important steps in an ERW project. The chemical content of the feedstock has a great effect on the ultimate amount of carbon dioxide removed from the atmosphere. To maximize the carbon removed by a given field, ERW project developers want feedstock with the greatest proportion of positively charged atoms, or cations. Specifically, they want oxides of magnesium, calcium, sodium, and potassium, which react well with the carbonic acid created when carbon dioxide is dissolved in rainwater. The amount of these oxides present is used to calculate the theoretical maximum carbon removed through weathering one tonne of material, referred to as  $CDR_{max}$ , which is the most common metric used by ERW developers<sup>1,2</sup>.

The task, then, is to find naturally occurring, easily accessible material with the greatest  $CDR_{max}$ . Those four elements: magnesium, calcium, sodium, and potassium, are found in minerals like augite, orthopyroxene, plagioclase feldspar, and olivine, which most commonly appear in high concentrations in mafic volcanic rocks like basalt and basanite. The term “mafic” merges the words “magnesium” and “ferric,” referring to the high concentrations of magnesium and iron. Basalt and basanite are also “extrusive” rocks, meaning they form from lava which reaches the surface before cooling, as opposed to “intrusive” rocks such as granite, which do not reach the surface and as a result cool slower. Since extrusive rocks cool faster, they cannot form the large crystals which give rocks like granite their speckled appearance.



Basalt's high concentrations of magnesium and calcium, its small crystal size, and its abundance at the earth's surface make it ideal ERW feedstock.

Besides crystals, extrusive rocks can also contain a significant proportion of volcanic glass, lava which cooled too quickly to form crystals at all. The outer shell of the lava cools the fastest, forming a greater proportion of glass, while the inside of the flow develops fine mineral grains as it solidifies. Basalt glass weathers faster<sup>3</sup>, making it the best material for ERW. However, volcanic glass does continue to gradually crystallize even after it is quenched, a process called devitrification, meaning that extrusive rock is most ideal for ERW if it is less than approximately 60 million years old<sup>4</sup>. Younger rock is also preferable since it has had less time to undergo physical processes like faulting, which can lead to the formation of toxic asbestos<sup>5</sup>.

Basalt is the most common rock in the earth's crust, but most of it is found under the ocean. Basalt deposits on land are mostly the result of mantle plumes, fountains of materials from deeper in the earth which push up through the crust and erupt at the surface. On land, these often form clusters of volcanoes and lava flows called large igneous provinces (LIPs). Examples include the Deccan Traps in western India or the Columbia River Basalt Group in the northwest US.

In the ocean, mantle plumes create groups of submarine volcanoes like the Canary or Hawaiian Islands. Basalt outcrops can be new as a few weeks or as old as one billion years. The specific chemical makeup of basalt outcrops is highly dependent on the conditions under which it formed, so a little geologic context can help ERW developers better understand their  $CDR_{max}$  values.

For instance, sulphur, which acts to inhibit carbon removal by creating sulphuric acid<sup>2</sup>, is extremely volatile and tends to escape to the atmosphere over time. As a result, basaltic lava which is allowed to fully degas at the surface will have slightly higher  $CDR_{max}$ .

# Constraining factor: heavy metal content

Another commonly discussed problem with ERW is the release of toxic trace metals normally found in small quantities in mafic rocks. The mineral olivine is particularly prone to contain trace amounts of nickel and other heavy metals. Olivine, while extremely common in the earth's mantle, is relatively rare on the surface because it is the first mineral to crystallize and be deposited by basaltic magma cooling as it approaches the surface. It is also highly prone to weathering, making it ideal for ERW but also hard to find still intact. Olivine crystals normally contain magnesium or iron atoms but can sometimes contain nickel as well. As a result, regulations covering inorganic soil additives currently in place in Germany, China, Brazil, and elsewhere may limit the use of rocks containing olivine in agricultural settings<sup>6</sup>.

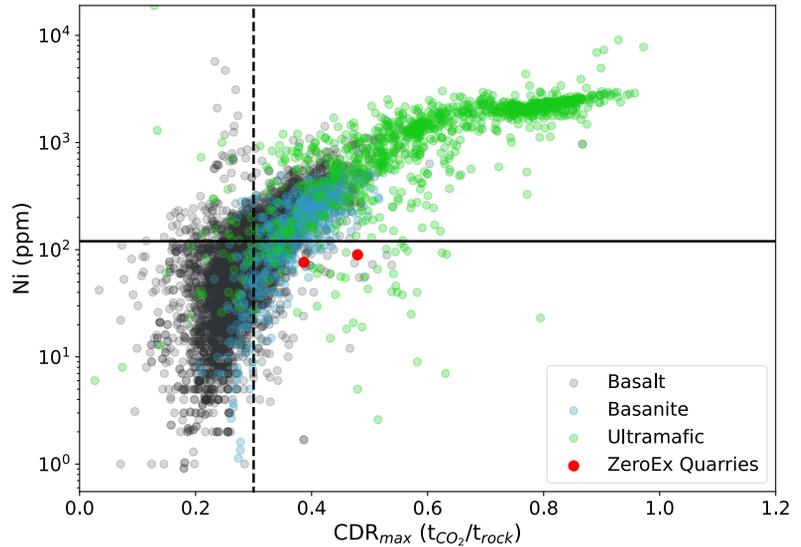
The plot below shows  $CDR_{max}$  and nickel content for thousands of rock samples from the open-source GEOROC database<sup>7,8</sup>, separating basalt, basanite, and ultramafic rocks, which include peridotite and dunite, from which pure olivine is sometimes refined. Overall, the greater the  $CDR_{max}$  the higher the nickel content, making it extremely difficult to find

feedstock material that is both cost-effective and compliant with regulations.

As a result of this restriction, ERW projects may have to go through more preliminary explorations and test a significant number of feedstock sources to find compliant material. It also means that rather than the theoretical maxima of olivine-rich rocks like dunite or peridotite, which can be as much as 1.1 t CO<sub>2</sub> per t, ERW developers may have to settle for  $CDR_{max}$  values in the range of 0.2–0.3 t CO<sub>2</sub> per t<sup>9</sup>.

This will become especially important if regulations on heavy metals are adopted more widely, but even projects in regions without such laws will still likely have to satisfy the environmental impact requirements of independent carbon credit certifiers.

$CDR_{max}$  and nickel content for thousands of rock samples from the open-source GEOROC database, annotated with ZeroEx's specific criteria. The horizontal line shows the German nickel content limit, 120 ppm, while the vertical dashed line shows the company's minimum threshold for cost- and emissions-effective  $CDR_{max}$ . Data from two of ZeroEx's quarries are plotted in red, showing how difficult and critical it is to find satisfactory feedstock.



## Quarrying and processing

One additional issue in calculations of the practicality of enhanced weather is the cost of grinding rock into a fine powder suitable for spreading onto fields. One estimate for ERW development in the UK found that the process of grinding rock into small enough particles for spreading, comminution, might generate enough carbon emissions to completely negate the carbon removal potential of a project<sup>10</sup>. A different estimate for global scalability was not quite as pessimistic, but still found that quarrying and comminution could reduce a project's net carbon removal by as much as a quarter<sup>8</sup>. The cost of ERW feedstock can be dramatically reduced by using material which is generated as waste by other industrial processes.

Basalt is quarried for use as aggregate, which provides filler in products like asphalt and concrete<sup>11</sup>. Globally, the basalt market totals USD 310 million as of 2022<sup>12</sup>. As part of their normal quarrying and grinding processes, basalt quarries generate significant quantities, of "fines," particles less than 4 mm in diameter that are too small for commercial applications. This waste material can incur additional costs for quarries in countries like Germany which impose specific requirements for dust transportation, storage and disposal. This gives quarries an added incentive to find a partner like an ERW developer looking for feedstock.

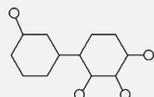
# Transportation

The last consideration for an ERW company seeking feedstock material is location. Choosing a quarry too far away from the application sites can dramatically decrease the net carbon removal ( $CDR_{net}$ ). Since most of the academic literature on ERW involves small-scale experiments, there is still a dearth of research on the true cost of providing ERW-ready feedstock to field sites at scale. The most thorough life cycle analysis (LCA) of the carbon footprint of an ERW project to date is the resources that would be required to conduct ERW in São Paulo, Brazil in 2019<sup>13</sup>.

Using emissions data from quarry equipment and trucks, they found that that transportation distances above approximately 1000 km completely negated the carbon removal potential of the project. That study assumed a conservative  $CDR_{max}$  value of 0.225 t CO<sub>2</sub> per t based on rock samples from the region, but not even the  $CDR_{max}$  rock can overcome transportation emissions; one other assessment found that the truck transportation distance for which net-positive ERW is cost-effective varies the most for  $CDR_{max}$  values between 0.2–0.5 t CO<sub>2</sub> per t<sup>14</sup>. Above that point, cost-effectiveness depends almost entirely on the distance traveled.

## Just the right rock

The telltale characteristics of ideal ERW feedstock:



### Chemical makeup

High in magnesium, calcium and sodium oxide



### Cooling rate

Fast  
(leaves higher glass content)



### Age

Less than 60 million years



### Trace metals

Very little nickel, chromium, arsenic, cadmium and mercury



### Current usage

Already being mined, and ideally also crushed for industrial applications

# Key Lessons

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- Rock for ERW must be evaluated for a variety of factors, geological and otherwise, and a careful material selection process is only going to become more important as the industry matures.
- Logistical considerations such as transportation and processing costs can dramatically reduce the efficacy of an ERW project and must be considered throughout the feedstock selection process, not after.
- Designing a safe, efficient, and sustainable ERW project from feedstock to application is critical for developers to be responsible corporate citizens while furthering their core goal of climate change mitigation.

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