Deltares

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Date	Our reference		Number of pages
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Subject
Update CO2 sequestration potential Basalt

Dear Mr Faber,

In 2023 The Balkan Basalt Holding commissioned Deltares to conduct a literature study for the first exploration of the potential of basalt for CO_2 sequestration, this literature study resulted in a memo. In 2025 The Balkan Basalt Holding commissioned Deltares to conduct an additional literature study to update the previous memo dated from 2023 with the newest developments on basalt sequestration. This document contains the updated memo.

Yours sincerely,

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1 Introduction

The Balkan Basalt Holding owns and operates a basalt mine in Spaç, Albania. The basalt extracted from this mine is mainly used in crushed stone or dike revetment. In addition to this use, they want to investigate the potential of basalt for the sequestration of carbon dioxide (CO_2) from the atmosphere, with the following main questions:

1. Does basalt sequester CO_2?
2. Is CO_2 sequestered sustainably?
3. How much CO_2 can potentially be sequestered?
4. What does the efficiency with which CO_2 is sequestered depend on?
5. What does the rate at which CO_2 is sequestered depend on?
6. What is the impact of the chemical/mineralogical composition?
7. How does the chemical composition of basalt from Albania relate to other sources?

These questions were briefly addressed in a memo completed in 2023. The current document contains an update of the 2023 memo with the newest developments on basalt sequestration.

2 Sequestration of CO_2 by basalt

Global climate change is caused by anthropogenic emissions of greenhouse gases, mainly CO_2. To limit the far-reaching consequences of climate change as much as possible, a reduction of emissions is required. In addition, limiting global warming to a maximum of 2 °C requires sequestering CO_2 directly from the air [1]. One of these options is the geochemical sequestration of CO_2 in rocks, such as basalt. Basalt is a rock formed by the solidification of lava at the earth's surface, with a silica content between 45 and 52%. Basaltic rock contains potentially reactive elements such as calcium (Ca), magnesium (Mg) and iron (Fe). The sequestration of CO_2 by basalt is based on the reaction of CO_2 with these reactive elements, denoted in the equation below by "X" . In the presence of water, this reaction leads to the formation of bicarbonates and dissolved cations (Ca^{2+}, Mg^{2+}, or Fe^{2+}; see Figure 1) [2],[3]:

$$XSiO_3 + 2CO_2 + 3H_2O \rightarrow X^{2+} + 2HCO_3^- + H_4SiO_4$$

Depending on the conditions under which this reaction takes place, such as pH, the bicarbonate with the reactive elements will precipitate as calcium, magnesium, or iron carbonate: depending on the conditions, these newly formed carbonate minerals are stable:

$$X^{2+} + HCO_3^- \rightarrow XCO_3 + H^+$$

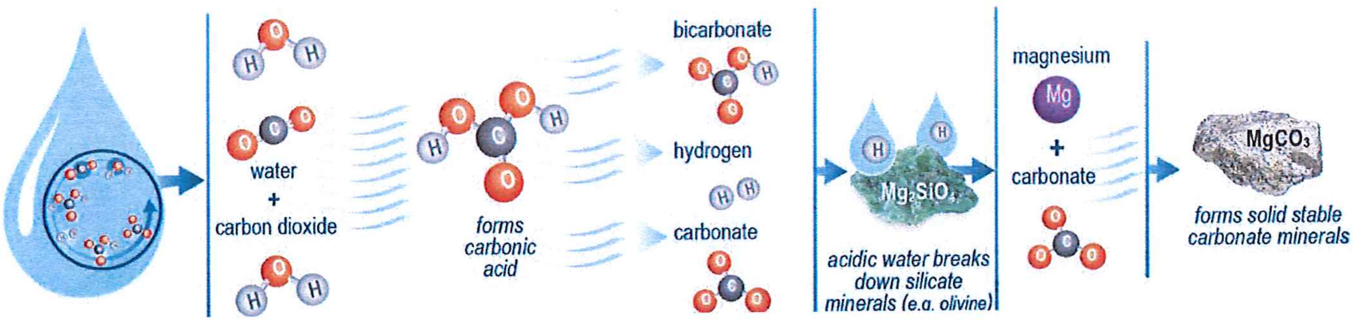

Figure 1. Schematic representation of the uptake of CO_2 by basalt, from Raza et al., 2022 [30]

On average, basalt is made up of ~25% by weight calcium, magnesium, and iron oxides and occurs naturally all over the world. Approximately 60% of the earth's total surface, including the ocean floor, and 10% of the continental surface consists of basalt [4]-[6]. In the presence of water, basalt reacts relatively quickly with CO_2, this reaction takes place without the need to add extra energy [6]. The CO_2-binding capacity and ample presence of basalt make it an interesting rock to sustainably capture CO_2.

Over the years the potential of basalt to sequester atmospheric CO_2 has been studied in various ways. Roughly, there are two main research directions in which the CO_2 sequestration was investigated. There have been experiments with injecting CO_2 into basaltic rocks, such as in the USA and Iceland [6]-[10]. A large part of the injected CO_2 turned out to be mineralized in this way, and thus sustainably captured; around 95 % in Iceland, where the CO_2 for injection was dissolved [5],[7],[11], and 60 % in the US [10]. Due to the lack of direct applications in the Netherlands and despite potential applications in Albania, this track has not been further developed.

In addition, many studies have been done on the addition of (ground) basalt to the (agricultural) soil [12]-[21]. This option is interesting both for use in the Netherlands and in Albania and thus for Balkan Basalt Holding. Therefore, this memo elaborates only on the latter application.

2.1 Uptake of CO_2 in basalt by weathering (Enhanced Weathering)

The processing of crushed basalt in (agricultural) soil to capture CO_2 is also called 'enhanced weathering' (EW). This is based on the idea that the natural weathering of rocks such as basalt is accelerated, for example by increasing the (surface-) area and/or optimising exposure (to water), and/ or chemical- agricultural conditions, by facilitating the absorption of CO_2 by basalt [16]. This method to use basalt as a CO_2 sink can be applied in areas where basalt does not naturally occur. However, in such cases a complete CO_2 balance must be made [17],[22].

In a recent field trial in Belgium by Vienne et al. [13], 50 tonnes of crushed basalt per hectare were added to a test field with potatoes. The model they developed based on this, predicted a CO_2 uptake of 1.83 tonnes of CO_2/ha after one year, and 4.48 tonnes of CO_2/ha after five years. That comes down to about 3-4% absorption after 1 year to 10% after 5 years. It should be noted that these levels could not be analytically determined during the trial period (99 days) and were therefore only calculated with models.
However, strongly elevated concentrations of calcium and magnesium in pore fluid were measured, which indicates the release of these reactive elements from the basalt [20]. In a laboratory experiment by Van der Kloot et al. [19] in which CO_2 reacted with basalt in tropical climate conditions, an uptake of 2.8 to 6.8 tonnes of CO_2/ha per year was calculated, whereas in a model calculation by Lewis et al. [17] in Northern European climate conditions, an equivalent of 50 tonnes of basalt per hectare of agricultural land showed an absorption capacity of CO_2 between 1.3 and 8.5 tonnes per hectare after 15 years[1]. A team of researchers calculated that the application of basalt to arable land in the United Kingdom could sequester 6 to 30 megatons of CO_2 per year [13].

Beerling et al. (2024) conducted a large-scale field trial on a maize-soybean rotation farm in the United States and quantified a carbon dioxide removal (CDR) potential by assuming that the loss of major cations Ca^{2+} and Mg^{2+} from basalt is balanced by the formation of bicarbonate ions (see beginning of this chapter and figure 2 for more information) resulting in a conservative time-integrated cumulative CDR potential of 10.5 ± 3.8 t CO_2 ha^{-1} after cumulative addition of 200 t ha^{-1} of crushed basalt (50 t ha^{-1} y^{-1} for four years). However, a field trial in Australia showed different results. Holden et al. (2024) conducted a 5-year field experiment in which a cumulative addition of 250 t ha^{-1} of crushed basalt (50 t ha^{-1} y^{-1})

[1] Since most studies involve lab tests or model calculations, often 50 tonnes/hectare has not actually been added, but an equivalent of this. Adding 50 tonnes of basalt to 1 hectare corresponds to 1.7 mm basalt with an average density of about 3 g/cm^3.

resulted in a statistically insignificant in-field CDR of 0.026 t CO_2 ha^{-1} y^{-1}. Holden et al. (2024) indicates that low soil pH may have been partially responsible for low CDR, because of the effects of pH on carbonate equilibria, and that an increased soil pH with continued basalt addition will eventually lead to increased CO_2 sequestration.

Even though currently global scientific research is being done into the sequestration of CO_2 in basalt, there are still many uncertainties about the absorption capacity in the field. Most studies in the field of EW that have so far measured or calculated an absorption capacity are based on models or controlled laboratory experiments. So far, this provides a good indication and a proof of concept. However, additional field trials are necessary to determine capacity and determine in-field factors influencing actual CO_2 uptake, such as pH. An overview of measured and calculated absorption capacity of basalt by means of EW was summarized in the earlier memo in 2023, see Table 1 in Appendix 1, no adjustments were made to this table in 2025.

2.2 Additional effects of the application of basalt

In addition to the CO_2 absorption capacities of basalt, research shows that the addition of basalt has positive effects on agricultural land and the crops grown on it. The Netherlands has a relatively large agricultural area, namely 2.2 million hectares, which accounts for approximately 54% of the total surface area of the Netherlands (4.2 million hectares) (CBS)[2]. The surface area of Albania is about 2/3rd of the Netherlands (2.9 million hectares), of which approximately 1.18 million hectares has an agricultural purpose (40%)[3]. For example, Kelland et al. (2020) found a positive effect of basalt addition on harvest yields of approximately 20% of the grain *Sorghum bicolor*, and Skav et al. (2024) found up to 21 % higher yields in spring oats after basalt application. Kelland et al. attribute this effect to the silicates, which would increase the plant's resistance to abiotic and biotic stressors [14]. This may be an indication that the addition of basalt could reduce the use of fertilizers [13]. Beerling et al. (2024) also observed significantly ($P < 0.05$) increase maize and soybean yields of up to 16%, a result they attribute to, amongst others, improved soil fertility and decreased soil acidification following EW. Beerling et al. (2024) also attribute yield enhancements to significantly increased micro- and macronutrient concentrations (such as magnesium and phosphorus), which in turn lead to improving or maintaining the nutritional status of the crops (maize and soybean). Research by Desmalles et al. (2025) does indicate that the effect of basalt application on harvest yield could be largely dependent on soil type: yield gains of rye grass were reaching approximately 30% on sandy soils, however no significant yield gains were observed in silty clayey soils. It should be noted that this additional crop yield, contributed to the basalt addition is an indirect CO_2 sequestration effect.

No elevated concentrations of trace metals were found by Kelland et al. (2020) and Beerling et al. (2024) and no accumulation of potentially toxic elements, such as cadmium or nickel, were detected in the spring oats by Skav et al. The latter results indicate that these crops would be safe for human consumption.

In addition, adding basalt increases the pH of the soil. A study by Desmalles et al. (2025) showed an increase in soil pH of between 0.5 and 1 pH point after application of basalt dust. Current common practice is to use calcium carbonates, or calcium oxides to increase the soil pH, calcium oxides do take up CO_2, but this CO_2 was released during their production, calcium carbonates do not take up CO_2 from the atmosphere, but do release bicarbonates in the groundwater . This indirect additional effect is not considered quantifying the current CO_2 sequestration potential. In acidified (sandy) agricultural soils, a higher pH has a positive effect on the retention of nitrate, phosphate, and other substances. It could also have a positive

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[2] Translaters note: CBS is the Dutch abbreviation for *Centraal Bureau voor de Statistiek* = Statistics Netherlands.
[3] Information retrieved from https://agriculture.ec.europa.eu/international/international-cooperation/enlargement/candidates_en.

effect on the retention of (ground) water, although less attention is paid to this in the literature. This reduces emissions of nitrous oxide (N2O), a strong greenhouse gas, from the soil [23]. Basalt increases the uptake of silicates by the crops, which in turn could lead to reduced toxicity by aluminium, increased availability of nutrients such as potassium, phosphorus, and calcium. This leads to increased resistance of the crops to pathogens and insects [20], [24]. Elevated concentrations of silicates when basalt is applied to agricultural land have been measured in for example wheat, barley, and sugar beet [25].

3 Is CO_2-sequestration with basalt sustainable?

CO_2 converts into carbonate minerals such as calcite/ aragonite ($CaCO_3$), siderite ($FeCO_3$) and dolomite/ magnesite ($CaMgCO_3$) when reacted with basalt. These minerals are in potential geologically stable, i.e. difficult to dissolve, but can (partially) dissolve through exposure to acids. Sequestration of CO_2 by means of EW ensures that the minerals formed via drainage water in the soil would eventually end up in the ocean, where it is estimated that they are stable for a period of 100,000 to 1,000,000 years [26]. For storage of CO_2 by injection into rocks, it has been modelled that a leakage of 1% or less CO_2 into the atmosphere over a period of 1000 years is required to ensure a future with limited warming (a maximum of 2.0°C); Sequestration of CO_2 with basalt thus contributes to the CO_2 reduction required for achieving climate goals [27].

4 Factors influencing the sequestration of CO_2 by basalt

Several factors play an important role in the sequestration of CO_2 by basalt. First, the chemical composition of the basalt is important. The higher the concentration of magnesium, calcium, and iron, the higher the potential absorption of CO_2 that can be achieved. A 2012 study injecting CO_2 found a direct relationship with the magnesium concentration in basalt and the CO_2 uptake capacity of the basalt, with an average content of 8% MgO leading to a maximum conversion to magnesite of 0.087 g CO_2/g basalt [28]. In a column test with soil in Germany, a capacity of 0.2-0.4 g CO_2/g basalt was measured (D. Paesler, pers. comm.).

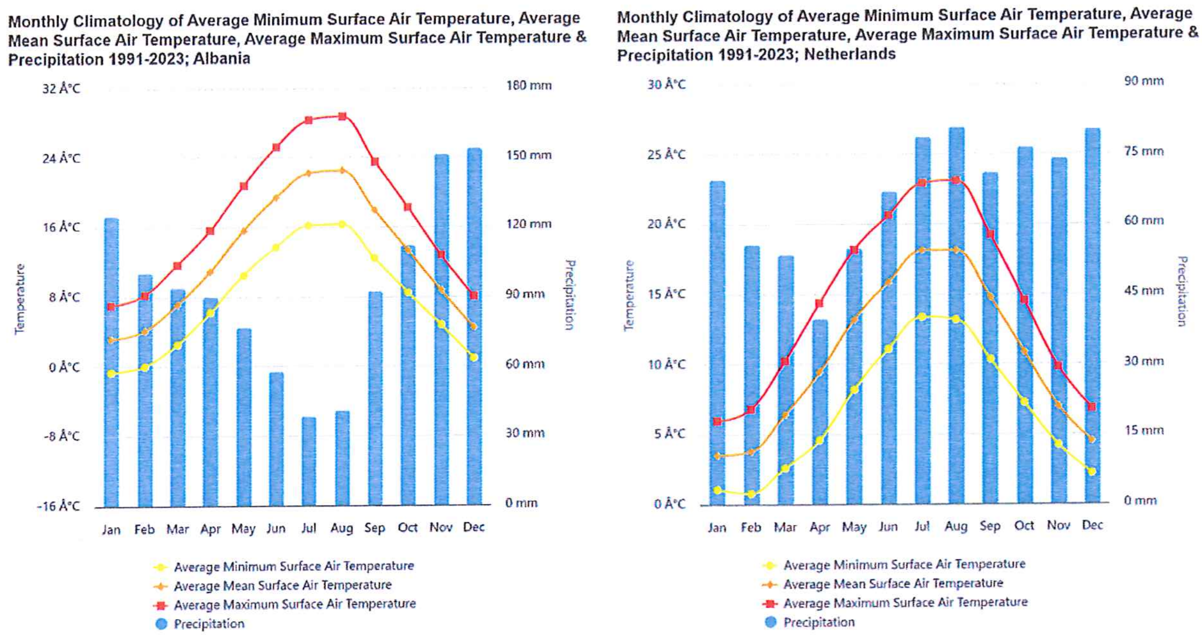
Temperature, precipitation, and grain size also play a role, whereby the law applies that a higher temperature, more precipitation (or irrigation) and a smaller grain size are conducive to the speed, but not the capacity, at which the CO_2 is sequestered [19]. In addition, the pH of the soil also affects the reaction rate of the silica minerals in basalt with CO_2 and the stability of the precipitated CO_2-minerals. This is important, for example, for the rate at which the cations (Ca^{2+}, $Mg^{2+,}$ or Fe^{2+}) dissolve, making them available for reaction with CO_2. For some minerals (such as olivine), a low pH promotes this solution; for others (such as Ca-plagioclases), a high pH is conducive to dissolution [20]. Also the presence of competing acids plays an important role in the potential CO_2-sequestration.

The presence of biota, especially microorganisms, can also affect the sequestration of CO_2. For example, certain enzymes can accelerate the formation of bicarbonates from basalt [20],[29]. Finally, the particle size, and thus the available reaction surface of the basalt, are also important, whereby a small particle size leads to an increased CO_2 absorption rate. Two different studies state that a 10-fold reduction in grain size corresponds to a doubling of the reaction rate [17],[19].

Albania has a subtropical Mediterranean climate, with, on average, higher temperatures than in the Netherlands, which is favourable. The basalt mine of the Balkan Basalt Holding is located in the Northern part of Albania, which is amongst the regions with the highest amounts of rainfall[4]. In figure 2 a comparison between the average climatical conditions in The Netherlands and Albania is made. As mentioned in the previous chapter both higher

[4] Information retrieved from https://climateknowledgeportal.worldbank.org/country/albania.

temperature and higher precipitation level are conducive to the speed at which the CO_2 is sequestered.



– *Figure 2 Average minimum, mean and average surface temperature and precipitation of Albania (left) and The Netherlands (right) from climateknowledgeportal.worldbank.org.*

5 How does the chemical composition of basalt from Albania compare to other sources?

The basalt extracted at a depth of 35m in the basalt mine of the Balkan Basalt Holding contains 48.8% SiO_2, 9.83% CaO, 6.62% MgO and 14.01% Fe_2O_3. This data was provided by Balkan Basalt Holding, the variation within the mine is unknown. Important to note is that the nickel concentration is <0.01% and therefore this basalt meets the standards for subsidy material for agricultural land in the Netherlands, EU and Albania[5].
As mentioned earlier, the potential of basalt to sequester CO_2 mainly depends on the concentration of calcium, magnesium, and iron. In comparison, the basalt used in the experiments and modelling of Vienne et al. (2022) as mentioned in section 2.1, contained 12.9% MgO and 10.8% CaO; With this basalt, they calculated an absorption capacity of about 9% after five years [20], Vanderkloot's group tested different types of basalt, the basalt with a composition of 7.14% MgO and 11.29% CaO, which can be compared to the basalt of the Balkan Basalt holding, had an absorption capacity of 8 to 9% after 1 year [19] (Ø=150-450µm).

The group of Lewis and colleagues investigated the absorption capacity of six types of basalt with varying compositions, showing that the CO_2 absorption capacity depends on the magnesium and calcium concentration [17] (see also Table 1 in the Appendix).

In addition to the chemical composition the mineralogical composition is also important, i.e. the structure in which the elements occur. This is also important for the use of basalt in agriculture. Lewis and colleagues have shown that the amount of phosphorus (P) and

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[5] VERORDENING (EU) 2019/1009 VAN HET EUROPEES PARLEMENT EN DE RAAD van 5 juni 2019

nitrogen (N) that rocks can release when used in agriculture is highly dependent on the type of mineral these substances are found in [17]. The mineralogical composition of the rock of the Balkan Basalt holding is not known to us, so a comparison with this study cannot be made.

Of most interest for the Balkan Basalt Holding are basaltic particles of 0-4 mm as these are a by-product and therefore currently considered of no economic value. The literature on EW typically focusses on particles smaller than 100 µm in diameter as a key area of focus, however, various studies were conducted using coarse basalt particles (ranging from 0-5 mm) (Desmalles et al., 2025; Skov et al., 2024).

6 Examples of basalt applications

6.1 Basalt applications in the field

Basalt applications in the field are not limited to those applications linked to scientific research. Currently the UK-based company UNDO is carrying out multiple projects where ground basalt is applied to agricultural fields in the UK and Canada. On their website they sum up their current accomplishments so far, showing the scale of their work: 292,660 tonnes of rock[6] spread over 19,730 hectares across the UK on 350 farms, thereby removing 64,471 tonnes of CO_2[7]. UNDO also collaborates with scientists, a collaboration with Newcastle University recently lead to the peer-reviewed paper 'Initial agronomic benefits of enhanced weathering using basalt: A study of spring oat in a temperate climate' (Skav, 2024), which was cited earlier in this memo. Another example of a company carrying out projects in which they apply basalt on agricultural land is InPlanet. This company is based in Germany, but focusses on tropical agriculture area's. The basalt is mined in mines in Brazil and applied in proximity of these mines.

6.2 Certified carbon removal

InPlanet worked together with Isometric to deliver the first verified carbon removal credits through enhanced rock weathering of crushed basalt in early 2025[8]. These carbon credits are aligned with the Isometric Standard[9], which ensures that carbon removal projects are validated and verified. Isometric only issues carbon credits for the removal of atmospheric CO_2, all carbon removals should be verified against the Isometric Certified Protocol. The maximum crediting period is 5 years.

UNDO aligned their method of enhanced weathering with the ICROA[10]-endorsed Puro Standard methodology, underlining that by enhanced weathering CO_2 can be stored sustainably, as one of the ICROA endorsement criteria is 'Carbon credits are issued for permanent emission reductions or removals'[11]. The Puro Standard methodology ensures a framework for certifying engineered CO_2 removal and issuing carbon credits[12]. Various steps need to be taken in order to obtain a certificate by Puro earth for certified carbon removal and issue carbon credits. These steps are described in the Puro Standard General Rules, the certification process consists of three phases: project development, project validation and performance validation, of which the latter two are included in the Puro Standard General Rules[13]. Despite UNDO complies, and follows these rules, at this moment they have not

[6] UNDO focuses on both basalt rock and wollastonite, another silicate rock, so this number includes both basalt and wollastonite.
[7] https://un-do.com/, consulted on 06-08-2025.
[8] See https://inplanet.earth/press/worlds-first-enhanced-rock-weathering-carbon-removal-credits-issued/.
[9] See https://registry.isometric.com/standard#introduction.
[10] International Carbon Reduction and Offset Alliance
[11] See https://icroa.org/standard-endorsement/#criteria
[12] See https://puro.earth/
[13] See https://puro.earth/document-library?tab=standard_documents

successfully claimed carbon credits yet. It is unknown in which timeline they are able to claim these credits successfully, however, the crediting period is set to 15 years.

7 Conclusion

Through the "enhanced weathering" of basalt by adding it to agricultural land, CO_2 will be sequestered in geologically stable minerals. How efficiently this is done depends on several factors: First, the chemical and mineralogical composition of the basalt, where a high concentration of magnesium, calcium and, to a lesser extent, iron are conducive to its absorption capacity. For the rate at which CO_2 is absorbed by the basalt, both abiotic (temperature, rainfall, pH, grain size) and biotic (microbes) factors are important when used in agriculture. Laboratory experiments and (reaction) models have shown that basalt used as a soil improver can absorb a maximum of 10% of CO_2 per year, i.e.1 ton/per year of CO_2 can be sequestered for 10 tonnes of basalt.

For basalt, with the chemical composition of Balkan Basalt Holding, the maximum total uptake of CO_2 will further increase to a maximum of 20-25%, of which approximately 110 million tonnes are available. An uptake of 20-25% corresponds to 4-5ton of basalt sequestrate 1 ton of CO_2. Field experiments have so far shown contrasting results with regards to the CDR potential of enhanced weathering of basalt. Targeted field experiments are still needed to further investigate the CO_2 sequestration rates of basalt and determine the role of internal (such as the composition of the basaltic rock) and external (such as pH) factors on CO_2 sequestration.

In addition to the CO_2 sequestration potential of basalt, several studies show that adding basalt to agricultural soil has positive effects like combating acidification in the soil, improved soil fertility, leaching of nitrate, phosphate, and the availability of potassium and magnesium. Furthermore, application of basalt can have a positive effect on crop yields, maintaining crop nutritional status and increase the resilience of the crops to both biotic and abiotic stressors. Which has an indirect CO_2-sequestration effect, these effects are not taking into account when quantifying the above mentioned CO_2 uptake potential.

Various field applications of basalt additions to agricultural land are known and the application of basalt as a carbon removal strategy has been aligned with both the Isometric standard and the Puro standard technology for certified carbon removal, enabling the issuing of carbon credits. Currently only InPlanet and Isometric have successfully developed and delivered carbon removal credits.

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9 Appendix

Table 1: Uptake capacity calculated or measured in different basalt experiments. EW = Enhanced weathering (see Section 2.1), NB = not known/calculated

Reference	Method (application-form)	Abiotic conditions	Basalt - origin	Basalt – grain size	Period measured	lab/ field/ model	Absorption capacity (tonnes CO_2/ha)	Quantity of basalt for calculation of absorption capacity (tonnes basalt / ha)*	Percentage absorption capacity CO_2 per mass basalt after 1 year
Vanderkloot et al. [19]	EW	Tropical climate	Blue Ridge Province, Virginia, VS	150-500 µm	2 weeks	lab/model	2,8 per year	50	5,6
Vanderkloot et al. [19]	EW	Tropical climate	Blue Ridge Province, Virginia, VS	<45 µm	2 weeks	lab/model	6,8 per year	50	13,6
Vanderkloot et al. [19]	EW	Tropical climate	Pioneer Valley Basalt, Massachusetts, VS	150-500 µm	2 weeks	lab/model	4,0 per year	50	8
Vanderkloot et al. [19]	EW	Tropical climate	Pioneer Valley Basalt, Massachusetts, VS	<45 µm	2 weeks	lab/model	6,7 per year	50	13,4
Kelland et al. [14]	EW	Northern European climate	Cascade Mountain Range, Oregon, VS	80% <1250 µm	120 days	lab/model	2-4 t over 1-5 year	100	2 tot 4
Kantzas et al. [13]	EW	Northern European climate	NB	NB	NB	model	1,6 – 8,1 per year	NB	NB
Lewis et al. [17]	EW	Northern European climate	diverse	diverse	NB	model	1,3 – 8,5 t after 15 year	50	2,6-17 after 15 year

Amann et al. [12]	EW	Northern European climate	dunite (olivine)	NB	340 days	field (mesocosm)	0,023-0,049 per year	220	0,01-0,02
Vienne et al. [20]	EW	Northern European climate	DURUBAS basalt	99% < 500 µm	99 days	field (mesocosm)	0,77 after 99 days	50	1,5 after 99 days
Vienne et al. [20]	EW	Northern European climate	DURUBAS basalt	99% < 500 µm	1 year	model	1,83 after 1 year	50	3,7 after 1 year
Vienne et al. [20]	EW	Northern European climate	DURUBAS basalt	99% < 500 µm	5 year	model	4,48 after 5 year	50	9,0 after 5 year
Matter et al. [7]	Injection	Northern European climate	IJsland	NB	2 year	field	NB	NB	95 after 2 year
White et al. [10]	injection	Mediterrean/continental	Colombia river basalt (VS)	NB	2 year	field/model	NB	NB	60 after 2 year

*Since most studies involve lab tests or model calculations, often 50 tonnes/hectare has not actually been added, but an equivalent of this. Adding 50 tonnes of basalt to 1 hectare corresponds to 1.7 mm with an average density of basalt of approximately 3 g/cm^3.