

Perspective

Enhanced rock weathering — A nature-based solution for climate mitigation

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Cite This Article:

Manning DAC. Enhanced rock weathering — A nature-based solution for climate mitigation. *Green Energy Sustain.* 2025;5(2):0003.
<https://doi.org/10.47248/ges2505020003>

Received: 2 Jan 2025

Accepted: 4 Mar 2025

Published: 20 Mar 2025

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Abstract

Much of Paul Younger's work focused on nature-based solutions that addressed environmental problems, especially relating to removal of contaminants from minewaters. Enhanced Rock Weathering (ERW) has emerged during the last few years as a new paradigm, taking advantage of natural processes of rock weathering to remove CO₂ from the atmosphere. This approach makes use of existing infrastructure in mining and processing silicate rocks, especially those used as aggregates in the construction industry. Weathering of silicate minerals has long been known to influence the Earth's atmospheric CO₂ content, and the process of ERW artificially enhances this by crushing the rock to increase its reactive surface area, prior to application to soils. The key challenges include verification of claims for CO₂ removal, and scaling up production to meet the need to remove billions of tonnes of CO₂ globally. Although multidisciplinary, these challenges are similar to those associated with widespread deployment of passive minewater treatment systems, and are addressed using sound knowledge of mineralogy and geochemistry.

Keywords: enhanced rock weathering; ERW; dolerite; basalt; silicate mineral; quarrying

1. Introduction

The importance of working with nature to (a) provide society with energy and (b) to repair the damage caused by energy production was at the heart of Paul Younger's work, both in research and in putting research into practice. Pioneering work on geothermal energy [1,2] led to gathering momentum in low enthalpy systems [3], which created the Glasgow UK Geoenergy Observatory [4], a design very closely based on Paul's experience in NE England.

For a long period of time, passive treatment of water originating from old coal mines was the focus of Paul Younger's research, with particular interests in the use of materials such as steel slags as substrates in reed beds [5]. In these systems,

minewater drains into a contained reed bed, where biologically-driven chemical reactions neutralise acidity and remove contaminant metals, which accumulate in the solid substrate. Integrating biology and geochemistry [6,7], these systems rely on solar energy for plant growth, and once established have no significant external energy inputs.

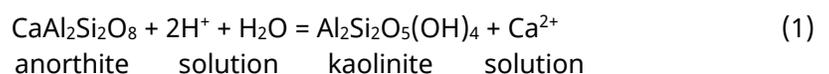
Similar in its integration of biology and geochemistry, Enhanced Rock Weathering exploits photosynthetic removal of CO₂ from the atmosphere to the coupled plant-soil system [8]. Through the largely microbial decomposition within soils of plant and root tissue and root exudates, a complex cocktail of organic chemical species is transformed ultimately to CO₂, some of which partitions into the soil solution as bicarbonate (at near neutral pH values, typical of agricultural soils) [9]. The bicarbonate ultimately drains to the ocean, or enters groundwater systems. This process transfers CO₂ from the biological carbon cycle to the inorganic (geological) carbon cycle, generating stable products that persist for hundreds of thousands if not millions of years.

Recently, especially since COP 26 in Glasgow, the practice of 'Enhanced Rock Weathering' (ERW) has developed into an industry with the potential to remove significant amounts of CO₂ from the atmosphere. This approach to mitigate global climate change would undoubtedly have appealed to Paul, given its dependence on rocks such as the dolerite of Northumberland's Whin Sill, which were an important part of his early training as a geologist. Bert Randall's day trips to Barrasford Quarry stuck in the mind of all in Paul's undergraduate class, but at that time no-one had any idea of the potential of the rock for artificially-enhanced CO₂ removal.

As a concept, Enhanced Rock Weathering is similar to the use of reedbeds to clean up contaminated waters. It uses natural processes to facilitate soil-based reactions that consume CO₂ pumped into the soil by plants. It has very low energy costs when set up, and can be associated with increased biodiversity and crop production. It uses materials that might have been regarded as mine wastes, but which become a specified product. The approach is potentially highly scalable globally and could become a significant process for removing CO₂ from the atmosphere to mitigate climate change (a key challenge is the availability of sufficient rock of the right type [10]). Importantly, the process takes advantage of the fact that, in the carbon cycle, annual exchange between the soil-plant system and the atmosphere is a sixth of the atmosphere's carbon stock [11]. This means that rapid interventions that affect atmospheric CO₂ can be made by intercepting the biological carbon cycle and transforming carbon into inorganic forms, such as carbonate and bicarbonate.

2. Formation of Carbonate in Soil and the Soil Solution

When silicate rocks weather, they release cations, and the silicate component of their structure enters complexes that overall have no charge. These include clay minerals such as kaolinite (Al₂Si₂O₅(OH)₄), or dissolved species such as H₄SiO₄, e.g., Equation (1), weathering of anorthite.



The cations originally held within the silicate mineral cannot exist alone in solution – there has to be a counter-balancing negative charge. In natural weathering systems, this is bicarbonate. Evidence of this comes from the chemical composition of groundwater, where bicarbonate is the dominant anion close to the surface [12,13]. As an example, Gastmans *et al.* [14] show very clearly that bicarbonate, derived from weathering, is the dominant anion in basaltic aquifers that supply tens of millions of people with safe drinking water in São Paulo State, Brazil, and that other anions in these waters, such as chloride, sulfate and nitrate, have artificial origins.

Once in solution, changes in solution chemistry may mean that the dissolved anions and cations precipitate, in circumstances where the saturation index of a mineral is reached. This is calculated using geochemical modelling software, such as PHREEQC [15]. In specific climates and soil systems, calcite (CaCO_3) precipitates as a pedogenic carbonate mineral. Early work using C and O stable isotopes [16,17] clearly showed how pedogenic carbonates relate to vegetation type and climate. Both C and O are derived from atmospheric CO_2 , entering the soil system as a consequence of photosynthesis. Within the soil, plant root exudates and dead plant tissue both are metabolised by soil microbes and fauna, ultimately producing CO_2 . A portion of this enters the soil solution, where it forms bicarbonate (in near-neutral pH). This then combines with Ca in solution to form calcite.

Pedogenic carbonates are known to develop on basaltic rocks (e.g., [18,19]). When they occur, they represent a solid product of the weathering process. However, it is unusual (but not unknown [20]) to find pedogenic carbonates in basaltic rocks in temperate climates. In contrast, they are known to form readily in urban soils that contain crushed concrete derived from demolition. Washbourne *et al.* [21] were able to measure increases in soil calcite content that correspond to removal of 85 T CO_2 per hectare annually, with stable C and O isotope compositions that demonstrated a pedogenic, non-geological origin, and ^{14}C data that showed significant modern carbon. This is 4–5 times more rapid than removal of carbon through growth of trees, and is permanent.

3. Enhanced Rock Weathering

Against this background, the paradigm of Enhanced Rock Weathering (or ERW) has been developed, largely since COP26 was held in Glasgow in 2021. In the UK, commercial deployment has involved companies such as Un-Do Carbon Ltd, which was set up in 2022.

ERW embraces the long-established scientific background to silicate rock weathering, which influences atmospheric CO_2 (e.g., [22]). This natural process is enhanced by artificially crushing and grinding silicate rocks so that a fine grained fraction is available to be applied to soil, where natural weathering processes take over.

ERW appears to have many advantages and benefits that go beyond CO_2 removal, especially for crop nutrition as the crushed rock can provide elements that would otherwise have to be added as fertilizers [8,23].



(a)



(b)



(c)

Figure 1 Quarrying in the dolerite of the Whin Sill, Northumberland. (a) operating face at Barrasford Quarry, Tynedale (2007); (b) crushing operations at Barrasford quarry (2022); and (c) quarry fines typical of those used in ERW. Photographs taken by David Manning.

Given their extensive global occurrence [24], basaltic rocks are widely used in commercial deployments for ERW, although there is considerable interest in the use of other materials such as the calcium silicate mineral wollastonite (CaSiO_3) in Canada [25], and material returned from ready-mixed concrete deliveries (Republic of Ireland [26]). There is substantial independent evidence that these materials weather on a human timescale. Work in Iceland [27] clearly showed evidence of basalt weathering, with elevated bicarbonate concentrations in water draining especially through slopes with woodland growing on basalt. Similarly, Peters *et al.* [28] provide evidence of rapid weathering of wollastonite in the Hubbard Brook catchment, with measurable increases in stream Ca concentration. Rapid weathering of concrete within soil with measurable increases in pedogenic carbonate formation has been reported by Washbourne *et al.* [21].

In the north of England and Scottish Midland Valley (*i.e.*, in Paul's 'backyard') the dominant rock used for ERW is dolerite (classified by the British Geological Survey as quartz microgabbro) from Carboniferous sills, which are quarried at many locations [10]. **Figure 1** shows an example of a large quarry in the Whin Sill in Northumberland (Tarmac's Barrasford quarry, which Paul visited as an undergraduate). The most rigorous published description of the mineralogy and geochemistry of the quartz microgabbros of the Whin Sill is still that published by Bert Randall, who taught Paul and dedicated his career to these rocks [29].

The operations shown in **Figure 1a** show (to the left of the image) the pile of broken rock produced by a blast. Mobile crushing plant is often used within a quarry, and most material then progresses to the fixed plant (**Figure 1b**), where it is crushed and graded to produce different sizes of aggregate aimed at specific markets. The piles of material visible in **Figure 1b** represent stockpiles of different size products destined for market. The fine fraction, <5mm (**Figure 1c**), is stocked in this way.

Sourcing suitable quarry fines is only part of the ERW process, which is summarised in **Figure 2**. The material needs to be transported to (typically) farmland, where it is spread at application rates from 5-40 tonnes/hectare (20 tonnes/ha at Newcastle University's Nafferton Farm [30]). The weathering process then takes place, as the crops grow.

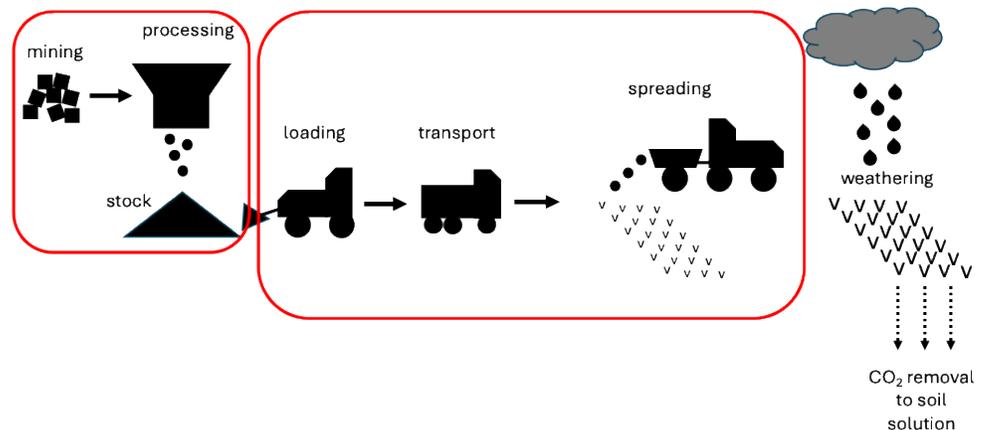


Figure 2 Summary of the Enhanced Rock Weathering process.

The natural weathering of the crushed dolerite in the soil removes CO₂ ultimately derived from the atmosphere, by generating alkalinity in the soil solution that is reflected by increased bicarbonate concentration in solution. On drainage, some of the soil solution enters surface water systems directly, while some drains into groundwater systems. Ultimately, a proportion of the bicarbonate enters the ocean, counteracting ocean acidification. Experimental evidence for the natural process that underpins artificially-enhanced weathering comes from Iceland, where Moulton *et al.* [27] very clearly demonstrated for waters draining through a weathering basalt under woodlands that up to 12 kg C per hectare was produced annually as bicarbonate (60 kg bicarbonate), and exported via through-drainage. Globally, Dessert *et al.* [31] estimate an annual flux to the ocean from terrestrial weathering of 4.08×10^{12} mol CO₂. However, the global flux to aquifers is unknown [32].

4. Estimation of Potential CO₂ Removal

Basaltic rocks are widely used for ERW, globally, but in detail they vary in their chemical and mineralogical composition. In addition, other rocks can also be used for ERW, the key requirement being that they contain silicate minerals that are inherently unstable in soils, decomposing to release cations and so demanding the presence in solution of counterbalancing bicarbonate anions.

The amount of CO₂ that can be removed by silicate rock weathering is estimated using an adaption of the 'Steinour' formula [33], simplified in Equation 2, which calculates the molar proportions of the oxides:

$$\text{erwCO}_2 = \frac{44}{100} \cdot \left(\frac{\text{CaO}}{56} + \frac{\text{MgO}}{40} + \frac{\text{Na}_2\text{O}}{62} + \frac{\text{K}_2\text{O}}{94} - \frac{\text{SO}_3}{80} - \frac{\text{P}_2\text{O}_5}{142} \right) \cdot 10^3 \cdot 1.5 \quad (2)$$

In this, it is assumed that a correction is needed for cations bound in minerals to sulfate (e.g., as anhydrite) and phosphate (as in apatite), as if they dissolve through weathering these contribute the counterbalancing anions sulfate and phosphate. However, the correction for phosphate in Equation 2 does not take into account the stoichiometry of apatite (Ca₅(PO₄)₃(OH)) [34]; 1 mole of CaO is equivalent to 0.3 moles P₂O₅. This has a negligible effect on the calculated value, as P₂O₅ concentrations are low compared to the major oxides. Typically, using this calculation [34] basaltic rocks potentially can remove 230-250 kg CO₂ per tonne of rock applied, and sometimes up to 300 kg CO₂ per tonne of rock [33].

The rate of CO₂ removal is key to the success of ERW deployment. Basaltic rocks contain a range of minerals, each with a unique weathering rate which depends on the mineral's dissolution rate and also the specific surface area of each mineral species (**Figure 3**). Consequently, it is necessary to determine the mineralogical composition of the rock so that the weathering rate of the bulk material can be modelled, as a first step in the prediction of CO₂ removal for a particular application [35]. Models then are used to predict the removal of CO₂, so that claims for payments from sales of CO₂ removed can be generated. However, these need to be validated with reference to agreed protocols, a matter that is not yet resolved completely [36].

The data shown in **Figure 3** are expressed as logarithm values, so they show a range that is considerable. For example, nepheline's dissolution rate (-3.30) is 8 orders of magnitude greater than that of quartz (-11.40). The plagioclase feldspars (anorthite - bytownite - labradorite - andesine - oligoclase - albite) show a progressive change, with a range of 5 orders of magnitude. For ERW, minerals with the least negative values in **Figure 3** are most desirable, however deposits of nepheline and wollastonite-bearing silicate rocks are few and small compared with the widespread occurrence of basalt.

Figure 3 relates to the ideal situation for an igneous rock that preserves the mineralogical composition of the material that crystallised from a magma. In many cases, basaltic igneous rocks used in ERW may have been metamorphosed or altered, in which case they contain minerals such as amphiboles or clays, reducing their potential for further weathering (e.g., [37]). Care needs to be taken to properly characterise the rock, and to consider the implications of changes in mineralogical composition that arise through weathering or alteration prior to use in ERW.

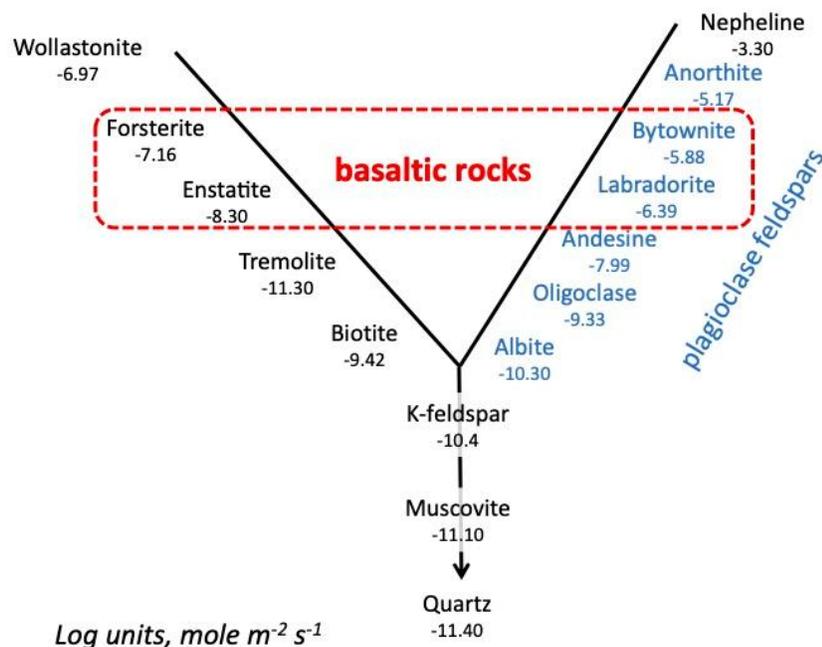


Figure 3 Dissolution rates for key minerals considered for ERW. Data from Heřmanská *et al.* [38] and (for wollastonite and nepheline) from Heřmanská *et al.* [39].

5. Benefits to Agriculture

Crushed silicate rocks have been added to soils to improve crop production for centuries [9]. Descriptions appear in the literature from the end of the 19th century (e.g., [40]), with specific examples of the beneficial use of basalt in forestry from the 1930s [41,42]). More recently, descriptions of the potential benefits of using nepheline-bearing rocks, especially as sources of K, were reported by Bakken *et al.*

[43,44]. However, although some studies describe improvements in crop yields (e.g., [45]), others were inconclusive [46]. This can be explained by weaknesses in experimental design, especially with failure to take into account the mineralogical composition of the soil, and the effects of different composts. Challenging the plant by using a pure quartz 'soil' in pot trials with no additional compost allows the effects of crushed rock treatments to be determined with confidence [47]. In these experiments, the crushed rock treatment is the only possible source of nutrients other than N.

Field trials to determine the benefits of application of crushed rock for the purposes of ERW are still few in number. Skov *et al.* [30] showed an increase in yield for oats on a heavy clay soil in Northumberland with application of basalt. They reported increased yields, up to 20%, in crops that underperformed overall due to poor weather and late sowing, demonstrating the value of crushed rock for plants that are stressed. Naturally milled rock, glacial rock flour from Greenland, has been used in sandy soils in Denmark with increases in crop yield [48].

Other field trials, not necessarily associated with ERW, in different climates show benefits [49], with improved crop production in China (e.g., [50]). Crushed silicate rocks have long been used in Brazil [51], where a registration system for crushed rock products ideally requires a peer-reviewed publication as evidence of effectiveness [52].

In addition to work reported in peer-reviewed journal papers, there is considerable growth in the 'grey' literature (including claims made on websites by companies involved in ERW), as well as anecdotal evidence of the benefits to agriculture of application to rock dust to soils. Paul Younger would have liked the evidence that comes from conversations with farmers who have been buying 'rock dust' for years. These include improvements to biodiversity, more contented dairy cows, and reduced veterinary bills, all factors that are yet to be considered rigorously by researchers.

6. Carbon Cost of ERW

As shown in **Figure 2**, there are three components to ERW. Production of the crushed rock, the first stage in the process, takes place at fixed locations and, at scale, involves plant and machinery that is installed in the quarry with a long-expected lifetime. This equipment is usually powered by electricity, and can (as in Brazil) have a very high proportion of electric power generated from renewable sources. The second stage involves distribution to farms, where the crushed rock is spread to land. This involves a large number of 'customers', each with a unique trajectory from the source to the destination. Finally, the material is spread to land, using equipment that varies from one farm to another, but generally corresponding to equipment used to spread agricultural lime.

Detailed carbon life cycle analyses vary in their conclusions (e.g., [37,53,54]), partly because of differences in definition of the system (including differences in target particle size) as well as differences in practice. Nevertheless, the carbon cost of production in a quarry can be low compared with the benefits of CO₂ removed. Lefebvre *et al.* [53] showed that the carbon cost of quarry production in Brazil,

assuming electric power is generated using fossil fuels, is 5.4 kg per tonne of rock (similar to the carbon cost of producing 2–5 litres of milk [55]). Breunig *et al.* [37] report 'costs' of 18.38 kg CO₂ per tonne of rock, for quarry production in California. However, once the material leaves the quarry, transport and spreading become the dominant carbon cost (21.45 kg CO_{2e} per tonne of rock [37]; 75 kg CO_{2e}/tonne of rock for 65 km transport [53]). Similarly, for a cradle to farm gate analysis in the US, Zhang *et al.* [56] estimate a total of 41 to 359 kg CO_{2e}/tonne of CO_{2e} captured, consistent with the value reported for 65 km transport by Lefebvre *et al.* [53], which was equivalent to 250 kg CO_{2e}/tonne of CO₂ captured.

These studies emphasise the need for carbon life cycle analyses to be carefully tailored to specific circumstances, especially as reduction in particle size to increase reactive surface area and transport are dominant components. Care needs to be taken when comparing published carbon life cycle analyses, as system definition differs from one study to another. It is important to minimise transport distances between the source and the location where the rock is to be spread [54]. It needs to be remembered, however, that the production in quarries of crushed rock for construction is necessarily a very efficient process, because of the need to supply aggregates in large quantities to construction markets. The quarrying industry has reduced costs to a minimum, especially those associated with energy use. This efficiency is reflected in the low price of the crushed rock products, the USGS [57] giving figures that suggest an average of US\$17/tonne in the USA, which will of course vary from product to product.

7. Conclusions

Enhanced rock weathering is a nature-based solution designed to remove atmospheric CO₂, much in the same way, conceptually, that reed beds are designed to remove contaminant metals from polluted waters, especially from old coal mines. With his strong social conscience, Paul Younger would have grasped the opportunity to lead work on ERW with tremendous energy. Sadly, that was not to be, but his inspiration drives his successors, former students and colleagues.

There is growing interest in ERW, especially amongst students who now can see the point of learning about the rock forming minerals. There's a new sense of purpose. ERW is an energetic and growing field of research, where it is vital to remember and to use the basic science, traditional hard-rock geology, that was taught to Paul's generation so many years ago.

Declarations

Competing interests

The author has declared that no competing interests exist.

Acknowledgements

The author acknowledges the many conversations he has had with others with interests in Enhanced Rock Weathering, in industry and academia.

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