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Mineral Carbonation using Mine Tailings – A Strategic Overview of Potential and Opportunities

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MINERAL CARBONATION USING MINE TAILINGS

- A STRATEGIC OVERVIEW OF POTENTIAL AND OPPORTUNITIES

KEY MESSAGES

- Three decades of research and development work on accelerated mineral carbonation (AMC) has demonstrated that ultramafic, magnesium rich minerals in mine waste materials has the potential to sequestrate CO₂ via mineralisation. However, despite three decades of R&D most concepts have not advanced beyond Technology Readiness Level (TRL) 4.¹
- Although the stockpiled amounts of material are vast, the suitability of these materials is highly dependent upon specific conditions imposed by mineralogy, geochemistry, petrology, permeability and hydrology. AMC treatment and effectives is therefore highly site-specific.
- The limited scale-up from laboratory-scale investigation is partly due to the energy requirements and chemical kinetics to a timeframe of minutes rather than hours or days, as is still commonly being reported.
- Carbonation of mine wastes using CO₂ divided into two broad groups: direct carbonation, which often ends in struggling with a passivating silicate layer that prevents rapid chemistry and high conversion levels; while the second group focusses on stepwise extraction and conversion aimed at reaching higher conversion levels in shorter times.
- Extraction methods can produce materials of marketable value. The evidence from this review is that there are very few AMC approaches that could be economically viable at an industrial CO₂ mineralisation scale in a single facility.
- Although most AMC technology related to Mg rich waste streams is still at TRL 4 a few have progressed to TRL 6 or 7. One company, Mineral Carbon International (MCi), reported in 2021, that its aqueous process has advanced from TRL 6 to TRL 7. The company has received support to develop the technology subject to the results of final pilot studies and engineering designs.
- Calcium-based AMC has niche deployment opportunities as a result of the large markets for calcium carbonate based products. The relative reactive properties of calcium compared with magnesium means that the chemistry is less challenging than for conversions that produce magnesium carbonate.
- There have been very few cost assessments to determine the potential for commercial AMC deployment, even when possible revenues from the sales of metals or other by-products have been included. The most promising candidates for marketable products from AMC using magnesium silicate-type rock feedstock is nesquehonite (MgCO₃·3H₂O). However, large-scale production could lower the price to uneconomic levels.
- There is a lack of reported evidence on the economic effectiveness of metal recovery from mine waste.
- Adverse environmental impacts caused by handling Mg-rich silicate host rocks include toxic metallic by-product streams, and other problematic solid, liquid or gaseous effluents, that can be produced by processing mine wastes. This aspect has received less attention.
- Life cycle assessment (LCA) tools are being increasingly used to quantify the environmental footprint of AMC. The technique does require impacts such as land use, water use and resource depletion as well as the benefits from a reduction in global warming potential.
- Deployment of large AMC facilities presents a public acceptance challenge which has yet to be adequately addressed. Experience from CarbFix does show that positive engagement with the public can produce favourable attitudes to power generation and associated environmental impacts. In this case subsurface *in-situ* carbonation.

¹ TRLs are a useful method for understanding the technical maturity of a technology. TRL 4 is the fourth level out of nine possible levels with nine being the highest.'



BACKGROUND

There is widespread recognition that naturally occurring ultramafic rock formations, with high concentrations of Mg and Ca silicates, react with atmospheric CO_2 to form Mg and Ca carbonates. Significant concentrations of key industrial mineral resources are often present in ultramafic formations, notably nickel, PGE, Chromium. Consequently, there are large accumulations of mine tailings with the potential to react and sequester CO_2 either as a solid phase carbonate or modified into a useful material. Countries with mineral resources hosted in ultramafic formations such as Canada, the USA, South Africa, Finland and Norway have been actively investigating the potential to use mine tailings as a means of *ex-situ* CO_2 sequestration and the potential for reuse or additional mineral recovery.

The most promising route proposed for *ex-situ* mineral carbonation is aqueous processing of Mg and Ca rich naturally occurring silicate minerals. The overall carbonation reaction consists of the dissolution of MgO- or CaO-bearing silicates such as olivine, serpentine, and wollastonite, followed by the precipitation of carbonates such as magnesite and calcite. Experimental investigation of both dissolution and the precipitation processes has been conducted in recent years.

There are, however, a number of complicating factors that need to be taken into consideration. Mine tailings are heterogeneous with varied compositions depending on the host geology of each location. Research results show that different Mg-rich minerals react at different rates as the reactivity of Mg-silicate rocks is a function of both chemical and physical properties of rocks. Slow kinetics of mineral–fluid reactions, and dealing with the large volume of source material, plus the energy needed to hasten the carbonation process, and related adverse environmental impacts presents significant challenges.

Carbonation treatment processes of mine waste tailings with high concentrations of Mg-silicates have been advocated as a CO₂ mitigation option that could incorporate recovery of valuable metals. Accelerated mineral carbonation might provide an economic incentive to develop this technology.

This review provides an overview and an assessment of the current status of CO_2 mineral sequestration, also referred to as accelerated mineral carbonation (AMC). The technology is based on processes that accelerate natural carbonation reaction rates to enhance CO_2 capture and achieve economic quantities of valuable metals. One of its attractions is the use of significant quantities of tailings, overburden and other residues that have accumulated at mining sites.

The review has assessed the current TRL status of AMC, its techno-economic viability, environmental benefits and drawbacks. It has also attempted to assess the most promising products and markets for recoverable valuable materials, with emphasis on metals (PGE's, REE's, Cr, Ni, V, Mg). Materials for civil construction and other applications sourced from carbonated Ca minerals forms a minor part of the investigation.

SCOPE OF STUDY

The aim of this review is to evaluate the techno-economic viability of AMC, and the comparative maturity of the technology, based on publicly available information. This report is primarily concerned with magnesium-silicate rich mine tailings and *ex situ* processing to induce carbonation suitably reactive rock. Magnesium silicate rocks can potentially offer significant volumes of material for CO_2 capture compared with calcium-based materials

In-situ AMC, relies on the comparatively rapid carbonation caused by CO_2 from the air reacting with tailings and other residues at mining sites. Direct injection of CO_2 (dissolved in water) into Mg-rich reactive rock formations, is also covered in this review. This approach has been an active area of



research in recent years, as about a quarter of the literature listed since 2016 deals with *in-situ* cases. Most in situ development has taken place in three sites in Iceland (CarbFix), Canada and Australia.

It is important to reiterate that the scope of this review is primarily to address *ex-situ* CCU, rather than *in-situ* CCS, although many mining operations may offer opportunities for effectively and successfully incorporating both. It is also useful to distinguish between waste generated at the mine site and that produced during metallurgical processes, as reactive properties may vary considerably. Figure 1 is an attempt to further clarify definitions of mine waste, including overburden, which may be ultimately be used again in site restoration and stockpiling of low-grade ore. This material may be refined at a later date, or used as backfill in underground workings or open pits. Tailings are mineralogically refined and enriched as a result of the processing and can therefore be expected to behave differently with respect to *in-situ* sequestration; the presence of water and sulphide phases is, for example, significant in this regard.



Figure 1 Summary of mining waste, mineral and metallurgical materials

The report is divided into three parts which address: magnesium-based resources (Part 1), the main focus of this report; followed by much shorter Parts 2 on calcium-based resources; and Part 3 on *insitu* CO₂ mineralisation process cases. Part 1 is further subdivided into four sections that separately consider years 1990-2009, 2010-2015 and years 2016-today, plus a section that assesses the status from the viewpoint of the key performance indicators. The appendices include tables with compilations of worldwide resources of potentially suitable feedstock rock, and a brief description of the variations of the so-called Åbo Akademi (ÅA) University route. This approach has resulted in five different variations of *in situ* AMC. The preferential input rock is serpentinite, containing primarily serpentine, $3MgO-2SiO_2\cdot 2H_2O$, or $Mg_3Si_2O_5(OH)_4$ besides some other species, primarily iron oxides and silicates.

STUDY FINDINGS

The two major mineral carbonation categories have been sub-divided into direct and indirect carbonation illustrated in the Figure 2.





Highlights / advancements 1990 – 2009:



- The concept of mineral carbonation was introduced (and large potential quickly grasped)
- Most abundant and suitable minerals were identified (olivine, serpentinite)
- Multiple routes have been identified, the most promising being additive enhanced (0.64 M NaHCO₃ and 1 M NaCl) direct aqueous carbonation
- Multi-step routes introduced for producing high-value products (product valorisation)
- *In-situ* mineral carbonation was introduced
- Investigations into various industrial waste and by-product streams started
- Understanding that using pure CO₂ is too expensive, use of CO₂ containing flue gas should be pursued instead

Remaining priority issues that were not addressed during the review period 1990 – 2009:

The main issues hindering mineral carbonation from advancing on the technology readiness level (TRL) ladder at the end of 2009 were:

- Extracting or activating the reactive component MgO from a silicate mineral
- Speeding-up the carbonation chemistry kinetics
- Energy economy (noting in particular that the heat produced of the exothermic carbonation reaction was not actively considered / utilized in the processes)
- Recovery and recycling of chemicals used.

Prior to 2010 most AMC was conducted at laboratory scale. In 2011 a field trial where flue gas from a large coal-fired power plant was reacted with fly ash. This experiment demonstrated CO_2 capture via mineralisation, but reduction levels were modest from 13.0% to 9.6%. A research project in China in 2013 successfully extracted Ca from fly ash with the help of ammonium salts. In this process, up to 93 % of the Ca precipitated as CaCO₃ (precipitated calcium carbonate, PCC). Furthermore, the purity of the PCC was up to 98 %, making it suitably clean for industrial use.

A multi-step pH-swing process to obtain Mg suitable for CO_2 sequestering was reported in 2014. The goal was also to extract other valuable metals from the raw material, in this case a mineralized ore sample. Different forms of magnesium carbonate (MgCO₃) and iron hydroxide Fe(OH)₂ were obtained. Moreover, the research group was able to get a purity > 99 % for the MgCO₃.

Between 2010-2015 there was significant activity in Canada AMC based on mine rock waste. One of the general conclusions from this period is that brucite-rich ores from nickel mines can offer a significant passive or accelerated carbonation potential. However, under certain conditions the formation of nesquehonite (MgCO₃·3H₂O) produces a passivating layer that chemically inhibits carbonation on the brucite surface and the availability of water also limits the progress of carbonation.

In Finland, at the Åbo Akademi (ÅA) University, research into stepwise carbonation of serpentinite was published in a large number of reports on the thermal extraction of magnesium using ammonium sulphate, the production of magnesium hydroxide and the carbonation of this in a gas/solid pressurised fluidised bed. Of significance from this time was detailed analysis of the role of water vapour during magnesium hydroxide (Mg(OH)₂) carbonation and the details of the decomposition of ammonium sulphate flux salt during the thermal extraction of magnesium.

Life Cycle Assessment (LCA) based on CO_2 mineralisation was investigated between 2010 – 2015. Significantly LCA applied to the application of AMC using serpentinite at a Combined Cycle Gas Turbine (CCGT) power plant was reported. The best results (obtained without CO_2 pre-capture) gave an avoided 55-66% CO_2 emissions, dropping to 42-58% when the impact of shipping and mining was included. Emissions of NOx, SOx and particulate matter were accounted for in the LCA. Estimated system costs in the range 71 – 159 US\$/t CO_2 were calculated, which corresponds to 18 - 40 US\$/t solid products for land reclamation.



An evaluation of aqueous mineralisation applied to eleven alkaline feedstocks (olivines, a serpentine and several industrial alkaline by-products) for 1,000 t/day CO_2 sequestration was conducted during this period. The lowest CO_2 emissions (267 kg/t CO_2 processed) were obtained with 10 μ m olivine particles (155°C, 90 bar, 24h). The impact of energy input for upstream and downstream process steps, and water use, were also considered. Avoided CO_2 emissions equal to 317 and 483 kg/t mineralised CO_2 for these processes were reported. However, it was concluded that with a CO_2 capture step, (involving solvent-based capture of industrial flue-gases), mineralisation of CO_2 could not, from an LCA point of view, compete with underground storage of CO_2 .

The LCA of CO_2 mineralisation used to scrub flue gas on a waste incinerator in Singapore had to take account of the ultramafic mineral material sourced from Western Australia or alternatively from Malacca, Malaysia. Heat-activated serpentine is reacted with an aqueous solution of ammonium carbonate obtained from scrubbing flue gas with aqueous ammonia. The heat activation and carbon capture step, and especially the transport of rock, generate significant CO_2 emissions requiring CO_2 neutral alternatives.

Highlights and progress between 2010-2015:

- Advancements in simultaneous capture and mineralisation of CO₂ directly from flue gas
- Carbonating flue gas via leachate e.g., NH₄HCO₃ as an indirect carbonation route studied at lab-scale in several laboratories
- Better modelling of the kinetics for dehydroxylation in host minerals
- Better understanding of the temperature's impact on carbonate precipitation
- Emphasis on the solid products and their economic value
- A first study (from BC, Canada) presents a 15-year (2012-2027) opportunity of mine residue carbonation via a NPV estimation
- A significant number of LCA studies reported

Outstanding issues remaining to be addressed after 2010-2015:

- Higher carbonation rates are needed for the CCS to pose a viable solution to for green house gas mitigation.
- Deployment at industrial scale, which would demand TRL 5 (demonstrated in the laboratory).
- None of the reporting from 2010-2015 refers to TRL levels
- The. fate and consequences of potentially toxic by-products (primarily heavy metals) needed more study. This is at least one impact category of LCA studies

Since 2015 research activity in AMC has been expanding. There have been around 100 publications covering *ex-situ* CO₂ mineralisation with a focus on the use of mine/mining tailings. These studies are almost exclusively investigations on magnesium silicate based material. In addition there have been around twenty-five publications on *in-situ* CO₂ mineralisation, primarily reporting on findings at two sites in Australia and Canada. It is significant that despite the attention over the last 30 years most research is still concentrated on laboratory-scale carbonation experiments run over hours. The focus of this work is the conversion of magnesium-based materials into carbonate. There is only a limited amount of literature on technology development, LCA, public acceptance and potential markets for carbonate based materials. Environmental impacts, especially toxicity, water use and energy requirements are seldom addressed.

Mine tailings are recognized as a potentially simple and sustainable way to simultaneously reduce the environmental impact of the tailings and CO_2 emissions. Recent examples have included the carbonation of ultramafic mine tailings using field-deployable methods. Two different approaches have been applied: direct carbonation using an onsite CO_2 source; and indirectly via heap leaching using sulphuric acid. By 2021 neither method has been demonstrated at full field-scale.



Other research, summarised in the main report, suggests that to make a significant impact on CO_2 emissions, AMC processing of Mg rich material needs to be enhanced using *ex-situ* carbonation processes. Recent research has also shown that the mineral content as well as composition influences the rate and susceptibility to carbonation. This phenomenon is evident from the comparison of the difference in carbonation rates of olivines ((Mg-Fe)₂SiO₂) and serpentinites compared with pyroxene-rich rock (containing primarily enstatite (MgSiO₃)) which is less reactive.

One particular study has highlighted the energy penalty associated with AMC used to process an 18.2 %-vol (dry) flue gas from a cement plant. The reported energy penalty is 7.8 GJ/tonne CO₂ while sequestering 234 kg CO₂ per tonne of rock (serpentinite, eventually aiming at chrysotile). The assessment was made for an input of 200 tonne/hr rock input, processed after heat treatment in a pressurised aqueous solution, and the precipitation of magnesium carbonates in a series of vessels. Some limitations include the removal of CO₂ from the gas (62.5 %) and the extraction of MgO from the serpentine (50%) from the rock. Costs were estimated to be 144 \$/tonne CO₂ (127 ϵ /tonne CO₂) 146 \$/tonne CO₂ (129 ϵ /tonne CO₂) avoided).

Despite these observations recent technological progress towards the development of AMC is becoming apparent. Advances by Mineral Carbon International (MCi), reported in 2021, claimed that the aqueous process under development by the company has advanced from TRL 6 to TRL 7. The company has also received a grant from the Australian Government to support the development of a mineral carbonation mobile demonstration plant in the country. The scale of the demonstration will be dependent on final pilot studies and engineering designs. It is anticipated that MCi Carbon Plants could be scaled up to several million tonnes of CO_2 at suitable industrial sites.²

A list of recent pilot and demonstration projects is listed in Table 1

² https://www.mineralcarbonation.com/blog/ccusdf website accessed 22/02/22



Project	Technology and feedstock	Comment
Carmex (New Caledonia, France)	Direct aqueous mineral carbonation of mafic/ultramafic mining wastes	New Caledonia is an excellent candidate for implementing mineral carbonation due to the availability of both suitable mineral feedstocks and proximity to CO ₂ emission sources. (Ended 2012)
MCi (New South Wales, Australia)	Proprietary direct aqueous carbonation of various industrial wastes and mine tailings	Demonstration projects planned with Japanese ITOCHU Corporation. The business model of MCi is that the cost of CO ₂ capture is outweighed by producing valuable materials
Québec process (INRS, Québec, Canada)	Aqueous mineral carbonation process using heat treated serpentinite-based tailings and cement plant flue gas	Potentially commercially viable process, provided there is sufficient market for the produced magnesium carbonate
HiGCarb process (CSC, Kaohsiung, Taiwan)	Rotating packed bed using hot- stove gas (28.8 vol% CO ₂) and wastewater for blast oxygen furnace slag carbonation	Carbonate product used as cement additive and fast conversion times indicate potential feasibility for further scale-up in the near future
Kawashima- Daini project, Japan	Indirect aqueous carbonation of concrete sludge to produce CaCO ₃ using boiler flue gas	Net CO ₂ reduction achieved, but the low reaction rates and large feedstock amounts needed / ton of CO ₂ represents a barrier for further development
CarbonVault [™]	Carbonation of diamond mine tailings by De Beers Group using various AMC technologies	Pilot testing delayed in 2020/2021. Environmental targets include carbon neutral mining operations by 2030

Figure 2 highlights the relative technological advancement of AMC and the status of magnesium carbonate and calcium carbonate as CCU products.

Concept	Formulation	Proof of concepts	Lab prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial Final engineering	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9
Malates 🔵	Carbamates 🔵	Acetic acid 🔵	Ethylene 🔵 glycol	CO ₂ -based Fischer-Tropsch	Ethanol 🔵	Calcium ★ carbonate	Cyclic carbonates	Methanol
	Formaldehyde 🔵	Acrylic acid 🔵	Lactones	products	Formic acid	★ Sodium carbonate	Dimethyl or carbonate	CO ₂ -based Polycarbonates
	Isocyanates	Dimethyl ether	Magnesium carbonate	CO2-based biofuels	Syngas 🔵	CO ₂ -based Polymers	Dry algae powder	Polyols
			 Oxalic acid 				Methane	Polyurethan
	Fine chemicals (e.g., alkanes, aromatics, or	CO ₂ -based enzymatic and microbial products					Sodium bicarbonate ★	Salicylic acid
	olefins)						Concrete ★ curing	Urea

Figure 2 TRL for main CO₂-based products. The list is not intended to be exhaustive (taken from data sources between 2018 and 2019)



One option that is mentioned in two dozen papers since 2010, but not taken further than that by most authors, is the recovery of metallic by-products that have potential market value. Besides Mg and Ca, Fe is the first significant by-product from many serpentinites and other magnesium silicate rock types. Indeed, several researchers have been able to (magnetically) separate much of this iron from rock after crushing/grinding. Fe and other metals like Cr, Ni, Zn, Ti, Cu, Al, Mn can be obtained during staged processing, after extraction of Mg from rock, in the iron hydroxide precipitate or as separate metals. Other authors have targeted platinum group metals (PGM), with the most comprehensive work reported from South Africa. Al (60%) Ca (80%), Fe (35%), Si (32%), Cr (27%) and Mg (25%) were extracted from platinum mine tailings using thermal treatment with ammonium sulphate. Improvements are needed, however, in order to extract more of the 12% MgO present in the rock, integrating CO₂ mineralisation with metals extraction.

Progress highlights between 2016 – 2021:

• The realization that mining tailings represent a significant untapped potential for CO_2 sequestration via mineralisation

Important issues still to be addressed following 2016 – 2021:

- The main issues hindering mineral carbonation from advancing on the TRL ladder are still largely the same as ten years ago:
- Speeding-up the carbonation chemistry kinetics;
- Energy economy (i.e. processes are still too energy intensive);
- Recovery and recycling of chemicals used.

Environmental Impacts

Mining and recovery of metals from rock waste and tailings is an attractive proposition and and could become commercially viable at many locations but this will depend on site specific circumstances that need to be taken into account by investors.' Additionally, there are legacy issues, particularly the neutralization of acid mine drainage, that could potentially lead to such projects obviating the potential benefits obtained through mineral carbonation. This partly depends on whether monitoring criteria and performance targets are set at mine scale or national level.

Oxidation of pyrite is one of the main sources of acid mine drainage, when tailings are exposed to the atmosphere or oxidizing vadose groundwaters. The condition could lead to the dissolution of carbonate minerals and CO_2 release offsetting the benefits of carbonation elsewhere. Moreover, limestone is commonly used as a neutralizing agent in acid mine drainage. Its extraction, transport and application could incur penalties in a full LCA analysis of mineral carbonation efficiency.

Metallic species in magnesium silicate rocks can be leached into the surroundings during *in-situ* ambient air carbonation as a result of pH fluctuations. Heavy metals (e.g. cadmium, antimony etc.) and trace elements such as selenium, mercury and arsenic, or dissolved metals like iron and copper, also present health and environmental risks.

Further analysis is required to assess the reactive potential of individual sites, in terms of proportions of favourable minerals and the possibility of negative feedback flows from oxidation of sulphides and carbonate dissolution associated with acid mine drainage.

One very attractive side-benefit of CO_2 mineralisation is that a hazardous solid waste such as chrysotile (asbestos) can be neutralised. In principle, this can be processed in the same way as serpentinites and indeed it is highly recommended to carbonate asbestos wastes once a facility for serpentinites is available.

In contrast to AMC technologies based on magnesium silicate minerals, calcium rich waste materials, and olivine, are attracting increasing interest as building products. Companies active in this area are



tabulated in Table 3. Current estimates of these materials suggest it will be very difficult to reach a level above 1 Gt CO_2 sequestration with calcium-based resources unless a very large fraction of these materials is directed towards carbonation.

Company	Technology	TRL	Product	References (in [6])
Alcoa	Treatment of bauxite waste with CO ₂ (from an ammonia plant)	6	Construction fill, soil amendment	Global CCS Institute, 2011
Carbicrete	Carbonation activation of steel slag	6-7	Carbonated "concrete"	Savage, 2017; Carbicrete, 2020
Carbon8 systems	Accelerated Carbonation Technology	9	Aggregates/ fill e.g., for blocks/ concrete/ screed	Carbon8, 2020b
Carbstone Innovation	Carbonation of steel slag	9	Construction materials including roofing tiles	Vito, 2020
Blue Planet	Carbonate coating over an alkaline substrate	6-7	Aggregate	Blue Planet, 2020
Carboclave	Nano-CaCO ₃ crystals producing a densification effect	7	Concrete blocks	Carboclave, 2020
Green minerals	Carbonation of olivine	3	Building materials	On-Site, 2020

Table 3 Summary of companies actively developing construction materials via carbonation of industrial waste products.

Magnesium-based cements are receiving increasing interest, as are magnesium-based batteries. Current market prices for magnesite MgCO₃, nesquehonite (MgCO₃·3H₂O) and silica SiO₂ are around $80 \notin$, 420 \notin and 40 \notin per tonne, respectively. Combined with avoided costs for CO₂ emission rights, this offers significant OPEX revenues after the CAPEX investment for the process equipment has been made. For example, a CAPEX investment of 500 M \notin for a facility that allows for sequestration of 0.5 Mt CO₂/year during 20 years gives an immediate minimum cost of 50 \notin /t CO₂.

CarbFix

The original idea of the CarbFix project was to capture the CO_2 within gas emissions from the Hellisheiði geothermal power plant in south-east Iceland. The gas emissions from the power plant consists of 60 vol-% CO_2 , 20 vol-% H_2S , 18 vol-% H_2 , 2 vol-% N_2 and some trace amounts of CH_4 and Ar. The CO_2 and H_2S were first separated from the less soluble gases and then from one another. The toxic H_2S was then re-injected into the deep geothermal reservoir together with spent geothermal water. In the CarbFix project, CO_2 gas is mixed with water and dissolved at elevated pressure before injection into the bedrock. The acidic properties of the mixture promotes dissolution of the basaltic rock and the liberation of metal cations, e.g. Ca^{2+} , Mg^{2+} and Fe^{2+} . These cations react with the carbonate ions which then precipitate in the form of stable metal carbonates.



The project's original aims have been successfully achieved. The pilot study has confirmed that 95 % of the CO_2 injected has mineralised successfully within a year of injection. The H_2S has also mineralised successfully within four months of injection.

The success of the concept has led to a scale-up to a dedicated CO_2 storage site based on mineralisation in basalt. In April 2021 CarbFix announced the establishment of a hub called the Coda Terminal, at Straumsvik. The facility can accommodate specialised CO_2 tankers. The first CO_2 shipments are scheduled for 2025 and the construction of the hub is estimated to be between 190 to 220 M \in . At full capacity, the revenues are projected to be between 25 and 45 M \in . The planned injection rate for the CarbFix facility is 300,000 tons by 2025, ramping up to 3 million tons per year at full capacity by 2030. For comparison, CarbFix has so far injected 70,000 tons of CO_2 .

Public acceptance of the project has been positive largely because of the proactive engagement of stakeholders and the public. Another contributing factor has been the vast amount of open-source academic publications and theses produced during the project. In contrast, the Hellisheiði Geothermal Power Plant has been subjected to harsh criticism on several occasions because of its financial management and short-sightedness. It has also received negative press coverage related to two different seismic events which occurred in 2011 and the other in 2016, linked to the reinjection of geothermal fluid shows. Successful engagement with the public has subsequently improved the public reaction to the project. This has been attributed to greater interaction with the public and the promotion of the positive effects that the reinjection brings.

A study from 2020 also shows that incorporating the CarbFix CCS method had a positive impact on the Hellisheiði Geothermal Power Plant's life cycle assessment, contributing to green-house gas (GWP 100) reduction from 15.9 g CO₂e/kWh to 11.4 g CO₂e/kWh for electricity and 15.8 g CO₂e/kWh to 11.2 CO₂e/kWh for heat over the period of the investigation.

EXPERT REVIEW COMMENTS

The main comments received from external reviewers are as follows:

- The chapter with Conclusion should be restructured to include clarity on key Messages, where the findings that related to the scope these included TRL of the technology, assessment of the techno-economic viability of *ex-situ* mineral carbonation, positive and negative environmental impacts. The assessment of the most promising products and markets for recoverable valuable materials, with emphasis on metals (PGE's, REE's, Cr, Ni, V, Mg) and materials for civil construction and other applications. The authors have responded to these requests, although the review has only been able to partially address all these aspects because of the lack of published information and the current status of AMC technology.
- Recommendations on the direction and content of future research in a few bullet points should be included. This should be based on where there are still significant uncertainties or lack of knowledge or the limitations of what can be currently achieved. These have been included.
- An acknowledgement that the lead author, Prof. Ron Zevenhoven, is very knowledgeable about mineral carbonation and mine tailings. The research group he leads at Åbo Akademi University has a well-balanced view of the topic.
- The omission of enhanced weathering as an ex-situ method. A short section on this topic has been included. The external reviewer does acknowledge there may be adverse environmental impacts such as heavy metal contamination associated with this practice. There is a brief discussion on this aspect in the report.
- One reviewer observed that there has been abundant research on laboratory based experiments over a period of 30 years. The authors have reflected on this observation, however this situation is the reality of the current status of the technology.



- The same reviewer also commented on the complexity of the mineral assemblage of many silicate rocks. This aspect is recognised in the report. The significance of particle size in mine tailings was also highlighted. Minerals of interest are not sufficiently exposed for reaction, even though chemical and mineral analysis suggests that they have carbonation potential. A recommendation to standardized ways of determining the mineral carbonation or enhanced weathering was also proposed.
- Greater clarity on the trends in research and development particularly how particle size effects are dealt with. There is discussion at a general level on how size reduction impacts on the efficiency and rate of carbon capture reactions, plus the related comminution requirements in terms of energy input calculations. Further detail was added to the report on this topic.
- The calculation of energy penalties covered in the report can produce erroneous results. Calculations should be based on exergy analysis. This should be stressed more and included in the conclusions.

CONCLUSIONS

- Three decades of research and development work on accelerated mineral carbonation (AMC), have still not resulted in significant market uptake. Increased costs of CO₂ emissions, or the potential production of value-added materials, have not created sufficiently strong market incentives.
- Despite growing interest in AMC as a means of CO₂ mitigation the concept has not advanced beyond experimental laboratory investigation, with a few notable exceptions during the last five years. Most AMC technology related to Mg rich waste streams is still at TRL 4 although a few have progressed to TRL 6 or 7. AMC using Ca rich wastes is further advanced ranging from TRL 6 – TRL 9.
- The limited scale-up from laboratory-scale investigation is partly due to the energy requirements and chemical kinetics to a timeframe of minutes rather than hours or days, as is still commonly being reported.
- *In-situ* carbonation of stockpiles and other deposits at mining sites has been the subject of considerable R&D in recent years. This activity has been concentrated in only a few countries (Australia, Canada, Iceland, South Africa).
- The R&D community is still divided into two broad groups: one represented by teams that aim at direct carbonation, which often ends in struggling with a passivating silicate layer that prevents rapid chemistry and high conversion levels; while the second group focusses on stepwise extraction and conversion aimed at reaching higher conversion levels in shorter times. The latter offers the benefits of pure, separated product streams but at the penalty of a more complex process lay-out. This route does, however, hold out the prospect of producing materials of marketable value. The evidence from this review is that there are very few AMC approaches that could be economically viable at an industrial kg/s CO₂ mineralisation scale in a single facility.
- This report has focussed on magnesium-based rock resources found primarily as silicates occurring as tailings, overburden and other residues at sites mined for minerals or metallic ores. Although the stockpiled amounts of material are vast, the suitability of these materials is highly dependent upon specific conditions imposed by mineralogy, geochemistry, petrology, permeability and hydrology. AMC treatment and effectives is therefore highly sitespecific.
- Calcium-based AMC has niche deployment opportunities as a result of the large markets for calcium carbonate based products. The relative reactive properties of calcium compared with magnesium means that the chemistry is less challenging than for conversions that produce magnesium carbonate.



- There have been very few cost assessments to determine the potential for commercial AMC deployment, even when including possible revenues from the sales of metals or other by-products. One major factor that constrains deployment of AMC using magnesium silicate-type rock feedstock is the uncertain future market value and scale for magnesium carbonate (hydrate). First movers might benefit from transiently high market prices of 300 €/ton for nesquehonite (MgCO₃·3H₂O). There is a risk that the volume of material from several large AMC facilities could lower the price to uneconomic levels. Industrial deployment also shows that the use of a carbon-based fuel for AMC process will make a facility much larger than when only zero-emissions heat or power is used.
- There are some adverse environmental impacts caused by handling Mg-rich silicate host rocks. Toxic metallic by-product streams, and other problematic solid, liquid or gaseous effluents, can be produced by processing mine wastes. This aspect has received less attention. It is more encouraging that life cycle assessment (LCA) tools are being increasingly used to quantify the environmental footprint of AMC. It is unfortunate, however, that in many cases only the global warming potential (GWP) is considered while, for example, land use, water use and resource depletion should be included.
- Deployment of large AMC facilities presents a public acceptance challenge which has yet to be adequately addressed. Experience from CarbFix does show that positive engagement with the public can produce a favourable attitudes to power generation and associated environmental impacts. In this case subsurface *in-situ* carbonation.
- The deployment of AMC beyond TRL levels 5 6 needs stronger financial support focused on technology that could be extensively deployed within less than 10 years, at TRL 8-9. Repeating the work from the 1990s is hardly productive if it reiterates the limitations of AMC.
- The amounts of mine waste material that could be used are very large, making CO₂ emissions mitigation very visible. Experience with mining activities and the state-of-the-art process technology, especially in countries with significant suitable mine tailings resources, has the potential for AMC if it can become economically viable without causing adverse environmental impacts.

RECOMMENDATIONS FOR FUTURE WORK

- Demonstration of the technology at a tonnes per day level is required to advance AMC technology using Mg-containing mining tailings to progress towards TRL 9 within the next 5-10 years. Costs estimated for CO₂ mineralisation processes operating at levels of many tonnes per day currently suffer from large error margins when based on laboratory-scale information for a kg CO₂ per day scale. Performance results, including operational details such as energy use from recently proposed pilot-scale demonstrations, needs to be scrutinised by IEAGHG and included in future networks and GHGT conferences.
- The boundaries for LCA analysis, as a mature tool for quantifying the overall environmental footprint of *ex-situ* CO₂ mineralisation, needs to be clearly defined. This should include the use of water and chemical additives besides the obvious features of global warming potential versus the use of energy.
- Social acceptance studies for large-scale CCU based on mineralisation are needed.
- To quantify how much CO₂ mineralisation potential, and valuable metal by-products can be extracted, standardisation of analysis and characterisation methods will be needed. Details will need to include proper definitions of ores, leached ores, tailings, etc and the wet/dry processing and possible aging and weathering paths at each site. Current information on material sampled from a mining site in most cases is too vague or imprecise.
- Compilation of mine wastes for all countries with significant mineral production associated with Mg-silicates. Quantitative systematic time-series monitoring of passive "background" carbonation in waste and tailings, would be ideal so that the significance of *in-situ* versus active carbonation and product development can be compared.



• The operations of a CO₂ producer from that of a CO₂ mineralisation entity, could be connected via energy integration. The second entity would be responsible for the sales of carbonate and other products, and the purchase of suitable rock feedstock as specialities, while the former can benefit via avoiding costs for emitting CO₂. Looking at current trends in waste processing, circular economies and markets for "green" products, the use of solid products from AMC could have a promising future.

Mineral carbonation using mine tailings

A strategic overview of potential and opportunities

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Executive summary

The carbonation of magnesium (Mg) and calcium (Ca) rich minerals by reaction with CO_2 is a wellknown naturally occurring phenomenon but the process is very slow under atmospheric conditions. There are additionally large volumes of mine waste tailings, and other industrial waste products, which are potentially reactive with CO_2 and could form permanent repositories of stored CO_2 in a solid carbonate phase.

This report provides an overview and assessment of the state-of-the-art of CO₂ mineral sequestration, also known as accelerated mineral carbonation (AMC), making use of tailings, overburden and other residues available at mining sites and using processes that include acceleration of carbonation reaction rates significantly beyond those that occur naturally.

Climate change has become a reality and the need for mitigation measures is recognized as urgent. It is therefore certainly timely to review the information and data available in the public domain relating to AMC. The aim of this review is to evaluate the techno-economic viability of AMC, and the comparative maturity of the technology, based on publicly available information, enabling large-scale CO_2 producers, decision makers and politicians to make informed decisions.

 CO_2 mineralisation is typically considered to be a carbon capture and utilisation (CCU) rather than a carbon capture and storage (CCS) technology. In practice the CCU/CCS distinction is made based on whether or not the material that contains the carbon has a commercial application. It is also implied that legislation and other regulatory frameworks would need to be implemented, along the lines of, for example, the 2009/31/EC directive on CCS, as well as ensuring alignment with for carbon trading mechanism, such as the EU emission trading system (ETS). Current (end of 2021) prices for emitting CO_2 under the ETS are already > 80 €/t, which is arguably the main driver for bringing AMC to industry and markets.

In addition to the techno-economic viability, the wider implications of large-scale AMC need to be considered as it may result in a significant impact on the environment. Integration with existing or earlier mining activities, especially the use of tailings and other residues, for CO₂ sequestration as solid carbonates (which are stable under ambient conditions) would be advantageous. Apart from CO₂ emission mitigation, removal of waste piles from mining sites, while simultaneously producing materials with market value, is a potentially attractive proposition.

However, the production of large material streams may overwhelm existing markets, for example Mg carbonates, for which the currently traded volumes are of the order of 50 Mt annually¹. Re-processing of waste rock and tailings (with new, more efficient technologies) at mining sites also offers the possibility of recovering minor, yet highly valuable commodities including Ni, Cu, Ti, platinum group metals (PGMs) and rare earth elements (REEs). Many of these metals are also of increasing strategic

¹ O'Driscoll, M. 2020 World magnesia supply, presentation at Northeast Asia Magnesia Exchange webinar 9 July 2020 (http: https://imformed.com/magnesia-in-question-china-world-trends-discussed/ Accessed 31.1.2022). *Reported worldwide 26.4 Mt magnesia for 2018 corresponds to 55.2 Mt magnesite before calcination.*

demand for zero-emission energy technologies such as solar PV, wind turbine generators and electric vehicles.

AMC processes can also be used to treat problematic waste streams from mines, offering significant environmental benefits, in both abandoned and operating mines. However, the wider environmental implications such as the excessive use of water also need to be taken into consideration. For this reason, life cycle assessment (LCA), in addition to public acceptance studies that identify concerns in society, is essential to ensure that large-scale deployment of AMC is a viable option. The processing of industrial wastes using AMC that can deliver a series of solid products and other market opportunities also should form part of any LCA.

This report is fundamentally concerned with magnesium-containing mine tailings and other residues, primarily magnesium silicate-based, and *ex situ* processing using dedicated process equipment located at a CO₂ production site to which suitably reactive rock is transported, or *vice versa* (Part 1). The reasoning behind this is that magnesium silicate rocks can potentially offer the volumes needed for a significant climate change mitigation effect while calcium-based materials cannot. A brief listing of calcium-based materials is however included (Part 2). Ultimately, the volumes of material accumulated at mining sites determine the potential of large-scale AMC. Tables (Appendices A1 and A2) of metal producing mines and industrial minerals in Finland are given as appendices in this report, as an example of the quantities of materials of relevance to AMC. Listing the suitable rock resources piled at minerals in Finland shows around 320 Mt material at metal mining sites and around 350 Mt material at minerals mines exists. If, after analysis, ~20 % is found to be a suitable AMC resource then this has the potential of binding around 40 Mt CO₂.

In situ AMC, aiming at speeding up the natural chemistry of CO_2 from the air reacting with tailings and other residues at mining sites, and direct injection of CO_2 (dissolved in water) into Mg-rich reactive rock formations, (Part 3) is also covered in this review. This has been a very significant and active area of research in recent years, as about a quarter of the literature listed since 2016 deals with *in situ* cases. Reporting is primarily from three sites in Iceland, Canada and Australia.

The overriding conclusion that can be drawn from a detailed literature review, and direct research experience in AMC R&D, is that there is very limited evidence at present which could be relied upon to produce a business plan for the implementation of AMC at large-scale (> 0.1 Mt CO₂/ year, by an industrial-size CO₂ producer). The authors' own work, in the form of the so-called ÅA routes and their applicability (not only in Finland), appears at the forefront of what may soon find commercial application, acknowledging that this is more motivated by current trends in pricing of CO₂ emissions than the business opportunities offered by solid products sales or the valorisation of waste stockpiles at mining sites.

Fewer than ten publications since 2015 could be regarded as useful for making a quantitative or robust techno-economic viability assessment. It is also significant that only one actor operating in the field claims a technology readiness level (TRL) of 6.

Despite the potential benefits of recovery of valuable metals from mine tailings, there does not appear to be much attention to this issue, or the challenges of having to deal with toxic metals, or other hazardous side-streams that could result from recovery processes. The increasing use of LCA is an ideal and strongly recommended methodology for addressing and encompassing all environmental and social acceptance issues. However, most research on AMC conducted over the last two decades has concentrated on laboratory scale work on the chemical kinetics of carbonation or the activation of magnesium in what is considered to be suitable rock material. It is poignant that the public today is largely unaware of this CO₂ mitigation alternative, despite having some knowledge of CCS and some of the publicity around this climate mitigation option.

To summarize, AMC still needs the market- or legislation driven push or pull that would make it a relevant and economically viable addition to other, more mature CCS/CCU technologies. According to the authors' own experiences, as awareness about climate change continues to increase (together with various forms of carbon taxation), AMC is today appearing on shortlists of decision-makers inside carbon-intensive industries. The potential benefits of AMC for mining industries looking to reduce / offset CO_2 emissions are simply too attractive to be overlooked, meaning that the option to carbonate mine tailings are a likely trigger for an accelerated development of AMC in the near future.

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List of abbreviations

ABS	ammonium bisulphate
AMC	accelerated mineral carbonation
ARC	Albany Research Center
AS	ammonium sulphate
BMED	bipolar membrane electrodialysis
CCGS	carbon capture and geological storage
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilisation and storage
EGR	enhanced gas recovery
EOR	enhanced oil recovery
ETS	emission trading system
FB, FBC	fluidised bed, fluidised bed combustion
GWP	global warming potential
JORC Code	Australian Joint Ore Reserves Committee Code
JORC Code LCA	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis
JORC Code LCA MSWI	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator
JORC Code LCA MSWI MVR	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression
JORC Code LCA MSWI MVR NETL	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory
JORC Code LCA MSWI MVR NETL NPV	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value
JORC Code LCA MSWI MVR NETL NPV PCC	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate
JORC Code LCA MSWI MVR NETL NPV PCC PF	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel
JORC Code LCA MSWI MVR NETL NPV PCC PF	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel pressurised fluidised bed combustion
JORC Code LCA MSWI MVR NETL NPV PCC PF PFBC PGM	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel pressurised fluidised bed combustion platinum group metals
JORC Code LCA MSWI MVR NETL NPV PCC PF PFBC PGM RCA	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel pressurised fluidised bed combustion platinum group metals recycled concrete aggregate
JORC Code LCA MSWI MVR NETL NPV PCC PF PFBC PGM RCA REE	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel pressurised fluidised bed combustion platinum group metals recycled concrete aggregate rare earth element
JORC Code LCA MSWI MVR NETL NPV PCC PF PFBC PGM RCA REE RO	Australian Joint Ore Reserves Committee Code life cycle assessment / analysis municipal solid waste incinerator mechanical vapour recompression National Energy Technology Laboratory net present value precipitated calcium carbonate pulverised fuel pressurised fluidised bed combustion platinum group metals recycled concrete aggregate rare earth element reverse osmosis

TRL	technology readiness level
UNECE	United Nations Economic Commission for Europe
UN SDG	United Nations sustainable development goal
ÅA	Åbo Akademi University

Part 1 - Magnesium-based resources

1 Objectives and scope

This study provides a summary and assessment of the current status of available and appropriate technologies for mineral sequestration of carbon dioxide, CO_2 , with particular attention given to the viability of large-scale applications. Here, a large-scale process unit is defined to sequester 0.1 Mt/CO₂ or more annually. Viability in this context refers to economic viability based on economic, social and environmental performance parameters such as technology readiness level (TRL), revenues and costs related to products and by-products, life cycle assessment (LCA) and public acceptance, as illustrated schematically in Figure 1.1.



Figure 1.1. Schematic illustration of the need for comprehensive life cycle analysis in assessing the relevance and effectiveness of mineral carbonation as a viable CCUS mechanism. It is necessary to simultaneously evaluate the energy input requirements associated with mining, including transport of reagents and final products, as well as energy used in extraction, crushing and grinding, and subsequent metallurgical processes. Depending on whether mineralogy is appropriate, waste rock and tailings can contribute to passive carbonation, offsetting mining-induced emissions, while mine wastes can also be used to generate new mineral products having commercial value.

Since it was first proposed, in 1990 [2], as a potential abatement mechanism for addressing CO_2 emissions, mineral sequestration, commonly referred to as accelerated mineral carbonation (AMC), has primarily been understood in terms of carbon capture and utilization (CCU) rather than merely a

carbon capture and storage (CCS) technology. This is aptly illustrated in the 2009 EU directive on CCS [1], as well as in the first comprehensive summary publication, in the form of a specific chapter "Mineral carbonation and industrial uses of carbon dioxide" in the 2005 IPCC Special report on carbon dioxide capture and storage (SRCCS) [3]. However, there has also been considerable research into the potential for natural, passive or enhanced mineral carbonation *in situ* in environments that provide access to suitably reactive rock materials; of these, tailings and waste rock in active and abandoned mines have received most attention [4].

Until around 2010 the research into CO₂ mineral sequestration focussed on chemical kinetics and minimizing energy input requirements. The early studies on waste rock and tailings in the mining industry from the 1990s were joined after 2000 by efforts to valorise alkaline industrial wastes, the latter being almost exclusively calcium-based [5]. This opened pathways to commercially viable processing of CO₂, in most cases yielding precipitated calcium carbonate (PCC). Conventional CCS, implying CO₂ capture and purification at a point source, transport by pipeline and storage in an underground geological formation, progressed to the stage of demonstration projects of megaton (Mt) scale cases where CO₂ is stored underground in "dedicated" sealed sedimentary formations, i.e. saline aquifers, as well as several dozen commercial operations where captured CO₂ is used for enhanced oil recovery (EOR). While EOR can generate the revenues that make the upstream CO₂ capture economically viable, this concept inherently results in net positive CO₂ emissions through downstream use of the extracted fossil fuel [6].

Experience acquired during these projects has made it abundantly clear that revenues, subsidies or other financial drivers are needed for CO₂ emissions mitigation, whether via CCS or CCU, or as some combination of CCUS, to become a realistic option with a relevant and significant effect on climate change and global warming. A very recent publication addressing the financing of CCS in the Netherlands demonstrates how taxes, subsidies and a proactive stance by government can interfere with the free-market operation of large-scale CO₂ emitting industries [7]. The current leadership of the EU has taken CO_2 emissions mitigation, including CCS/CCU, to the top of the agenda during 2020, in order to respond more effectively to commitments under the 2015 Paris agreement. As a consequence there is increased interest in the potential of CCS/CCU in all its forms and approaches. This is also timely with respect to the circular economy concept, where there is a growing emphasis on more efficient use of natural resources, with less waste and more recovery and recycling of both primary resources and secondary side-streams [8]. Accordingly, the mineralisation and usage approach appears to offer a range of benefits beyond the conventional and demonstrably enormous CO₂ storage potential in the form of carbonates that are more (thermodynamically) stable than CO₂ itself. This last feature largely explains why the energy input requirements of CO_2 mineralisation are similar or less to that of a CO_2 capture solvent based step as part of conventional CCS [9].

The challenges facing commercial scale, economically viable carbonation and usage projects are analogous to those accompanying more conventional basin storage of CO₂. Just as storage in saline aquifers will be more feasible where infrastructure already exists and where there are synergetic opportunities for enhanced oil and gas recovery, investment in mineral carbonation technologies will have greater potential in active mining districts, particularly those proximal to carbon emission sources related to heat and power production. The earliest publications presenting the concept of mineral sequestration [10] provided theoretical estimates of potential, assuming ideal accessibility and reactive potential. Subsequent research has focussed on both laboratory scale exploration of reactive materials and reaction kinetics, as well as case studies of specific mine environments. The critical issue

is that of access to sufficiently large rock volumes, and whether kinetics are favourable for reactive processes over time scales relevant to the agenda set by the IPCC. Recognition of this inevitably leads to the fundamental question – can engagement with the mining industry worldwide lead to volumetrically significant sequestration as part of the global greenhouse gas drawdown strategy, or is the scale such that it will only lead to the mining industry becoming more efficient and environmentally compliant, which is of course a desirable outcome in any case.

The mere existence of enormous volumes of mafic and ultramafic rocks composed of magnesium silicates in areas such as the Semail ophiolite in the mountains in Oman, or the basalts of the Deccan traps in India (cf. Tables in Appendices) cannot be directly inferred to correspond precisely with real amounts of reactive material available and accessible for CO₂ mineral sequestration [11]. On the other hand, although they are volumetrically smaller, there are numerous and in some places, large stockpiles of mining tailings, overburden and other mine wastes produced by the global mining industry (see the Appendix tables) which offer significant potential for sequestration of CO₂ while simultaneously providing side-stream or by-product materials, or opportunities for ameliorating environmental geohazards (for example asbestos). Given that such materials are already partially processed and may additionally still contain substantial amounts of valuable metallic species, these magnesium-containing rocks could offer significant business opportunities, even though the volumes of produced (hydrated) carbonates and silica may appear overwhelming.

In this report we assess the feasibility of large-scale implementation of CO₂ mineralisation using (primarily magnesium-containing) wastes generated during various stages of mining and metals refining processes, as illustrated below in Figure 1.2. Potentially reactive material is available throughout the process chain, from the primary resource, with its distinctive mineralogical composition - through to metallurgical metal recovery. The key expectations are that the process is possible, feasible and acceptable, offering significant CO₂ mitigation using sustainable and profitable technologies that are demonstrably beyond proof-of-concept stage, rather than abstract or unproven potential concepts.



Figure 1.2 Simplified schema describing the origins of mineralized waste and material flows in the mining industry (taken from [12]). Note that through all stages of the mineral supply and production chain, opportunities exist for both in situ sequestration as well ex situ usage applications.

It is important to reiterate that the scope of this review is primarily to address *ex situ* CCU, rather than *in situ* CCS, although many mining operations may offer opportunities for effectively and successfully incorporating both. It is also useful to distinguish between waste generated at the mine site and that produced during metallurgical processes, as reactive properties may vary considerably. Figure 1.3 is an attempt to further clarify definitions of mine waste, including overburden, which may be ultimately used again in site restoration and stockpiling of low-grade ore, which may be refined at a later date, or used as backfill in underground workings or open pits. Tailings are mineralogically refined and enriched

as a result of the processing and can therefore be expected to behave differently with respect to *in situ* sequestration; the presence of water and sulphide phases is, for example, significant in this regard.



Figure 1.3. Example of potential materials available for CCU purposes at successive stages of a mining operation, from active quarrying, through closure, to reworking of legacy tailings (or waste rock). Waste rock and tailings remaining at the site will contribute towards in situ CCS.

The results of more than three decades of R&D aiming at deployment of the technology at a level that impacts climate change and global warming may indeed find practical application and integration within current markets, as well as social acceptance, although several questions arising from potential side-effects will require careful consideration. When these technologies are aligned with local and international mitigation legislation and directives, it is for CO₂ producers and governments to work together to provide incentives for effective adoption of the opportunities listed and summarised in this report.

This report can in the first instance be seen as an update of other overviews commissioned and published by IEA GHG (PH3/17 (2000), 2005/11 and 2013/TR6). Noting that the authors (at Åbo Akademi University) have published several literature reviews on the topic as well (2008, 2010, 2014 and 2017), the main focus of this report is on the last 5-10 years.

The report is divided into three Parts which address Magnesium-based resources (Part 1), the main focus of this report, followed by much shorter Parts 2 on Calcium-based resources and Part 3 on in situ CO_2 mineralisation process cases. Part 1 is further subdivided into four sections that separately consider years 1990-2009, 2010-2015 and years 2016-today, and a section that assesses the status from the viewpoint of the key performance indicators. The appendices include tables with compilations of mines of industrial minerals in Finland, worldwide resources of potentially suitable feedstock rock (Appendices 1 & 2), and a brief description of the variations of the so-called ÅA routes (Appendix 4).

A few additional points of notice: below, the material amount "ton" implies a metric tonne of 1000 kg. And, while *in situ* processes are distinguished from *ex situ* processes, some *in situ* process research reporting on work involving samples taken from a mining site to a laboratory, for chemical kinetics or other studies, may in this report be addressed in the sections on *ex situ* processes. Consequently, enhanced weathering is here primarily addressed in the section on in *situ* processes. Bio-geosciences are outside the scope of the assessment

Sources (this chapter):

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2 Literature review and status 1990 - 2009

In 1990, the concept of capturing CO_2 in minerals was suggested by Seifritz [1] in an article titled " CO_2 disposal by means of silicates". This is widely accepted as the birth of the field of mineral carbonation (or CO_2 mineralization) as a CO_2 sequestration method. Since then, work on the topic has accelerated and diversified. One significant differentiating feature between various mineral carbonation methods is that if the carbonation reaction is separated from the mineral leaching step, this is known as indirect carbonation. Thus, the two major mineral carbonation categories have been dubbed, direct and indirect carbonation and these have been illustrated in the Figure below.



Figure 2.1 Simplified schema exemplifying the difference between direct and indirect carbonation routes (modified from [2])

The purpose of this chapter is to summarize the main achievements and status of mineral carbonation until the end of 2009. The main purpose of this is not to reiterate existing knowledge and challenges but rather to provide a strategic overview of the future potential and opportunities of mineralization using mine tailings. Accordingly, this chapter will be relatively concise and rely on a number of previously prepared literature reviews.

Up to around the year 2000, the number of articles published in the field of mineral carbonation was rather limited and was extensively summarized in a study commissioned by the IEA GHG [3] around that time. That report presented six different alternatives for large-scale mineral carbonation and concluded that the carbonation of dissolved magnesium silicate rock in a melt of MgCl₂ would be the best alternative of the six, although none of the processes were considered to have high potential. Since then, the number of research papers in the field has grown significantly, even though the report had recommended that this area did not warrant any further research effort.

Nevertheless, and rather fortunately, a second literature review update was funded by the IEA GHG some five years later [4], with the outcome being that the previously identified carbonation routes had been superseded by other alternatives, primarily aqueous process routes. In general, research began to focus more on cost reduction while in addition to the large amounts of naturally occurring suitable mineral resources already identified, industrial wastes were introduced as a source of magnesium and calcium. This might indeed help to bring costs down, but it was soon recognized that the approach would not provide a significant CO₂ sequestration solution on a large scale. Another cost reducing alternative was introduced by proposing the use of less concentrated sources of CO₂, i.e., flue gases instead of purified CO₂. The most promising route at this stage was considered to be direct (i.e., mineral extraction and precipitation in the same step) aqueous carbonation of serpentine (or olivine [5]). In

2005, it was concluded in a special report on CCS by the IPCC [5] that "the technology is still in the development stage and is not yet ready for implementation".

Following the improvements made between 2000 and 2005, attempts to further develop the technology were made by separating the extraction step from the precipitation step (referred to as indirect carbonation routes) and by experimenting with different additives. In a review study [6] focusing on the developments made between 2005 and 2007, it was noted that the preferred benchmark process (direct carbonation) of an aqueous solution of 0.64 M NaHCO₃ and 1 M NaCl, developed at ARC [7] (nowadays NETL) in the US might be further improved by using e.g., concentrated alkali bicarbonate (e.g., 5.5 M KHCO₃ [8]) solutions. Other interesting findings were made in the field of product valorisation, i.e., the formation of valuable materials such as precipitated calcium carbonate (PCC) either from natural resources e.g., [9] or industrial wastes [9]. At this time there were also indications that the process might be suited for upscaling and become industrially feasible, as topics such as solids handling (on a large scale) began to be addressed. However, the general consensus at that time (2007) was that "significant technological breakthroughs will be needed before deployment can be considered" [11].

The first life cycle assessment (LCA) study [12] on the topic addressed the environmental footprint of the ARC/NETL routes, for coal-fired electricity production. This method for quantifying environmental impact converts the energy use into new CO₂ emissions, quantified as the global warming potential (GWP). Other environmental impact categories that can be considered are effects on human health, effects on ecosystem quality, resources depletion, acidification potential, ozone layer depletion and eutrophication potential. CO₂ mineralisation using wollastonite (a calcium silicate) or mechanically activated olivine (magnesium silicate) were considered to have the greatest potential for avoiding adverse environmental effects for several impact categories, whereas the use of heat-activated serpentinites (composed mainly of serpentine, also a magnesium silicate, formed by hydration of olivine) is rendered less favourable due to large energy input requirements. Toxic gaseous and metallic release related to these processes were also quantified. Energy input was concluded as being a major critical factor for both stand-alone processes, as well as those integrated with CO₂ capture (using chemical absorption).

When reviewing developments in 2008 and 2009, the overall conclusion was that further research was necessary, a statement which is echoed in an overview book chapter published in 2010: "no commercial silicate mineral carbonation technology for CCS has yet been developed" [13]. Nevertheless, industry was showing a discernible growth of interest in mineral carbonation technologies. The reasons for this interest were diverse, including the possibility of simultaneous capture of CO₂ and utilization and treatment of waste and by-product streams, such as asbestos and mine tailings, electric arc furnace (EAF) dust, steel-making slag, waste concrete, cement-kiln dust, coal fly ash, air pollution control (APC) residues, municipal waste incinerator (MSWI) ash, pulverized fuel (PF) firing and circulating fluidized- bed combustion (CFBC) ashes and oil shale ashes, as well as ash transportation waters [14].

Highlights / advancements 1990 – 2009:

- The concept of mineral carbonation was introduced (and large potential quickly grasped)
- Most abundant and suitable minerals were identified (olivine, serpentinite)
- Multiple routes have been identified, the most promising being additive enhanced (0.64 M NaHCO₃ and 1 M NaCl) direct aqueous carbonation

- Multi-step routes introduced for producing high-value products (product valorisation)
- In situ mineral carbonation was introduced
- Investigations into various industrial waste and by-product streams started
- Understanding that using pure CO₂ is too expensive, use of CO₂ containing flue gas should be pursued instead

Remaining priority issues that were not addressed during the review period 1990 – 2009:

The main issues hindering mineral carbonation from advancing on the technology readiness level (TRL) ladder at the end of 2009 were:

- Extracting or activating the reactive component MgO from a silicate mineral;
- Speeding-up the carbonation chemistry kinetics;
- Energy economy (noting in particular that the heat produced of the exothermic carbonation reaction was not actively considered / utilized in the processes);
- Recovery and recycling of chemicals used.

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[14] Zevenhoven, R., Fagerlund, J. 2010 Fixation of CO₂ into inorganic carbonates: The natural and artificial "weathering of silicates", Chapter 14 in: Carbon dioxide as chemical feedstock, M. Aresta (Ed.) Wiley-VCH, Weinheim (Germany) (ISBN 978-3527324750) p. 353-379

3 Literature review and status 2010 – 2015

This chapter readdresses the reporting from the period 2010-2015 seen from the viewpoint of the key performance indicators (see Chapter 5) for near-future deployment of CO_2 mineralisation using mine tailings, overburden and other residues. Year 2015 can be seen as the point where results from lab-scale work started to penetrate industry. At the same time though, the phase-out of fossil fuel-fired heat and power production gained momentum which shifted the attention of AMC (accelerated mineral carbonation) to metal, cement/lime and other industry sectors where feedstock containing fossil carbon materials cannot easily be replaced. An incidental benefit of this that there is often a higher concentration of CO_2 in gaseous waste streams, while (local) governments also became more aware of those industries and processes for which emissions remain hard to avoid and which are therefore largely insensitive to a transition to renewable energy.

Since during these years the economic feasibility and other key performance indicators (KPIs) for this study became relevant this half-decade is reviewed again, seen from today's objectives. Also, it became clear that AMC belongs under the CCU portfolio, being increasingly ignored by those actively developing CCS (CCGS).

3.1 Research papers

Up until 2010 most CCS research had been conducted at laboratory scale. In 2011, a study was conducted at a large coal-fired power plant, under field conditions, where flue gas was reacted with fly ash obtained from production at the plant itself, in a fluidized bed reactor. In the early experiments, the researchers managed to obtain a decrease in CO_2 levels from 13.0 % to 9.6 %. This early pilot scale study showed that it is possible to capture and mineralise CO_2 to carbonates from flue gas by means of fly ash in an AMC process. Furthermore, the fly ash also captured SO_2 and Hg from the flue gases. It may however be that the composition of carbonated fly ash apparently prevented its utilization [1]. In 2013 a research project in China studied on-site CCS via indirect carbonation, using Ca as a mineralisation agent. The Ca was extracted from fly ash, rich in Ca, from a power plant on site, with the help of ammonium salts. The best ammonium salt for this purpose was found to be CH₃COONH₄, ammonium acetate, which can easily be recovered and reused in repeating the process. To react the CO₂ with the Ca available the research group found that it was much better for both the carbonation rate and efficiency to introduce CO_2 as part of NH_4HCO_3 than just as $CO_2(g)$ into the leachate. In this process, up to 93 % of the Ca precipitated as $CaCO_3$ (precipitated calcium carbonate, PCC). Furthermore, the purity of the PCC was up to 98 %, making it suitably clean for industrial use. Calculations showed that 0.111 tonnes of CO₂ could be sequestered per tonne of fly ash [2]. The same ammonium salts had also previously been shown to be selective for calcium extraction while developing the so-called slag2pcc concept in Finland (which implies selective extraction of calcium from steel converter slag followed by carbonation of the calcium-rich solution while recovering the ammonium flux salt, all under (near) ambient process conditions [3-6]).

In the US, the ARC/NETL route was reappraised by a team led by Columbia University. The role of additives NaCl, assumed to act (slightly) in chelating and NaHCO₃ for pH buffering, which affects iron precipitation, was studied for olivine carbonation, confirming earlier findings. The differences between freshly ground versus aged olivine and the different behaviour of very fine particles (< 10 μ m), was shown, with faster dissolution competing with crystal growth to large magnesite crystals. The carbonation of asbestos-containing material was tested and compared with the less (environmentally)

problematic magnesium silicates serpentine and olivine. Results were encouraging as it was evident that the problematic fibrous structure of asbestos was significantly changed. Sodium oxalate was also observed to speed up the carbonation process [7-9].

Advances were also made in the preparation of the host mineral for CO_2 sequestering. In a 2014 report from ETH Zürich, a non-steady state kinetic model for dehydroxylation of lizardite was clarified. The model is based on one fully homogeneous and one heterogeneous pathway to obtain two different dehydroxylated particle structures for the lizardite materials. For this, two different ways of controlling the pH were used. In the first case the pH was adjusted by flue gas containing CO_2 and in the other one pH was controlled by HCl. The study was the first to describe in detail the kinetics of dissolution for dehydroxylated lizardite and to confirm this experimentally. In the experiment 83 % of Mg and 72 % of Si dissolved during the first 100 minutes. For both Mg and Si, the dissolution rate was observed to increase with temperature and partial pressure of CO_2 . This study improves understanding of the dissolution kinetics of lizardite and the modelling helps constrain the kinetics of materials that cannot be assessed via standard dissolution models. This can help optimizing a mineralization process for flue gas [10, 11]. The possibility and benefits of using flue gas rather than pre-separated or purified CO_2 had already been considered many years earlier but was addressed in this connection as well [12].

In 2014, researchers from Singapore and Iran reported on the impact of temperature and pH conditions in a multi-step pH-swing process to obtain Mg suitable for CO_2 sequestering [13]. Bipolar membrane electrodialysis (BMED) is used to produce a pair of acidic (HCl) and alkaline (NaOH) solutions from salt (NaCl) water, using the first solution to extract magnesium from silicate rock and the second to raise the pH of the dissolved magnesium solution so that a carbonation reaction becomes possible. The goal was also to extract other valuable metals from the raw material, in this case a mineralized ore sample. Different forms of magnesium carbonate and iron hydroxide were obtained, the form of the latter being highly dependent upon the reaction pH, while the magnesium carbonate composition was controlled more by reaction temperature. Furthermore, the research group was able to get a purity > 99 % for the MgCO₃. This is an important finding, since industries prefer high-purity materials in their processes. This increased value compared to a mixed aggregate material greatly enhances the prospects of CCS/CCU technologies which are otherwise confronted by the dilemma of what to do with the low-grade products obtained in earlier processes.

The same research team had earlier reported on the production of nanostructured magnesium carbonate from serpentine, according to the following process: magnesium is leached from serpentinite using 1 M HCl, followed by a stepwise pH increase from 0.76 to 9.00 using 1 M NaOH, then to 9.50 and finally 10.65 using 0.5 M Na₂CO₃ to produce hydromagnesite $4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$ with "nanoflaked honey-comb morphology". This material may find application as a flame retardant in polymers [14]. However, a drawback of this method is the energy penalty in the form of electricity for the electrodialysis [13]. Commenting on a similar approach reported earlier [15], Åbo Akademi University (ÅA) researchers pointed out common problems associated with calculating energy penalties. Simple addition of reaction heat inputs and outputs at different temperatures produces erroneous results; calculations should be based on exergy analysis instead [16]. An earlier paper from

the US had presented a similar electrodialysis approach, using the thermodynamic concept of availability (similar to but not the same as exergy) [17].²

The years 2010-2015 saw very significant activity in Canada. One research group operating from Vancouver, BC. One study [18] addresses the economic value of mine rock waste (from the Turnagain nickel mine in BC) when seen from a CO₂ sequestration potential viewpoint. No process route is outlined for accelerating the natural weathering process of silicate rock but a possible annual fixation of \approx 2.8 Mt CO₂ at the site is estimated for the 29 years proposed operation. A two-step calculation method is described for the valorisation of the rock for CO₂ sequestration – but no monetary value. A follow-up study [19] suggests experimental work using olivine rather than serpentinite from the same site using an autoclave following the ARC / NETL route. At the same time, the bioleaching of chrysotile tailings from an asbestos mine in Yukon was studied with *Acidithiobacillus spp.*, using its acid-generating metal and sulphur content [20]. A one-year test using lab-scale columns yielded ~14% leaching of Mg from the tailings, an order of magnitude more (faster) than what was found in waters from the site. One advantage noticed was the immobilisation of Cu, Fe and Zn; a disadvantage is that aqueously dissolved carbonate is obtained, requiring a downstream precipitation step. It is estimated that the Mg leached from the 10 Mt tailings may sequester \approx 0.46 Mt CO₂ during a single year.

An important report by Hitch and Dipple [21] takes economic feasibility as the starting point, making it one of the first to combine technical feasibility with costs. A net present value (NPV) of 131.5 million US\$ was calculated (using 8% discount) for the olivine-rich waste rock from a nickel mine in Northern BC. Sensitivity analysis shows the amount of CO_2 produced during the mineralisation process and thus the CO_2 avoidance ratio to be the most critical parameter (of ten parameters considered), followed by the costs for operating the process facility and the pre-separation of the CO_2 . Included in the work is a table listing several earlier case studies reporting a cost of 50 - 100 US\$/t CO_2 mineralised. Presumably assuming the traditional ARC/NETL process route, a CO_2 mineralisation cost of 82.5 US\$/t CO_2 was calculated, giving the mentioned NPV based on an assumed cap-and-trade CO_2 price increasing to 200 US\$/t CO_2 in 2027. An external supply of CO_2 to the site would nevertheless be required for profitable deployment.

The following year the same UBC team reported on the mineralisation of CO₂ using brucite-rich mine tailings, studying slurries containing 50 g/litre of 2-4 μ m brucite (90-95% pure) from Nevada [22]. Pure and dilute CO₂ streams were bubbled through the slurries during tests of 56-72 h ("short"), 198 h and 2856 h duration (with atmospheric CO₂) at apparently ambient conditions. Emulating the conditions at Mount Keith Nickel Mine in Australia where \approx 11 Mt tailings are produced annually, containing 1 – 2.5 %-wt brucite, it is estimated that 22-57% of the annual 0.37 Mt mining operation emissions (during the early 2000's) may be sequestered as carbonates, while in practice the annual value is around 56 kt CO₂. (This is nonetheless much more than what takes place as a natural process at a chrysotile mine in Québec, Canada.) Brucite-rich ores from nickel mines do offer a significant passive or accelerated

² Exergy analysis, based on the Second Law of Thermodynamics allows for calculating the maximum power or useful work that can be produced from a given energy form. For power P, the exergy Ex(P) = P; for heat Q at temperature T and surroundings temperature T⁰, $Ex(Q) = Q \cdot (1-T^0/T)$. This can be extended to chemical exergy of fuels and chemical compounds.

See: Szargut, J., Morris, D.R., Steward, F.R. 1988 Exergy analysis of thermal, chemical and metallurgical processes. Hemisphere Publ. Corp, New York; Szargut J. 2005 Exergy method. WIT Press, Ashurst, UK.

carbonation potential. A follow-up paper ([23] from the team on brucite carbonation studied magnesium carbonate precipitation in 10% CO_2 gas streams with varying humidity at ambient conditions with a 10% brucite / 90% quartz samples. Under these conditions the formation of nesquehonite (MgCO₃·3H₂O) produces a passivating layer that chemically inhibits carbonation on the brucite surface and the availability of water also limits the progress of carbonation.

A valuable technology summary addressing *ex situ* as well as *in situ* industrial carbonation of serpentinite opportunities and limitations concludes that *ex situ* industrial operations processing 0.1 - 1 Mt CO_2 / year are likely feasible with existing (in 2013) technologies [24]. Hoisted amounts of suitable ultramafic rock at mining sites at rates larger 10 Mt/year may result in accumulation of several Gt of reactive rock, such as can be found at chrysotile mines in Québec alone.

Another area of significant research activity was from the Canadian province of Québec. In a series of three papers, Assima and co-workers report on the direct ambient carbonation of five different ultramafic residues from nickel and chrysotile mining. Aiming at enhancing direct ambient carbonation of chrysotile mining residues with a theoretical CO_2 binding capacity of approx. 700 Mt, the first [25] paper reports on the importance of features such as particle size, water flow and pH on the carbonation dynamics. Layers of mining residue were sparged with humid CO₂ after saturation with water during four days under ambient conditions. It was found that the Fe/Mg ratio and especially the presence of Fe(III) in the form of magnetite has a strong limiting effect. Not surprisingly, brucite fractions carbonate much faster than magnesium silicate fractions. Mg carbonation conversion levels from 1.7% to 10.7% were obtained with size fractions 1.8-2 mm and < 75 μ m. As found in the studies from BC, the availability of water improves carbonation yields. The second study [26] considers a Québec nickel mine residue leached under a gas stream containing, besides 8-10 %-vol CO₂, O₂ levels ranging from 0 to 20%-vol, at $10 - 40^{\circ}$ C. A significant result was obtained in that conversion was an order of magnitude faster at 40°C compared to 10°C, partly facilitated by a temperature rise caused by exothermic chemistry. Addition of a chelating agent (CDTA) interferes with the precipitation of Fe(OH)₃, with increased Fe(III) levels in the pore water, resulting from increased O₂ levels. Mg conversions levels $\approx 8\%$ were obtained after 1000 s at 40°C with 106-850 µm (d20, d80) particles. The third [27] paper gives an assessment for five ultramafic mining residues, being two chrysotiles, two nickel mine residues and one diamond mine residue, all from Québec, capable of sequestering 0.27 -0.35 ton CO₂/ ton material. Also here, direct ambient air carbonation is emulated under mild conditions [25]. Again, brucite dissolution contributed significantly to the necessary pore water alkalinity for carbonation while Fe/Mg and Si/Mg ratios can explain carbonation chemistry-inhibiting passivation via precipitation of Fe(OH)₃ and formation of silica gel, respectively.

Other research efforts from Québec have involved the magnetic removal of iron after grinding of chrysotile mining residue and the role of water during the gas/solid carbonation of serpentinite residue after chromite mining residue, respectively. The first study [28] showed that, with a mean particle size of 75 μ m, 71 % of iron impurities can be magnetically removed, giving a 79%-wt (as Fe₂O₃) iron magnetic fraction and a final 3.4 %-wt (as Fe₂O₃) iron in the non-magnetic fraction, compared to 10.9 %-wt (as Fe₂O₃) iron in the feedstock material. The magnesium content (as MgO) increased from 42.5 %-wt in the feedstock to 44.9 %-wt in the non-magnetic fraction, and was only 9.2 %-wt in the magnetic fraction. Unfortunately, however, the energy input requirements for the magnetic separation were not given. Of a completely different nature is the second study [29], which reports on direct gas/solid carbonation of a serpentinite at up to 300°C, pressure up to 25 barg in a simulated cement kiln off-gas containing 18 %-vol CO₂. A Parr gas/solid batch reactor is used, with 1.5 g untreated material or 1 g

after 30 min pre-heat at 650°C. The best result is obtained with the pre-heat sample at 200°C, 25 barg. It is suggested that the reaction products are MgCO₃·3H₂O and Mg₂Si₂O₆·H₂O.

The research done in Canada during 2010-2015 addresses many relevant issues focussing especially on deployment as direct ambient air carbonation of mining residues at mining sites. At this point, only one reference [21] gives a quantified economic feasibility consideration in the form of a NPV, with an assumption for increasing taxes or other costs for CO₂ emissions.

In Finland, at the Åbo Akademi University, research into stepwise carbonation of serpentinite was published in a large number of reports on the thermal extraction of magnesium using ammonium sulphate, the production of magnesium hydroxide and the carbonation of this in a gas/solid pressurised fluidised bed. Thesis studies by Fagerlund [30] and Nduagu [31] on these respective subjects were followed by that of Romão who focussed on process integration, the co-extraction of metals and comparing Finnish and Portuguese serpentinites [32]. Of significance from this time too was the co-operation with Singapore, resulting in detailed analysis of the role of water vapour during magnesium (hydr)oxide carbonation [33,34] and the details of the decomposition of ammonium sulphate flux salt during the thermal extraction of magnesium [35]. Also, the team switched focus to processes operating on flue gas directly, avoiding a CO₂ capture step and reported on implementation of the (first) ÅA route and process integration at an industrial scale lime kiln [36]. (Brief descriptions of the various ÅA routes that have been developed since 2005 are given as an Appendix 4 to this report.)

Elsewhere in Europe, Wang and Maroto-Valer reported on a pH-swing process using ammonium bisulphate (ABS) for leaching magnesium from serpentine, followed by (after removal of solids and raising pH using aqueous ammonia) carbonation with ammonium bicarbonate (ABC) obtained from scrubbing flue gas with aqueous ammonia. Most critically, near 100% extraction of magnesium was obtained within 3h. Problematic disadvantages were the thermodynamics of reproducing ABS from the final ammonium sulphate (AS) solution via thermal decomposition, as well as the energy penalty for that [37,38] - see also the 1967 patent by Pundsack [39]. In Denmark, Eikeland and co-workers were able to fully carbonate olivine particles within 4 hours, at 190°C, in a solution of 0.5 M NaHCO₃ + 0.5 0.75 M NaCl. The (energy) cost comes from extra fine grinding (<10 μ m) and 100 bar CO₂ pressure needed [40]. This suggests that certain optimal concentrations of chemical additives exist when processing certain particle sizes. Energy inputs for crushing/grinding, mixing of solutions and heating can be mirrored against concentrations of reacting species and reaction time (and reactor volume).

In Australia, work continued along the path of aqueous carbonation of heat-activated rock, aiming at avoiding the presence of NaCl in the solution (as this may cause corrosion) [41]. The heat treatment process itself (applied to rock from the NSW Great Serpentine Belt) was also the subject of further optimization studies, reporting on energy requirements > 540 MJ/ton serpentinite and costs of 1.25 A\$ per ton active serpentine in the rock, with preferable (wet ground) particle size $d_{80} = 75 \ \mu m [42,43]$.

In South-Africa, following a scoping study by Doucet [44], Meyer and co-workers report on carbonation of platinum group metal (PGM) mine tailings containing large fractions of orthopyroxene minerals. Conversion levels were only 30%, 3% and 9% carbonation of the material's Ca, Mg and Fe, respectively, using 2 M HCl at 70°C for extraction. Addition of 15 M NaOH facilitated carbonation which was 96, 59 and 98% efficient for Ca, Mg and Fe, respectively. Clearly, extraction and carbonation levels for Mg need significant improvement [45].

In the US, a study by Kruse and Strosnider reviewed CO₂ sequestration using waters (especially acid mine drainage, AMD) and solid waste from mining operations and saw a large gap in knowledge. Much

is unknown on the interaction between carbonate, AMD that may contain sulphate, and the net uptake or release of CO₂, either as dissolved (bi-)carbonate or precipitate [46].

Renforth et al. [47] gives world-wide estimates for silicate-based materials generated by human activities, including mine tailings. The number given is 7 - 17 Gt capable of 700 - 1,220 Mt CO₂ (190-332 Mt C) sequestration. For mine waste, an annual production amount of 2,000 - 6,500 Mt is given (in 2011!) with "unknown" as the CO₂ sequestration potential. Assuming an MgO content of, say, 15 %-wt feasible for application in a CO₂ mineralisation process with give an estimated annual potential of 360 - 1065 Mt CO₂/year (2011 tailings production rate).

3.2 Life cycle assessment (LCA)

As summarised in the 2017 review by Zevenhoven and Romão [48], LCA considered from a CO_2 mineralisation viewpoint was the subject of around ten publications during 2010 - 2015. Khoo et al. [49]. reported on an application in Singapore, this time for the first ÅA route to a natural gas combined cycle (NGCC) power plant using serpentinite shipped in from Australia. Four calculated cases involve 90% and 100% Mg carbonation efficiency, and amine scrubbing for CO_2 pre-capture or operation on (pressurised) flue gases directly. The best results (obtained without CO_2 pre-capture) give an avoided 55-66% CO_2 emissions, dropping to 42-58% when the impact of shipping and mining is included. Emissions of NOx, SOx and particulate matter were accounted for, for the power plant as well as for the shipment of rock and its mining. Estimated system costs in the range 71 – 159 US\$/t CO_2 could also be calculated, which corresponds to 18 – 40 US\$/t solid products for land reclamation.

Kirchofer et al. [50] considered aqueous mineralisation applied to eleven alkaline feedstocks (olivines, a serpentine and several industrial alkaline by-products) for 1,000 t/day CO₂ sequestration. The lowest CO₂ emissions (267 kg/t CO₂ processed) are obtained with 10 μ m olivine particles (155°C, 90 bar, 24h). The impact (as CO₂ emissions) of energy input for upstream and downstream process steps and water use are considered as well. Nduagu et al. [51] compared the (first) ÅA route with the ARC/NETL direct process using exergy analysis as well as LCA, for a pre-captured CO₂ feed, with serpentinite rock. The energy input requirements for the processes were found to be very similar at \approx 3.5 GJ/t CO₂, but the LCA showed a smaller environmental impact for the ÅA process. Avoided CO₂ emissions equal 317 and 483 kg/t mineralised CO₂ for the ARC/NETL and ÅA routes, respectively, resulting from better recoverability of additional chemicals, lower temperatures and better heat integration for the latter. The analysis was updated during the following year [52]. Stasiulaitiene et al. [53] applied the (first) ÅA route to Lithuanian serpentinite and reported an LCA that compares it with CCGS (carbon capture with geological storage). It was concluded that with a CO₂ capture step, (involving solvent-based capture of industrial flue-gases), mineralisation of CO₂ cannot, from an LCA point of view, compete with underground storage of CO₂, reporting numbers that agree with Nduagu et al. [51].

Giannoulakis et al. [54] presented an LCA analysis comparing both the first ÅA route and the ARC/NETL work with CCGS, i.e. geological storage of CO_2 , for pulverised coal firing and NGCC power plants. It was concluded that the "life cycle greenhouse gas reduction" achievable with mineralisation is less than with geological storage. The reasons for this are the use of energy and chemical additives use, besides the health issues related to particulate formation during mining. Unfortunately, there is no mention made of the research reported by Khoo et al. [49] or of other studies that specifically mention the treatment of flue gas, without CO_2 pre-separation, as a significant benefit related to CO_2 mineralisation, when compared to CCGS.
Bodénan et al. [55] include LCA (albeit briefly) in reporting the Carmex project, distinguishing between direct aqueous carbonation of olivine as such, or with either organic ligands or mechanical exfoliation. This was compared with alternative scenarios of no CCS or with CCGS for nickel mining in New Caledonia. CO_2 is assumed to be transported over a 300 km distance from a coal-fired power plant. Of five LCA impact categories considered, climate change (GWP) decreases when compared to a no CCS scenario while for the other impact categories (resources depletion, non-renewable primary energy use, terrestrial acidification and photochemical oxidation) the environmental impact of *ex-situ* CO_2 mineralisation is also higher when compared to CCGS. The paper includes a world map showing where significant suitable mineral resources can be found within a 300 km distance from (at that time) large CO_2 emitters – see Fig 3.1.



Fig. 3.1 Ore deposits related to ultramafic rocks lying less than 300 km from a CO₂-emission site [55].

An extensive analysis including LCA of CCS and CCU (including CO_2 mineralisation) was reported by Cuéllar-Franca and Azagapic [56]. GWP is the main LCA impact category considered plus nine others. The work reported by Khoo et al. [49, 57] and Nduagu et al. [51] mentioned above represent three of the CCU studies considered, all producing MgCO₃ from a process with intermediate Mg(OH)₂. The assessment reports CO_2 emissions in the range 524-1,073 kg CO_2/t CO_2 fixed as minerals, mainly depending on (having) upstream CO_2 capture and CO_2 concentration, and the heat source/heat integration. Within the CCS + CCU portfolio, mineralisation is reported to have a larger GWP than "conventional CCS" (i.e. CCGS) and CCS + EOR (enhance oil recovery).

Highlights and progress between 2010-2015:

- Advancements in simultaneous capture and mineralisation of CO₂ directly from flue gas
- Carbonating flue gas via leachate e.g., NH₄HCO₃ as an indirect carbonation route studied at lab-scale in several laboratories
- Better modelling of the kinetics for dehydroxylation in host minerals
- Better understanding of the temperature's impact on carbonate precipitation
- Emphasis on the solid products and their economic value
- A first study (from BC, Canada) presents a 15-year (2012-2027) opportunity of mine residue carbonation via a NPV estimation
- A significant number of LCA studies reported

Outstanding issues remaining to be addressed after 2010-2015:

- Higher carbonation rates are needed for the CCS to pose a viable solution to the GHG challenge
- Deployment at industrial scale, which would demand TRL = 5 demonstrated in the laboratory. None of the reporting from 2010-2015 refers to TRL level
 The fate and consequences of potentially toxic by-products (primarily heavy metals) needs more study. This is at least one impact category of LCA studies.

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4 Literature review and status 2016 – 2021

A literature search covering the last five years - since the Zevenhoven and Romão (2017) literature review – found around 100 publications addressing the field of *ex situ* CO₂ mineralisation with focus on the use of mine/mining tailings, almost exclusively magnesium silicate - based material. Besides these, around twenty-five publications report on *in situ* CO₂ mineralisation, primarily reporting findings (mostly during 2017 and 2018) from two sites in Australia and Canada, respectively. (For a discussion on these, see Part 3 of this report.) Around twenty review papers since 2015 address the subject, with main findings and conclusions as summarised below.

When it comes to key performance indicators that quantify the technological maturity and economic viability necessary for developing a large-scale business model around CO₂ mineralisation using of mine/mining tailings, the information is (still) scarce or inconclusive. As described in the following chapters, TRL, LCA, public acceptance, possible revenues from carbonate and other materials obtained, toxicity and other material hazards, and input requirements for energy and water are seldom addressed, while many researchers (still) report on laboratory-scale carbonation experiments. After more than thirty years of R&D, most researchers (still) use hours rather than minutes as the time scale for significant conversion of magnesium-based materials into carbonate.

Only a dozen or so publications provide information that goes beyond chemical conversion experimenting and aim at upscaling technology from the laboratory to industry, short-listing several process routes or industrial sites. LCA is increasingly used as a tool, having been addressed in a dozen papers since 2006 (with four from the last five years).

4.1 Overview of research articles

Based on recent (2016 to mid-2021) publications, much work is still being done in the lab to further the understanding of the different mechanisms at play during mineral extraction and carbonation processes. The fact that there are still so many examples of basic research being published is in itself an indication that there is still considerable potential for new ideas and processes.

Specific examples of recent basic research include a study [1] of the formation of undesirable byproducts during direct aqueous mineral carbonation, which recommends a greater focus preventing such by-products, in order to enhance carbonation. Wang et al. [2] studied the kinetics and mechanisms of olivine carbonation with the intention to develop the theory further, while Rausis et al. [3] studied brucite (Mg(OH)₂) carbonation under various conditions.

Stopić et al. [4] used an autoclave to study direct aqueous olivine carbonation under high pressure and temperature conditions (for several hours), while Arce et al. [5] performed fundamental leaching studies of a specific mineral under relatively mild process conditions, indicating that certain minerals (in this case sterile from asbestos production) are more suitable for carbonation than others. Zarandi et al. [6] also studied carbonation reactions of nickel mine tailings containing brucite at ambient conditions, highlighting the main limiting factors (carbonate nucleation and surface layer inhibition) for carbonation at mining sites.

Rigopoulos et al. [32] studied ball-milling of mine tailings but did not consider the energy requirements (for 20 h of milling). However, the positive impact of ball-milling on carbonation was further considered in a later study [33] that investigated the enhanced weathering of pulverized and ball-milled peridotites and basalts. This study subjected the minerals to artificial seawater in a batch reactor open

to the atmosphere for two months. One goal of the study was to demonstrate that if ball-milling can be performed in a cost-effective manner (e.g. by integrating with existing cement and lime industry), then the sub-sequent carbonation step can be simplified (and made less energy intensive).

Carbonates are generally considered a stable sink for CO_2 sequestration, but additional information is still needed regarding the detailed behaviour of carbonates used for permanent CO_2 storage. For instance, Harrison et al. [34], noted that nesquehonite (Mg $CO_3 \cdot 3H_2O$) readily transformed to dypingite (Mg₅(CO₃)₄(OH)₂·5H₂O) or hydromagnesite (Mg₅(CO₃)₄(OH)₂·4H₂O) under ambient conditions, accompanied by a small loss in CO₂.

Others have studied novel ideas such as combining grinding media into a reactor with CO_2 partial pressure swing [7], but further studies are needed to make any conclusions regarding its large-scale feasibility. Santos et al. [8] and Turri et al. [9] are also furthering the development of a novel idea (Patent: NL2004851C2), a so-called "CO₂ energy reactor", but the results still warrant further research and testing on a larger scale.

Ebrahimi et al. [10] suggested combining alkaline industrial waste with acid tailings in order to reduce requirements for pH adjustment using e.g. NaOH in the carbonation step, while Power et al. [11] successfully used carboxylated polystyrene microspheres to catalyse magnesite precipitation at mild (ambient) conditions.

Many researchers recognise the need for pilot testing and using "real" materials, such as actual flue gas, industrial waste streams and mine tailings. For example, Kemache et al. [12, 13] experimented with real (cement plant) flue gas and heat-treated serpentinite but concluded that the method, still batch-wise, must be adapted to continuous flue gas flow in order to be industrially applicable.

Mine tailings are recognized as a potentially simple and sustainable way to reduce the environmental impact of the tailings and CO_2 emissions at the same time [14, 15]. Recent examples of this include Hamilton et al. [16] who studied the carbonation of ultramafic mine tailings using so called field-deployable (i.e. scalable and relatively simple) methods, but both of the employed methods (direct carbonation using an onsite CO_2 source or indirectly via heap leaching of Mg using sulphuric acid) should still be demonstrated outside the lab to establish their full potential.

Similarly, Power et al. [17] presents an example of sequestering CO_2 using simple aeration of ultramafic mine tailings. Due to the anticipated low-cost of the proposed method, this process becomes increasingly viable as carbon tax prices increase. However, it should be noted, that out of the significant CO_2 sequestration potential of various mine tailings only a small fraction is "easily" carbonated [18]. For example, Paulo et al. [18] estimated that only $3 - 9 \text{ kg } CO_2 / t$ material out of the full potential of 268 - 342 kg CO_2 / t was readily available for carbonation at Earth's surface conditions. This study suggests that in order to make a significant impact on the CO_2 emissions, the conditions need to be enhanced, for example using *ex situ* carbonation processes.

Studies suggesting the implementation of *ex situ* carbonation using mine tailings have increased during recent years. Suitable mining operations include e.g. diamond mines that have significant untapped potential according to Mervin et al. [19]. Jiajie and Hitch [20], on the other hand, focused on nickel mining and estimated that the operating cost for mineral carbonation at a nickel mine in British Columbia would be between 104.1 to 107.1 \$ /t of avoided CO_2 emissions. Mohamed et al. [21] experimented (at lab-scale) with a thermochemical method using ammonium sulphate to extract

elements from platinum group metals (PGM) tailings, but further work is needed to combine the method with selective precipitation of valuable products.

Examples where cost awareness is clearly driving the research are exemplified by studies focusing on product sales in addition to CO_2 capture. For example, one recent study by Chakravarthy et al. [22] investigated the possibility to utilize carbonate kimberlite tailings (from diamond production) as a substitution material for partial cement replacement. This study, similarly to others (e.g. [23]), attempts to provide solutions for decarbonization of the construction industry by reducing the need for virgin calcium carbonate in cement production. Kularatne et al. [25] proposed a mineral carbonation method that combines CO_2 sequestration with hydrogen production. However, that process is still at an early stage and is dependent on highly specific conditions (e.g. mine close to residual heat source).

Another example of cost awareness is provided by Pasquier et al. [24] who claim that a process (based on mine tailings) could be highly profitable depending on the market for magnesium carbonates. This process has been the subject of further research and significant improvements (25% lower heat demand) can be made by heat treatment optimization and integration with the existing plant (in this case a cement plant), as discussed by Tebbiche et al. [31] - see Figure 4.1. The reported heat requirements were 5 GJ/t CO_2 captured and 9.5 GJ/t CO_2 avoided.



Fig. 4.1 Carbon mineralization process description for application at a cement plant [31] (cooling and heating utilities are not indicated for simplicity).

Other recently reported research progress includes studies that aim to quantify the CO₂ sequestration of mining tailings or ultramafic rock samples using mild process conditions, which results in very low degrees of carbonation even after long reaction times. Testing of tailings from a PGM (platinum group metal) mine in Montana (US), using a flow-through reactor where a diluted CO₂ stream reacted with

Ca, Mg and other ions in pore water at ambient conditions for up to 60 h gave < 1% Ca and no Mg dissolution [40]. Another study that likewise aimed at quantifying the CO_2 sequestration potential for ten (ultra)mafic rocks from Southwest Portugal resulted in < 1% carbonate precipitates of Ca, Mg and Fe for the two most suitable materials after 64 days at 40°C, 80 bar in a supercritical CO_2 supersaturated natural brine (sampled from an old borehole in a saline aquifer) [41,42].

At the ACEME2021 conference hosted (on-line) from Tallinn, Estonia, Brent reported on the latest developments at MCi in Australia, where currently an aqueous process under "mild conditions" has advanced from TRL 6 to TRL 7 during this year [35]. Zevenhoven reported on the five alternative "ÅA routes" (see Appendix 4) for step-wise carbonation of serpentinites, using ammonium sulphate as the flux salt and presented "company neutral" results (assuming 0.5 Mt/year CO₂ sequestration) from ongoing work on large-scale implementation at one of the world's largest seaports [36]. Bourgeois reported on AMC as a supply chain driven design problem, addressing New Caledonia (viz. the Carmex project mentioned above) [37]. Two studies reported on AMC applied to cement production, offering the opportunity to sequester CO₂ while producing materials that can be mixed into the cement product [38,39].

4.1.1 Life cycle assessment studies

LCA analysis of CO₂ mineralisation has been addressed in fewer than ten studies identified as relevant for this report. Ekayaoglu and Deminel [26] do not address CO₂ sequestration but describe how to carry out LCA for mining activities (in Turkey), with a focus on material handling equipment. Likewise, the reporting by Ruan and Unluer [27] on cements containing MgO shows how LCA pinpoints the use of energy and the resultant emissions as the main contributors to the environmental footprint.

Zevenhoven and co-workers include LCA in the description of the ÅA routes for large-scale CO₂ mineralisation using serpentinite and ammonium sulphate as the flux salt. It shows the necessity of high levels of flux salt recovery, maintaining it inside the process, the importance of operating on flue gas directly without a CO₂ capture step, and that the contribution of transport of rock (5, 50, 500 km) to the overall environmental footprint is (surprisingly) small. Ncongwane et al. [29] give a comparison of five CO₂ mineralisation process routes using LCA and process system modelling, focussing on pyroxene-rich PGM mine tailings. The ÅA (first) process route (still with pre-separated CO₂) was shown to have the smallest overall environmental footprint, based on climate change as apparently the only impact category considered. It is noted that with pyroxene-rich rock (containing primarily enstatite) the conversion rates and degrees demonstrated by olivines and serpentinites have not yet been realised.

Very recently, Z.-Y. Khoo and co-workers [30] report a further LCA on CO₂ mineralisation from Singapore's perspective, with focus on transport distances of suitable rock, for twelve scenarios. Rock sourced from Western Australia or alternatively from Malacca, Malaysia are considered, with several options for heat pre-treatment, crushing/grinding and the energy sources used for that. Flue gas from a waste incinerator in Singapore (one example of a country without territorial geological storage options) is considered in a process where heat-activated serpentine is reacted with an aqueous solution of ammonium carbonate obtained from scrubbing flue gas with aqueous ammonia (patent application SG11201908958V, 2018). The heat activation and carbon capture step and especially the transport of rock generate significant CO₂ emissions, requiring CO₂-neutral alternatives, while the mineralisation process itself also has scope for improvement, for example via process integration.

Progress highlights between 2016 – 2021:

• The realization that mining tailings represent a significant untapped potential for CO₂ sequestration

Important issues still to be addressed following 2016 – 2021:

The main issues hindering mineral carbonation from advancing on the TRL ladder are still largely the same as ten years ago:

- Speeding-up the carbonation chemistry kinetics;
- Energy economy (i.e. processes are still too energy intensive);
- Recovery and recycling of chemicals used.

4.2 Overview of review articles

Consolidating the recent literature reviews in the area of accelerated mineral carbonation (AMC) provides an opportunity to collect well-informed conclusions as well as recommendations for next steps regarding AMC development efforts. It was noted that for many of these review papers, the authors are rarely, if at all active in the development of AMC technology themselves; therefore the reviews are treated in this separate sub-chapter.

Based on the reviews it is evident that no single process has yet risen to meet the challenge of large scale CO₂ emission mitigation. For instance, out of the 23 review papers included in this study, published between 2016 and 2021, only two mention TRL directly. Economic feasibility on the other hand is at least mentioned in 15 of the papers, but in general only superficially, with unquantified uncertainty as most technologies are at early stages of development. LCA studies are also still scarce and mentioned only in two of the papers. Public acceptance, however, is at least mentioned in ten of the papers, while the production of metals in conjunction with AMC is only mentioned in four of the papers [44, 52, 59, 64]. Issues with toxicity and the risk of generating new toxic waste streams during AMC is also noted (only) in five papers.

Despite the apparent lack of a systematic approach to presenting and evaluating new technologies in the field of AMC, the following findings have been found to summarize the recent review articles from the last five years:

- In general, significant progress has been identified in the field of AMC [58, 59] and AMC is most likely one of the first CCU technologies to be implemented commercially [15]
- Mining wastes, in particular tailings, represent the best opportunity for CCU and can be considered as the "low-hanging fruit" for AMC processes [47, 55]
 - Integrating AMC with mining operations (crushing/grinding) is recommended [51, 52]
 - AMC of industrial (alkaline) wastes should be the focus of further research [43, 45, 46, 47, 55, 56]
 - In particular the use of fly ash [53]
- Commercial efforts should be directed towards utilizing AMC (mainly Ca-based) as part of or replacing existing (Portland cement based) concrete production processes and products [43, 46, 49, 55, 62]
- Magnesium based AMC processes currently lack market demand for the product [55]

As an example of market potential, [13] gives the thermal decomposition enthalpies for magnesium-based fillers when used as flame retardants – see Table 4.1.

Filler	Formula	T _{decomp} (°C)	ΔH _{decomp} (kJ / g)
Nesquehonite	MgCO ₃ ·3H ₂ O	70 - 100	1750
Hydromagnesite	Mg ₅ (CO ₃) ₄ (OH) ₂ ·4H ₂ O	220 - 240	1300
Huntite	Mg ₃ Ca(CO ₃) ₄	400	980

Table 4.1 Physical properties of potential fire-retarding mineral fillers (taken from [55])

- Likewise, a proof-of-concept study for thermal energy storage (TES) at ambient, indoor house temperature conditions utilizing the reversible system nesquehonite <-> magnesite + water vapour has been reported from Åbo Akademi University [60, 61].
- The recovery and production of valuable (sufficiently pure) end-products (such as silica, iron oxides and other metals, Mg-carbonates) should be aimed for, in addition to capturing CO₂ [44, 52, 58]
- Indirect carbonation using ammonia and bipolar membrane electrodialysis for additive recovery should be studied further [56]
- The opportunity to avoid an intermediary CO₂ capture and purification step should be focused on [56, 58]
- Further research is needed,
 - but "it is time to put a stop to the repeated strategies, including elevating the process conditions, utilising energy-intensive thermo-mechanical feedstock, and large-scale expensive chemical consumptions." [58]

One of the reviews [49] included the mapping of recent patents (up to 2017). The study pointed out that the number of patents towards CCUS and AMC have accelerated in the recent past, and it is estimated that this trend will continue. The number of patents found between 1980 and 2017 in the field of mineral carbonation was 103 and from the results it could be seen that pace (numbers of patents issued) is accelerating.

Despite the significant amount of recent review papers, very little information about commercial maturity (expressed specifically as TRL) is available. However, in the review by Chauvy and De Weireld [59], a (non-exhaustive) list of processes with products utilizing CO₂ was provided. In line with other review authors [e.g. 49, 55], the AMC for the construction industry in the form of concrete curing has the highest TRL level of 8, together with sodium bicarbonate production. However, sodium bicarbonate production results in a highly unstable end-product in terms of CO₂ long-term storage. Calcium carbonate production using AMC was estimated at TRL 7 (demonstration scale), while magnesium carbonate is still at TRL 4 (lab prototype).

Chauvy and De Weireld [59] also assessed other aspects of the various CCU technologies in order to provide a qualitative comparison of the overall viability of AMC using the following indicators: technology status, energy performance, CAPEX, OPEX, CO₂ utilization, sustainability and social (public) acceptance. Overall, both carbonate production and concrete curing were provided relatively high scores with an average of 2.9 out of 4 across all seven indicators.

4.3 Lab-scale work versus large-scale application

Based on a number of recent literature reviews [e.g. 49, 52,58,63], it is evident that additional efforts to scale-up the various AMC approaches is needed (keeping in mind the overall energy efficiency and

sustainability of the proposed process). In the past, only a few methods have been tested outside the laboratories and currently (late 2021) there are only a handful of active AMC projects as presented in the Table below.

Project	Technology and feedstock	Comment
Carmex (New Caledonia, France)	Direct aqueous mineral carbonation of mafic/ultramafic mining wastes	New Caledonia is an excellent candidate for implementing mineral carbonation due to the availability of both suitable mineral feedstocks and proximity to CO ₂ emission sources. (Ended 2012)
MCi (New South Wales, Australia)	Proprietary direct aqueous carbonation of various industrial wastes and mine tailings	Demonstration projects planned with Japanese ITOCHU Corporation. The business model of MCi is that the cost of CO ₂ capture is outweighed by producing valuable materials
Québec process (INRS, Québec, Canada)	Aqueous mineral carbonation process using heat treated serpentinite-based tailings and cement plant flue gas	Potentially commercially viable process, provided there is sufficient market for the produced magnesium carbonate
HiGCarb process (CSC, Kaohsiung, Taiwan)	Rotating packed bed using hot- stove gas (28.8 vol% CO ₂) and wastewater for blast oxygen furnace slag carbonation	Carbonate product used as cement additive and fast conversion times indicate potential feasibility for further scale-up in the near future
Kawashima- Daini project, Japan	Indirect aqueous carbonation of concrete sludge to produce CaCO ₃ using boiler flue gas	Net CO ₂ reduction achieved, but the low reaction rates and large feedstock amounts needed / ton of CO ₂ represents a barrier for further development
CarbonVault [™]	Carbonation of diamond mine tailings by De Beers Group using various AMC technologies	Pilot testing delayed in 2020/2021. Environmental targets include carbon neutral mining operations by 2030

Table 4.2 Notable recent AMC pilot plant scale projects [49,58,63]

As also indicated from the (non-exhaustive) Table above, the number of processes considering mine tailings or natural mineral resources containing abundant magnesium are in a minority compared to processes utilizing various industrial wastes.

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5 Assessment on key performance indicators

5.1 Availability and quality of rock resources

Evaluation of potential sequestration reservoirs for conventional CCS has been the subject of numerous studies over several decades and has benefited greatly from the industry exploration data that provide robust modelling of basin architecture and reservoir rock characteristics. Based on this information, it has been possible to further assess the viability of potential sequestration sites in terms of proximity to CO₂ sources and synergies with respect to enhancement of petroleum recovery (EOR).

Similarly, a comprehensive and useful global assessment of suitable mineral resources for significant CO₂ carbonation needs to provide more than a simple theoretical inventory of potentially reactive rock volumes and should instead be informed by the following factors:

- Documentation of volumes of *in situ* and mined resources, ideally compliant with internationally recognized resource accounting mechanisms (UNECE, JORC; N43-101)
- Characterization of waste rock and tailings and water in mine environments, to determine carbonation effectiveness and reaction pathways and potential for recovery of by-products
- Documentation of infrastructure, material transport, energy sources and energy consumption related to extraction, processing and beneficiation; this information can be used in the LCA process and thus provides a way of assessing the relevance of sequestration within the overall scale and cost of operations.

This breadth of data is necessary to establish whether a specific mining region:

- has a resource endowment of sufficient magnitude that it could represent a CCUS carbonation site of global significance, or whether
- its potential resides rather in supporting the economic and environmental sustainability of individual local mining operations.

In both scenarios, it is important to evaluate the potential benefits of carbonation and by-product recovery in the light of overall mining costs and energy consumption. This too, is analogous to the situation facing saline aquifer storage combined with EOR, for example, whereas some EOR sequestration projects may become carbon emissions positive, if injected CO₂ volumes are exceeded by emissions related to burning extracted fuel. Similarly, it is necessary to fully understand the entire environment surrounding a given mining project and the mineralogical complexity of reactive tailings. It is not uncommon, in the case of sulphide ore deposits in ultramafic rocks, for carbonate minerals to be present in waste rock and tailings, along with such iron sulphides as pyrite or pyrrhotite which are generally devoid of economic interest. Oxidation of pyrite is one of the main sources of acid mine drainage, when tailings are exposed to the atmosphere or oxidizing vadose groundwaters, leading to dissolution of carbonate minerals and carbon dioxide release [1], which in turn may offset the benefits of carbonation elsewhere in the system. Further feedback effects on in situ carbonation, or carbonate dissolution are possible, depending on whether or not the tailings pore spaces are water saturated. Moreover, limestone is commonly used as a neutralizing agent in acid mine drainage; extraction, transport and application of limestone could thus incur penalties in a full life cycle analysis of mineral carbonation efficiency.

It is necessary to evaluate how and to what extent CCUS will be adopted alongside other mitigation strategies for emissions reduction. For large corporations with a diverse and possibly global resource portfolio, it is necessary to ascertain the proportion of emissions abatement that could be assigned to mineral carbonation in general and CCU in particular, compared to other strategies, such as divestment and changing energy sources. In corporate annual reports it has become routine and best practice to declare energy sources and flows and greenhouse abatement measures. In some cases, compliance with emissions reduction targets has been met by changing investment priorities, for example, and via abandonment of, or divestment from combustion-based energy resources (coal, gas and oil). At the scale of individual mining operations, investment in replacing diesel fuel in transport and power generation by electrification has already proven significant with respect to energy efficiency and emissions abatement.

Innovation has always been integral to the mining industry, through the development and refinement of processing technologies and products, or through efficiency gains, including those minimizing energy consumption. Mineral carbonation and generation of new mineral products through CCU can therefore be seen as yet another opportunity for improvement. This demand for innovation can be expected to continue, irrespective of the magnitude of the role that CCU plays in the global mix of greenhouse gas abatement strategies during the next few decades.

The role and potential of CCU may therefore be evaluated using two timelines. Over the longer term, the intention is to ensure a robust future minerals industry that is aligned and compliant with global sustainable development goals (SDGs). A more immediate, 30 year time frame is constrained by international treaties and recommendations within IPCC and IEA reports, as well as = various national governments and advisory bodies on the urgent requirement for mitigation and abatement strategies to achieve a net zero, ecologically and economically sustainable, dynamically balanced and global carbon flow by 2050. This makes it all the more essential to realistically assess the potential for CCU as a greenhouse gas abatement mechanism and underscores the need for advancing the TRL of bench scale projects to full-scale deployment, so that CCUS could make a meaningful contribution to the emissions reduction within the timeframe required under the 2015 Paris Agreement. Ultimately, there is a need for at least semi-quantitative estimates of the current volume of accessible mineral resources and where possible, anticipated production estimates over the next three decades. A review of past mining production where primary products and waste materials are mineralogically amenable to carbonation, as well as case studies that have monitored mineralogical changes and "passive" carbonation is also essential and instructive in providing constraints on long-term trends and expectations for this particular part of the minerals sector.

When searching for such information for this scoping study, it became apparent that the quality and availability of data is highly variable. In some jurisdictions, there is a long history of mining activity, as a result of which mining authorities and geoscience agencies have compiled and released comprehensive data for past and present production history. This applies for example to Australia, Canada and Finland, where significant mining projects are associated with rocks considered favourable for mineral carbonation.

A further development in recent decades has been the recognition by the mining industry that compliance with environmental legislation and improvements in energy efficiency can have pragmatic as well as ethical consequences. In many cases embracing of UN SDGs are overtly stated in corporate mission statements and this is particularly important in the case of transnational corporations. As a result of these factors and increased public awareness and shareholder concerns and scrutiny,

disclosures and statements of policy, including climate change commitments and investment and production figures are widely available in company financial and annual reports, providing transparent and valuable reference material for future studies.

5.1.1 Case study for national resource accounting – Finland.

The information in Appendix 1 pertaining to mining in Finland has been compiled by the Geological Survey of Finland (gtk.fi) and the National Mining Register (Tukes.fi) and illustrates the type of data that can be used to investigate potential mineral carbonation sources. Appendix 2 represents a preliminary global compilation of mafic and ultramafic rock units and selected mining data but there are difficulties in evaluating realistic carbonation potential at this broad scale. The gaps in data evident from this first-pass compilation nevertheless serve to indicate the type and quality of information that is needed for future studies. The Finnish example thus highlights how more detailed mining production and resource assessment figures are required for making more informed assessments of CCU potential.

Mining and quarrying operations in Finland have been separated in two groups, according to whether the primary project has been metal recovery or industrial minerals (Appendix 1.1 and Appendix 1.2). This is relevant to overall national inventories of energy and carbon flows and emissions in the mining industry, if for example quarrying of limestone and its applications in cement manufacture or neutralizing of acid mine waters is considered.

For completeness, historical workings are listed in the table but many of these have total production less than 500 tonnes. This is approximately the capacity of a single modern large-scale mining dump truck and therefore, even those mineral occurrences with potentially reactive mineralogy maybe dismissed at this stage, especially in the absence of knowledge concerning potentially feasible and accessible resource extensions.

A significant number of ore deposits in Finland occur in host rocks that would not normally be considered favourable for carbonation, with a cumulative mined ore tonnage of some 223 Mt. Nearly half of this can be attributed to a single mine at Talvivaara operated by Terrafame Oy, which only commenced production in 2008. The tabulated data show considerably more *in situ* resources and reserve, calculated in compliance with accepted reporting standards but a detailed analysis cannot yet made, in the absence of schedules and feasibility studies.

While renewed mining and recovery of metals from waste and tailings may become significant and profitable at many of these deposits, it important to appreciate that in the overall context, the need to treat legacy or ongoing issues such as neutralization of acid mine drainage could potentially lead to such projects obviating the potential benefits obtained through mineral carbonation at other mines. It depends to some extent whether monitoring criteria and performance targets are set at mine scale or national level.

Finland is also endowed geologically with significant volumes of mineralized mafic and ultramafic rocks, notable the serpentinites of the Outokumpu Cu-Co-Zn mining district and the Kemi Cr mine, which have been critical to the development of copper and steel refining in Finland. Accordingly, there is a close synergy between mining, processing and energy production and consumption, which could be favourable with regard to carbonation opportunities. There are also a number of nickel deposits within smaller ultramafic intrusions, such as Hitura, from which serpentinite material has already tested with extensive laboratory experiments during the early phases of carbonation research [2].

In total there are 326 Mt of recorded ore production and a similar amount is present in several projects awaiting evaluation and in reserves remaining at several mines.

Industrial mineral deposits have similarly been grouped into several categories, of which the most relevant for carbonation and by-product recovery are those in potentially reactive ultramafic rocks that are principally mined for talc. These are principally within the Outokumpu ore field and have a cumulative mined production of about 42 Mt with estimated reserves of additional 25 Mt. Together with the potentially reactive host rocks associated with metallic mining, this yields a total mass of almost 400 Mt.

Further analysis is required to assess the reactive potential of individual sites, in terms of proportions of favourable minerals and the possibility of negative feedback flows from oxidation of sulphides and carbonate dissolution associated with acid mine drainage.

The statistics for calcite and dolomite (total cumulative production of 301 Mt) are also presented, as these resources are used in cement manufacture and also in neutralization of mine tailings and hence in any national accounting evaluation, ought to be calculated as offsetting emissions sequestered by carbonation.

We recommend continuing compilation for all countries with significant mineral production, as well as quantitative systematic time-series monitoring of passive "background" carbonation in waste and tailings, so that the significance of *in situ* versus active carbonation and product development can be compared.

As reporting of energy consumption and emissions is becoming routine in mining company prospectuses and annual reporting, to shareholders and regulatory authorities alike, it would be a relatively small step to formalize reporting of sequestration potential, though this would require detailed mineralogical and textural analysis of side-streams and waste rock and tailings.

It is recommended that future studies make use of compilations in company reports that nowadays generally provide additional information on energy consumption and emissions in mining and transport operations. This would provide a further perspective on the potential opportunities for carbonation within overall strategies for dealing with emissions, as specified for example in the GHG Protocol Corporate Accounting and Reporting Standard, which classifies corporate GHG emissions into the following three 'scopes'.

Scope 1 emissions are direct GHG emissions from operations that are owned or controlled by the reporting company (e.g. emissions from fuel consumed by haul trucks or electricity generated by diesel at mine sites).

Scope 2 emissions are indirect emissions from the generation of purchased energy consumed by a company (e.g. emissions from electricity purchased from the grid for use at mine sites).

Scope 3 emissions are all other indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company (e.g. emissions from power stations burning the energy coal purchased from the mining company, or in processing of marketed iron ore to steel).

Integration of carbonation with value-added by-product and side-stream recovery may play a role in offsetting Scope 1 and Scope 3 emissions in particular, but case studies from specific mining companies will be needed to demonstrate their practical significance.

5.2 Technology readiness levels (TRLs) for *ex situ* process routes

After more than thirty years of development work, most research is still taking place at benchtop scale inside laboratories, with first mention of the concept of TRL appearing in AMC reporting in 2015. The figure below from [3] position magnesium carbonate and calcium carbonate as CCU products with TRL = 4 and TRL = 7, respectively.



Fig. 5.1 TRL for main CO2-based products. The list is not intended to be exhaustive (taken from [3] using data sources from 2018 and 2019)

Most encouraging are the efforts at (or coordinated by) Newcastle, NSW in Australia, where Mineral Carbonation International (MCi) announced a TRL = 6 in the early part of 2021 [4], for "breakthrough technology" that involves mild conditions (near ambient temperature and low pressure) aqueous carbonation. TRL 6 (following EU ranking) implies "Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)".

Besides this, TRL= 5 ("Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)" may be claimed by the researchers in Québec [5,6]. The first-mentioned study from 2016 is perhaps the most useful so far, as it reports the energy penalty (7.8 GJ/t CO_2) while sequestering 234 kg CO_2 per tonne of rock (serpentinite, eventually aiming at chrysotile), processing an 18.2 %-vol (dry) flue gas from a cement plant. The assessment is made for 200 t/h rock input, processed after heat treatment in a pressurised aqueous solution, precipitating magnesium carbonates in a series of vessels. Some limitations include the removal of CO_2 from the gas (62.5 %) and the extraction of MgO from the serpentine (50%) from the rock, which make the use of process equipment rather inefficient and the material flows unnecessary large. Costs are estimated at 144 \$/t CO_2 (146 \$/ t CO_2 avoided). Admirably the energy input requirements are separated into heat consumption and power consumption, rating it somewhat less efficient than the (first) ÅA route (assuming operation on pre-separated CO_2). Follow-up work [6] re-addressed the process chemistry of the conversion step. The recent reporting on the process [7] focusses on heat integration as clearly the efficiency of using the magnesium (i.e. make available for reaction with CO_2) in the feedstock is critical.

Perhaps it is appropriate to apply a TRL = 5 to the ÅA routes based on full extraction of magnesium from (preferably) serpentinites using ammonium sulphate / bisulphate and after removal of unreacted rock, silica and metals impurities, carbonation of either solid/gas Mg(OH)₂ or dissolved MgSO₄ directly with the flue gas [8]. The most advanced of five ÅA route alternatives (see the Appendix material for

descriptions of these) use membrane electrodialysis [b7, b8] for recovery of the flux salts and control the pH of solutions [9,10].

5.3 Valuable products and economic viability

Although the bulk of scientific reporting on AMC involves laboratory-scale work aiming at making a magnesium silicate-based rock react with CO₂, for those who are (or claim to be) beyond that point and take the technology to industry, the prime question is: what to do with the solid products? For magnesite, the world market of around 40 Mt annually is easily flooded when a similar amount of CO₂ is mineralised with a magnesium-based rock. Nevertheless, an increased demand for magnesium in the Asia-Pacific region is predicted [11] and magnesium is on the list of critical raw materials (CRM). Magnesium-based cements are receiving increasing interest, as are magnesium-based batteries. Current market prices for magnesite MgCO₃, nesquehonite MgCO₃·3H₂O and silica SiO₂ are around 80 \notin , 420 \notin and 40 \notin per tonne, respectively. Combined with avoided costs for CO₂ emission rights, this offers significant OPEX revenues after the CAPEX investment for the process equipment has been made. (For example, a CAPEX investment of 500 M \notin for a facility that allows for sequestration of 0.5 Mt CO₂/year during 20 years gives an immediate minimum cost of 50 \notin /t CO₂.)

One option that is mentioned in two dozen papers since 2010 but not taken further than that by most authors is the recovery of metallic by-products that have potential market value. Besides Mg and Ca, Fe is the first significant by-product from many serpentinites and other magnesium silicate rock types. Indeed, several researchers have been able to (magnetically) separate much of this iron from rock after crushing/grinding. Fe and other metals like Cr, Ni, Zn, Ti, Cu, Al, Mn can be obtained during staged processing, after extraction of magnesium from rock, in the iron hydroxide precipitate [12] or as separate metals [13,14]. Other authors target platinum group metals (PGM), with the most comprehensive work reported from South Africa [15]. Al (60%) Ca (80%), Fe (35%), Si (32%), Cr (27%) and Mg (25%) were extracted from platinum mine tailings using thermal treatment with ammonium sulphate. Improvement is needed in order to extract more of the 12% MgO present in the rock, integrating CO₂ mineralisation with metals extraction. How advanced is the concept & what stage has it reached

5.4 Toxic or otherwise problematic by-products

One very attractive side-benefit of CO₂ mineralisation is that a hazardous solid waste such as chrysotile (asbestos) can be neutralised. In principle, this can be processed in the same way as serpentinites and indeed it is highly recommended to carbonate asbestos wastes once a facility for serpentinites is available. Metallic species in magnesium silicate rocks may be leached into the surroundings during *in situ* ambient air carbonation as a result of pH fluctuations. It has also been observed that during *ex situ* processing the formation of (for example) Cr (VI) ions in solutions may present a health risk. Only one reference [16] lists "heavy metals (e.g. cadmium, antimony etc.), trace elements such as selenium, mercury and arsenic, or dissolved metals like iron and copper" as being harmful to the extent that it may limit the use of mine waste rock. Moreover, "waste containing sulphide minerals pose the greatest environmental risk because of oxidation and subsequent acid production." It should not be forgotten that many chemicals and chemical species present a larger threat to environment, society or economy than carbon dioxide, although on the other hand the use of toxic chemicals in mining operations is far from uncommon.

It should be noted that metals are part of the end-point or mid-point impact categories for LCA but as noted in the next section, many researchers up until now have limited their LCA to CO₂ emissions and global warming potential.

From the foregoing, it is clear that the issue of toxicity has not been taken very seriously so far in an AMC context. The matter will become more evident and urgent however, when larger amounts of materials are to be handled and disposed of in an industrial, rather than laboratory setting.

5.5 Environmental footprint and life cycle assessment (LCA)

Life cycle assessment/analysis, LCA, has progressed towards a serious tool for quantifying the environmental footprint or impact of processes or products. Cradle-to-grave, cradle-to-gate and several system or timeline boundaries can be defined, while databases such as Ecoinvent and quite a few others are continuously being updated and expanded.

For CO_2 mineralisation, the number of published studies so far is around twenty, including several that address steelmaking slags or construction wastes, since the first paper by Khoo and Tran in 2006. Several other studies relevant here address the mining sector, with an important paper on mine tailings management from 2009 [17] showing that backfilling and especially the use of cover with capillary barrier effects made of natural soils followed by revegetation gives the greatest environmental impacts. This early reporting (for a Canadian copper zinc underground mine) is important for CO_2 mineralisation since the removal and valorisation of mine tailings circumvents what would otherwise give the largest environmental impact of a mining operation during the closure phase, including the effects of land use. The authors note that the results are strongly mine-site specific and also affected by the inherent ambiguities of the impact categories selected and the databases used. (Selection criteria and databases available today leave less room for wide variations.)

An earlier paper on LCA and the Finnish metal industry [18] claims that the environmental impacts of the mining of metals are smaller than those from metal production. Regardless, Awuah-Offei and Adekpedjou pointed out ten years ago [19] that mining companies increasingly adopt ISO 14001 certified environmental management systems (EMSs). Defining the functional unit and system boundaries are often challenging, apart from a lack of (accurate) relevant reference data that covers the possible impact categories. A useful indicator is the relative mass energy economic (RMEE) value that weighs in energy use as an important impact factor. Land use of mining operations is an impact category that is difficult to correctly account for.

As discussed above (sections 3.1 and 4.1.1), LCA is being applied to CO_2 mineralisation but all too often, only energy use and overall CO_2 fixation in relation to global warming are considered as impact categories. Use of water and especially the use of chemical additives will enforce a wider scope with more impact categories quantified for.

5.6 Public acceptance studies

While public acceptance of CO₂ sequestration has been addressed and reported for CCS involving on underground storage (with the main result that off-shore CCS is acceptable to many while on-shore storage isn't), practically no studies address the public acceptance of CO₂ mineral sequestration. The reporting from the CarbFix *in situ* storage project in Iceland [20] mentions that long-term storage is a necessity in order to gain public acceptance, similar to claims that leakage cannot be accepted from underground storage. A Finnish study [21] addresses CO₂ mineralisation from a wider CCS viewpoint:

it is considered a positive feature that leakage from an underground storage will not occur from a thermodynamically stable solid material, which renders it more attractive than underground storage of CO₂ (which inside Finland's borders is geologically feasible anyway). Costs are seen as prohibitive while environmental contamination resulting from mining activities will make CO₂ mineralisation unattractive as well.

For proper discussion to take place, it is important that CO₂ mineralisation as a CCU method is not confused with (conventional) CCS. It is clear that a large gap in knowledge needs to be addressed, with international policies bringing CO₂ mineralisation potential to the attention of large-scale CO₂ emitters. A very recent publication on the public acceptance of CCU products illustrates this: the report did not refer to (inorganic) carbonate, being limited to carbonated beverages, plastic food storage containers, furniture made with foam or plastic, and shatterproof glass [22]. Or presumably some forms of precast concrete, fillers produced from industrial slags etc (not addressed in this report).

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Part 2 - Calcium based resources

6 Calcium-based resources

6.1 Calcium-based feedstock for CO₂ mineralisation

In addition to magnesium-based resources suitable for CO₂ mineralisation, calcium-based resources also offer significant potential. Natural calcium resources are primarily found as carbonates that leave limited room for CO₂ fixation, but large amounts of alkaline by-products and wastes from industrial activities potentially provide a pathway towards the production of precipitated calcium carbonate (PCC), a material with a wide range of possible applications and hence significant market value. Benefits compared to magnesium-based material carbonation is the higher reactivity which makes processing under mild, near ambient conditions possible where magnesium-based materials would not react with CO₂, and as a result, reaction times are also shorter. On the other hand, the volumes of calcium-based materials produced as by-products from human activities is modest and won't allow for more than 1 Gt CO₂ mineralisation annually, if even that, as shown below.

Types of calcium-based alkaline waste streams are steelmaking slag (SS), air pollution control (APC) residue (incl. flue gas desulphurisation gypsum), bottom ash from municipal solid waste or refusederived fuel incineration, oil shale ash, waste concrete, cement kiln dust (CKD), brines and phosphogypsum (PG). For the gypsum materials, a carbonation step would release sulphur dioxide, while for most resources the acidity introduced via CO₂ should be compensated for via added alkalinity, for example sodium hydroxide or ammonia.

The Table 6.1 below, taken from [1] lists for several calcium-based materials the amount of $CaCO_3$ that may be produced. As noted in [1] "With the assumption that only the calcium present in the materials is completely carbonated, while other elements such as magnesium remain inert, none of the solid waste streams would be sufficient to capture global CO_2 emissions at a level of even 1 day/year."

Mineral source	Ca content	Material availability	Max amount of CO ₂ captured ^{a)}	Max amount of CaCO ₃ produced	Part of annual CO ₂ emissions ^{b)}
Brine ^{c)}	3.3%	2.3 x 10 ⁹ m³/a	85.1 Mt/a	193.6 Mt/a	2.5 x 10⁻³
Cement kiln dust ^{d)}	24.7%	15 Mt/a	0.4 Mt/a	0.9 Mt/a	1.1 x 10 ⁻⁵
Fly ash ^{e)}	21.2%	1.3 Mt/a	0.3 Mt/a	0.7 Mt/a	8.7 x 10 ⁻⁶
FGD gypsum ^{f)}	23.2%	45.9 Mt/a	11.7 Mt/a	26.6 Mt/a	3.4 x 10 ⁻⁴
Oil shale ash ^{g)}	21.5%	5 Mt/a	1.2 Mt/a	2.7 Mt/a	3.4 x 10 ⁻⁵
Phosphogypsum h)	31.9%	40 Mt/a	14.0 Mt/a	31.9 Mt/a	9.2 x 10 ⁻⁴
Steel slag ⁱ⁾	~30%	1.6 Mt/a	0.5 Mt/a	1.1 Mt/a	1.5 x 10 ⁻⁵
Seawater ^{j)}	400 ppm	1.3 x 10 ⁹ km ³	5.9 x 10 ¹⁴ ton	1.3 x 10 ¹⁵ ton	16 900

Table 6.1 Estimated theoretical capacities of carbonation of some waste materials (taken from [1] references as footnotes given there)

a) Assuming that only calcium is carbonated, even if the material would contain other elements that could be carbonated.

b) Calculated with the annual emission rate of 2011, 34.8 Gt/a (ref. 55 in [1]).

c) Production in the United States and the United Kingdom (ref. 19 in [1]).

d) Production in the United States (2006) (ref. 56 in [1]).

- e) Victorian brown coal fly ash from Latrobe Valley, Victoria, Australia (ref. 22 in [1]).
- f) Production in the United States, EU, China, Korea, and Japan (ref. 57 in [1]).
- g) Production in Estonia (ref. 23 in [1]).
- h) Production in the United States (ref. 58 in [1]).
- i) Finnish steelmaking slag, year 2008 (ref. 5 (Table 10.6) in [1]).
- *j)* It is assumed in calculations that no additional calcium is dissolved to sea during the carbonation. The estimates for the total volume of seawater and average calcium concentration are obtained from Refs 51 and 59 (in [1])

The large phosphogypsum tailings heap at Huelva, Spain, at 120 Mt, for example, could contribute to fixation of around 40-45 Mt CO₂, which would also require vast amounts of NaOH or NH₃ (aq) to bind the released sulphur as Na_2SO_4 or $(NH_4)_2SO_4$ while producing PCC [2].

Table 6.2 below is reproduced from the study of mine tailings by Renforth et al. (2011) [3] referred to earlier (in Part 1). This compilation of data for silicate-based waste streams indicates sequestration potential of between 700 - 1220 Mt CO₂ (190-332 Mt C).

Material	Approximate	Global	Carbon capture	Historically
	divalent cation	production	potential	produced
	content	(Mt / a)	(MtC / a)	(Mt)
Fines from	20/ C= O 20/ M=O			
aggregate	3% CaO 3% MgO	3 300	51	Unknown
production	nominal			
Mine waste	Unknown	2 000 - 6 500	Unknown	Unknown
Cement kiln dust	65% CaO	420 - 568	57 - 59	9 000 - 12 000 (since
Construction waste	14% CaO	249 - 1239	9 - 37	Maximum limited by
Domolition waste	10% CaO	1 106 - 4 661	24 - 100	cement production
Demonuon waste	10% CaU	1 100 - 4 001	24 - 100	around 60 Gt
Blast furnaça slag	38% CaO 12%	250 - 200	20 - 25	7 900 - 9 500 (since
Didst furfidee sidg	MgO	230 - 300	25-35	reused)
Chaol molting alon	45% CaO 7%	120 200	15 22	4 200 - 6 400 (since
Steel making slag	MgO	130 - 200	15 - 23	1875)
Lignite esh	20% CaO 1%	22 61))	
Lignite ash	MgO	32 - 61	2 - 3	7 600 - 14 600 (since
Anthracite ash	3% CaO 1% MgO	20 - 46	< 1	1927)
Bituminous ash	3% CaO 1% MgO	146 - 276	1 - 3	
Total			190 - 332	

Table 6.2 Carbon Capture Potential of Silicate Minerals [3]

In 2019, the review paper by Woodall et al. gives tabulated data for alkaline (calcium based) industrial by-products as given in Table 6.3.

Feed	Production rate (Mt / a)	Carbonation capacity (kg CO ₂ / t feed) ^{c)}	Annual CCS potential (Mt CO₂ / a)
Brines	51 700 ^{a)}	5.5 ^{b)}	284
Cement kiln dust	500	570	284
Concrete	27 333	10	273
Steel slags	400	410	163
Fly ash	660	220	144
APCr	7.7	330	3

 Table 6.3 Global abundance and carbonation potential of industrial wastes. [4]
 [4]

a) Million m^3 / a

b) kg CO_2/m^3 feed

c) Capacity based on storing magnesite / calcite

In this context it is also worth mentioning wollastonite, $CaSiO_3$, a calcium silicate mineral typically obtained as a side-stream from limestone processing. It is rarely found as a pure ore with resources worldwide of several 100 Mt. Produced amounts were 1.1-1.2 Mt annually worldwide in 2018- 2019 [5]. Although wollastonite is still the subject of CO_2 mineralisation studies, its cost of > 50 US\$/ton makes it more attractive for production of additives and filler, or substitute for asbestos, than for CO_2 mineralisation. (In fact, for many of these applications magnesite offers a lower-weight alternative.)

6.2 CO₂ mineralisation processes using calcium-based feedstock

Probably the most promising in Europe is the UK based Carbon8, producing aggregates. Hills et al. [6] (also connected to Carbon8) recently presented the following table listing enterprises operating at TRL levels up to the highest possible value of TRL = 9 ("Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space"). The same reference mentions a current annual market for aggregates of 50 Gt, with a per annum mineralisation potential ranging from 1-5 Gt CO₂ using various waste streams (which may include magnesium-based feedstock).

Company	Technology	TRL	Product	References (in [6])
Alcoa	Treatment of bauxite waste with CO ₂ (from an ammonia plant)	6	Construction fill, soil amendment	Global CCS Institute, 2011
Carbicrete	Carbonation activation of steel slag	6-7	Carbonated "concrete"	Savage, 2017; Carbicrete, 2020
Carbon8 systems	Accelerated Carbonation Technology	9	Aggregates/ fill e.g., for blocks/ concrete/ screed	Carbon8, 2020b
Carbstone Innovation	Carbonation of steel slag	9	Construction materials including roofing tiles	Vito, 2020
Blue Planet	Carbonate coating over an alkaline substrate	6-7	Aggregate	Blue Planet, 2020
Carboclave	Nano-CaCO ₃ crystals producing a densification effect	7	Concrete blocks	Carboclave, 2020
Green minerals	Carbonation of olivine	3	Building materials	On-Site, 2020

 Table 6.4 Selected mineralization processes yielding construction products. [6]

US-based CarbonCure has developed technology for concrete where CO_2 is injected into a ready-mix concrete slurry during a batching process, also known as cement curing (see carboncure.com). This process is estimated to have so far "saved" 55 kt CO_2 during the last year. Another US-based company, Solidia offers technology for reacting cement with CO_2 , stating "the potential to eliminate at least 1.5 Gt of CO_2 " (see solidiatech.com). Concrete curing and concrete waste processing are receiving significant attention today, including a recent LCA study [6]; see also the technology offered by France-based FastCarb (see fastcarb.fr) producing recycled concrete aggregate (RCA).

The examples and tables given above point to one fact: it will be very difficult to reach a level above 1 Gt CO_2 sequestration with calcium-based resources unless a very large fraction of these materials is indeed directed towards carbonation, which will consequently bring a large amount of aggregate-type material to the market. Aqueous brines would also need to be used, for example as suggested by the Scottish-based The Carbon Capture Machine, producing precipitated calcium carbonate and hydrated magnesium carbonate by dissolving "combustion CO_2 from any source" in "abundantly available calcium and magnesium brines" (see ccmuk.com).

On the other hand, just as calcium-based resources are of limited potential when aiming primarily at climate change mitigation rather than (cheap) production of construction material, there are as yet no examples of industrial applications of magnesium-based resources at Mt scale.

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Part 3 - In situ process cases

7 In situ process cases

7.1 Introduction and objectives

There are numerous locations on Earth where geological characteristics and conditions in rocks and soils are favourable for reacting with CO_2 under mild conditions, when subject to some kind of activation. One such special location is Iceland, where for almost a decade CO_2 injection into basaltic rock has been investigated. Two other major sites are found in the Canadian Québec region and NSW in Australia, where the carbonation of asbestos-type mine wastes are being studied, not only with the aim of neutralising a hazardous material but also to quantify what may be seen as a sink for CO_2 . In most cases, however, a significant additional input is required, usually in the form of thermal treatment, biologically active additives or mechanical action (shaking up a pile or crushing/grinding), to achieve volumetrically significant CO_2 sequestration. On the other hand, some sites contain very large amounts of material with significant potential, such that when passive (under ambient air) carbonation chemistry can be accelerated by 10 - 100 times, annual CO_2 sequestration could attain Mt/year magnitudes. However, as noted earlier, the presence of sulfur may result in acidic leachates that will prevent carbonation or eventually dissolve carbonate precipitates, with potential release of metallic species into the environment, as discussed above in the context of environmental impact, LCA and public acceptance.

7.2 CarbFix

In Iceland, where basaltic rocks predominate, a consortium of researchers and industries have developed an alternative solution for CCS by means of sedimentary rocks as CO₂ storage hosts. The first large scale results were obtained in 2012 and 2013 when approximately 200 tons CO₂ were stored *in situ* as carbonate minerals in the so-called CarbFix project. The project has stakeholders from the energy sector, the EU and a variety of universities from several countries. At the beginning of the project, the main goal was to establish a proof of concept that CO₂ can be stored in basalt in an economically feasible way. For this, different modelling and laboratory experiments for basalt-CO₂ interaction were undertaken before the first field injection pilots were done. For the first field injections to be plausible, several laws, regulations and permits had to be secured. The timeline of the CarbFix project from its commencement until 2018 can be seen in Figure 7.1. The pilot phase of the project ran from 2006 until 2016 [1].



Figure 7.1: A brief timeline for CarbFix from the beginning in 2006 until 2018 [1].

The original idea of the CarbFix project was to capture the CO₂ within gas emissions from the Hellisheidi geothermal power plant, which has been one of the stakeholders from the beginning of the project. The gas emissions from the power plant consists of 60 vol-% CO₂, 20 vol-% H₂S, 18 vol-% H₂, 2 vol-% N₂ and some trace amounts of CH₄ and Ar. Of these gases, the H₂S poses the greatest challenges to obtaining pure CO₂ since the gas is highly corrosive and toxic. Via a scrubber-deareator process plant, the CO₂ and H₂S were first separated from the less soluble gases and then from one another in a distillation column. The toxic H₂S was then re-injected to the deep geothermal reservoir together with spent geothermal water. This process proved troublesome, however, since the apparatus constantly broke down. It was eventually determined that the cause of these breakdowns was corrosion caused by H₂S, which was potentially hastened by the presence of steam in the distiller. The CarbFix team was still determined to proceed with the CO₂ injections even though not all the process steps to obtain adequate amounts of CO₂ had been clarified. Some pure CO₂ was procured for the pilot experiment for carbon mineralization [1].

In the CarbFix project, CO_2 gas is mixed with water at elevated pressure before injection into the bedrock. By elevating the pressure, the dissolution of CO_2 is favoured according to Henry's law thus enabling more CO_2 to dissolve. Through this, the water becomes denser than fresh water and additionally the water becomes acidic due to the formation of carbonic acid. In practice the CO_2 gas is injected into water at a depth of 350 meters in the bedrock as small bubbles that subsequently dissolve in the water under high pressure. When the water is made denser, due to the dissolved CO_2 the risk of the injected gas re-surfacing is reduced. The acidic properties of the mixture in turn promote dissolution of the basaltic rock and thus liberate metal cations, e.g. Ca^{2+} , Mg^{2+} and Fe^{2+} . These cations can in turn react with the carbonate ions to precipitate in the form of stable metal carbonates [1].

The outcome of the pilot study was to confirm that 95 % of the CO_2 injected mineralised successfully within a year of injection. Likewise, the H_2S mineralised successfully within four months of injection. The cost of the pilot phase of CarbFix was approximately 12 million \in , including the following:

- laboratory studies
- pre-injection field hydrology studies

- numerical modelling
- studies of natural analogues
- design and construction of injection and tracer equipment
- operation of pilot injections and
- monitoring and coring. [1]

Since the summer of 2014 the gases CO_2 and H_2S have been directly injected into a geothermal system in the bedrock. The gases are firstly captured in a water-scrubbing tower by condensation. The acidic gases dissolved in the water are then injected at temperatures over 250 °C. Such high temperatures inhibit the formation of bio-clogs created by bacteria that had earlier disturbed the process by clogging the aquifer at the end of the outlet gas pipes. Sampling and geochemical calculations proved that both H_2S and CO_2 gases successfully mineralise as sulphides and carbonates respectively, within six to twelve months after injection. The gases used here are the exhaust gases from the Hellisheidi power plant and the process captured 34% of CO_2 emissions and 68% of H_2S emissions. This clearly demonstrates that the process is viable on an industrial scale. Furthermore, Reykjavík Energy calculated that by March 2018 the company had saved more than 100 million \in by using the CarbFix method for H_2S pollution reduction at the Hellisheidi power plant compared to conventional industrial sulphur removal methods. Unfortunately however, energy balance calculations that reveal the heat and power input requirements are not given [1].

There are also concepts based on the CarbFix technology to store CO_2 under the seafloor in areas with basaltic bedrock. It is estimated that in the mid-ocean ridges up to 100 000 Gt of CO_2 could be mineralised. One of the proposed advantages in this method is that there would be an abundant supply of seawater to be used in the process [1].

Throughout the project's existence, there have been no problems with public acceptance related to deployment of CCS technologies. One of the biggest partners in the CarbFix project, the Hellisheiði Geothermal Power Plant, has nevertheless been subjected to harsh criticism on several occasions. This criticism had concerned the company's financial management, short-sightedness and mismanagement and has in fact lessened in severity during the CarbFix project. It can therefore be argued that the CarbFix project has increased overall public acceptance of the Hellisheiði Geothermal Power Plants. This is mostly because the CarbFix project itself has received much favourable attention by the media and by the authorities, and this in turn has reflected on the Hellisheiði Geothermal Power Plant. One of the keys to the successful public acceptance of the project has been the systematic engagement of stakeholders and public. Another contributing factor has been the vast amount of open-source academic publications and theses produced during the project. A case study from two different seismic events, one which occurred in 2011 and the other in 2016, associated with reinjection of geothermal fluid shows that the negative press coverage concerning such events had practically disappeared when comparing the coverage between 2011 and 2016. This can be explained by the fact that the CarbFix project had started to interact with the public and promote the positive effects that the reinjection brings [2].

A study from 2020 also shows that incorporating the CarbFix CCS method had a positive impact on the Hellisheiði Geothermal Power Plant's life cycle assessment, contributing to GWP100 reduction from 15.9 g CO2e/kWh to 11.4 g CO2e/kWh for electricity and 15.8 g CO2e/kWh to 11.2 CO2e/kWh for heat over the period of the investigation time [3].

In April 2021 it was announced that CarbFix is building a hub, called the Coda Terminal, at Straumsvik which can accommodate specialised ships and receive CO_2 shipments. The first CO_2 shipments are scheduled for 2025 and the construction of the hub is estimated to be between 190 million to 220 million EUR. At full capacity, the revenues are projected to be between 25 million and 45 million euro. The CO_2 will be injected by a CarbFix facility on site starting with 300,000 tons in 2025 and then ramping up to 3 million tons per annum at full capacity by 2030. For comparison, CarbFix has so far injected 70,000 tons of CO_2 [4].

The CarbFix project and the technology used has aroused interest elsewhere as well. In the Xujiaweizi region in northeastern China an experiment with hydraulic fracturing has been conducted to increase the permeability of the basalt rock in an old oil well. The main problem encountered is that when the CO_2 is injected with water into the basaltic rock the precipitation of carbonates reduces permeability, precluding the water- CO_2 mixture from penetrating deeper into the storage medium and thus inhibiting the reservoir from reaching its fullest storage potential. Simulations and calculations based on the on-site experiments showed that hydraulic fracturing decreased by only 4.5 % in a decade. The CO_2 sequestration potential was calculated to be 1.19 kg/m³ and the total potential in the reservoir to approximately 57,200 tonnes. This is a significant number and economic calculations shows that CO_2 sequestration in such decommissioned oil or gas wells is both feasible and reliable [5].

7.3 Enhanced weathering

Perhaps one of the simplest ways of in situ CO₂ sequestration is a form of passive carbon mineralisation where mine tailings are left at the mining site (cf. Figure 1.3 above). For this kind of passive carbon mineralisation, brucite and chrysotile have been found to be the most promising candidates for the mineralisation process [6]. It is estimated that 419 Mt of such ultramafic mine tailings and mine byproducts are produced every year from Ni, PGMs, asbestos, diamond, chromite, and talc mines. If complete carbonation were to occur, these tailings and by-products would have the potential to sequester about 175 Mt CO₂ per year, which is equivalent to more than 100 conventional bedrock sites for CO₂ injection and storage. The additional combined tailings produced from Ag, Au, Pb, Cu, Mo, Sn, Zn, and W mines yields a total of 5560 Mt of tailings, further increasing the potential volume of rock available for capturing CO_2 . These tailings could in theory sequester up to 441 Mt CO_2 per year. It is calculated that 1.5 % of global CO₂ emissions could be sequestered via passive carbonation in mine tailings and other mining by-products if optimised and ideal conditions prevail [7]. Such ultramafic mine tailings can often contain some first-row transition metals e.g., Cr, Co, Cu, Ni, which are known to be toxic, even at low concentrations. These transition metals can be leached selectively during natural mineral carbonation processes, accompanied by sulphide oxidation, generating acidic solutions. These leaching processes must be understood in order to avoid natural disasters and also for potential recovery of these metals [8].

Another mineral suitable for *in situ* carbonation through weathering is serpentinite. In nature, CO_2 can react with serpentinite in a weathering-process if the hydrothermal environment is suitable. This process can be hastened if microorganisms are present. The metabolism of some microorganisms produces acids as by-products, which enhance the dissolution of the minerals and makes them more susceptible for CO_2 gas to mineralize. The reaction rate of the passive carbonation is substantial. One metric ton of tailings can sequester 0.1 to 10 kg of CO_2 in one year or up to 238 metric ton per year per hectare of wetland with ultramafic mine tailings in the presence of cyanobacteria [9]. In Figure 7.2, three distinct kinds of *in situ* techniques for CO_2 sequestration are described [10].



Figure 7.2: Schematic picture of three different in situ techniques for CO_2 sequestration: A. passive mineral carbonation in mine tailings, B. abiotic CO_2 injection into the tailings, C. CO_2 sequestration by dint of bioleaching and microbial carbonate precipitation. [10]

At the Woodsreef Chrysotile Mine in New South Wales, Australia, trials were conducted to determine optimal CO₂ sequestration factors for weathering of mine tailings . Analysis of results showed that the passive mineral carbonation at Woodsreef could sequester more CO₂ than earlier research predicted. In the *in situ* tests at Woodsreef Chrysotile Mine diluted H_2SO_4 (pH 1) was used in one test and water in another test for leaching the minerals to make them more susceptible for CO₂ sequestration. The presence of fluids also increased the weathering rate of the mine tailings by maintaining soil pore saturation within optimal levels. During the tests however, no increase or acceleration in CO₂ sequestration was observed. The technology used could nevertheless be used to increase the supply of CO₂ for mineral carbonation at the site and for future research in the field of tailings dissolution [11]. A 2013 study found that the mine tailings at Woodsreef had sequestered between 1,400 and 70,000 tonnes of atmospheric CO_2 via passive weathering since the decommissioning of the mine, 29 years ago. This recessive weathering has left the mine tailings covered with hydromagnesite-rich crusts [12]. Besides the hydromagnesite-rich crust, which extends down as far as 40 cm into the pile, other minerals, namely coalingite and pyroaurite form at depths of 40 cm to 120 cm beneath the surface, due to lower CO₂ concentrations [13]. The composition and quantity of the minerals can be established by combining the PONKCS and Pawley/internal standard methods and has also been done on samples from the Woodsreef Chrysotile Mine [14]. At the site in New South Wales, field tests with portable XRD instruments were also made to validate the use of such instruments in both engineered and natural environments outside the laboratory [15]. A study also found that microbes can be used to contain and stabilize hazardous asbestos, which is also present at the Woodsreef Chrysotile Mine. Microbial carbonation can also be used to develop more efficient CO₂ sequestration strategies [16].

Similar research has been conducted in Canada at the Dumont Nickel Project (DNP) where it is estimated that 1.7 Gt of ultramafic mining by-products will be produced over a time span of 33 years. It is calculated that via weathering of these by-products, 21,000 tonnes of CO₂ could be sequestered per year. In the DNP tests two cells were used, named EC-1 and EC-2, with different kinds of mining by-products. In cell EC-1, which contained waste rock from blasting of a dunite outcrop, the grain size varied from silt to gravel particles up to several centimetres in diameter. In cell EC-2, which contained milling residues produced in a pilot plant, including slimes, fluff, and rougher non-magnetic tails, the

material was much more homogeneous in size, with a diameter distribution D10 of 2.2 μ m, and D80 of 119 μ m. Both cells were then left to weather and no extra water was added. The pH of rainwater was measured at 5.5. Carbon sampling from cell EC-1 was only done from the surface area of the cell, and thus it was not possible to accurately determine how much carbon has been sequestered. In cell EC-2 more sampling was made at deeper levels, from both the centre and the edges of the cell, enabling calculations for quantifying captured CO₂. The calculations showed that CO₂ was sequestered at a mean rate of 1.4 (±0.3) kgCO₂/tonne/year [17]. Analyses showed that the total C content of the weathered DNP mine tailings varied from 0.2 wt% to 6.5 wt% [18]. Furthermore, it has been shown that at the Dumont Nickel mine the main mineral controlling CO₂ uptake is brucite [19, 20]. The pH of the weathering process was between 9 and 10. This promoted the formation of secondary Mg carbonates and prevented the mobilisation of many other metals available in the tailings e.g., Ni, Fe, Zn, and Cu [21]. It was found that both temperature change and wet-dry cycling have a great impact on the sequestration via weathering and on the stability and form of the precipitated carbonates. Additionally, when the tailing pile dries out and/or freezes, the newly formed carbonates crack and flake off and the Mg rich substrate is exposed to react with more CO₂ to form new carbonate [22].

Similar cell experiments were conducted at Thetford Mines in Québec, Canada in 2016. The Thetford Mines mine tailings mainly consist of magnesium-rich lizardite and chrysotile combined with smaller amounts of brucite, magnetite and antigorite. Here the experiment showed that the sequestration rate in the tailings was about 4 kg CO₂ per m³ of tailing per year over the four years duration of the experiment [23].

A study made in 2012 showed that CO_2 sequestration through weathering also occurs in mineshafts. In the microclimates of mineshafts, the mineral form of MgCO₃ is mainly lansfordite and – in smaller quantities – nesquehonite. These minerals form on the shaft surfaces as the carbonates precipitate in the presence of drip water. Studies showed that multiple entrances to the mines increased air circulation and evaporation in the mineshafts and such mines are widely coated throughout the entire system of shafts with precipitate. These carbonate minerals are often brittle and peel of the walls and fall to the bottom of the shaft, enabling new Mg-rich surfaces to react with CO_2 [24].

Weathering does not necessarily need to be restricted to mine sites or in areas above sea level. A research group suggested in 2017 that olivine could be placed in the sea just off the coast. This would cause an upsurge in the seawater alkalinity as the olivine dissolves and thus subsequently increase the absorption of atmospheric CO_2 as bicarbonate and carbonate into the sea. The CO_2 will then precipitate from seawater as carbonates, mainly $MgCO_3$ [25]. Furthermore, this negative energy technology (NET) has a positive effect in that it neutralises ocean acidification and does not destroy or displace land nor adversely affect natural terrestrial ecosystems. A lot of unknown factors are still present concerning the effectiveness of this technique under *in situ* conditions, including the ratesof carbonisation and long-term effects on the maritime biotope [26].

Other noteworthy in situ research from the last few years includes :

- Hasan et al. on soil, sludge and sediments from a gold mine as a resource for mineral carbonation and supplementary cementatious material [27, 28],
- Boshi et al. on brucite-driven CO₂ uptake in serpentinized dunites [29],
- Beaudoin et al. on passive mineral carbonation of Mg-rich mine wastes by atmospheric CO₂ [30],
- Siegrist et al. on analysis of the potential for negative CO₂ emission mine sites through bacteriamediated carbon mineralisation [31], and
- Li et al. also presented a review on integrated mineral carbonation of ultramafic mine deposits [32].

One of the earlier *in situ* studies was carried out by Kelemen and Matter and co-workers, accelerating natural carbonation at the Semail ophiolite in Oman by injecting CO_2 heated to 30°C and 90°C [33] or CO_2 containing fluid [34], thus initiating and taking advantage of exothermic chemistry which can be self-sustaining. It was claimed that the site could potentially sequester up to a Gt CO_2 annually in a relatively low-cost way when further developed.

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8 Conclusions

Three decades of research and development work on accelerated mineral carbonation (AMC), have still not resulted in significant market uptake, driven by either the increasing costs of CO_2 emissions or the business opportunities presented by the production of value-added materials.

The review of (primarily) peer-reviewed literature in this report shows that even during the five years since the COP21 Paris Agreement, the concept of AMC is mostly being dealt with through studies in laboratory environments. A large proportion of reporting in recent years still addresses the same challenges and questions that were being addressed a decade or more ago. The number of AMC technologies or process routes that appear to have matured to levels that motivate commercial application can be counted on one hand, and even for those, the technology readiness level (TRL) rarely approaches TRL 6 or 7. Fortunately, the authors of this report may claim to operate at the forefront of this.

The above statements apply primarily to *ex situ* AMC in dedicated process facilities. In contrast, it was found that *in situ* carbonation of stockpiles and other deposits at mining sites has been the subject of considerable R&D in recent years, albeit this too is concentrated in only a few countries (Australia, Canada, Iceland, South Africa).

This report has focussed on magnesium-based rock resources found primarily as silicates occurring as tailings, overburden and other residues at sites mined for minerals or metallic ores. While the stockpiled amounts of material are indeed vast, the suitability of these materials is highly dependent upon specific details of mineralogy, geochemistry, petrology, permeability and hydrology and can only be assessed from data for individual case studies. Although the volumes of residual material from mining operations are not comparable with an entire mountain range composed of potentially suitable reactive rocks, they are nevertheless considerable on a global scale and may mitigate CO₂ emissions at the required Gt/year magnitude for many years. This is orders of magnitudes larger than what can be achieved with calcium-based industrial by-products, a matter which has also been addressed in this report. Nonetheless calcium-based AMC will still find assured niche deployment as a result of the large markets for calcium carbonate and the fact that "acceleration" of the chemistry is less challenging than for conversions that produce magnesium carbonate.

Up to the present, there have been very few cost assessments or NPV calculations for potential commercial AMC deployment, even when including possible revenues from the sales of metals or other by-products from, for example, nickel- or PGM mining operations. An important factor here is, obviously, the cost of emitting CO₂. A major obstacle for wide deployment of AMC using magnesium silicate-type rock feedstock is the uncertain future market space for magnesium carbonate (hydrate). First movers might benefit from transiently high market prices of 300 \in /ton for nesquehonite MgCO₃·3H₂O but this price would be expected to drop rapidly when several large AMC facilities become operational. The first steps from laboratory scale to industrial deployment also shows that the use of a carbon-based fuel for AMC process heat or power will make a facility (much) larger than when only zero-emissions heat or power is used.

The challenges and obstacles for laboratories lie in transforming the reporting of energy requirements and chemical kinetics to the timeframe of minutes rather than hours or days, as is still commonly being reported. Otherwise, the R&D community is still divided into two broad groups – one represented by teams that aim at direct carbonation, which often ends in struggling with a passivating silicate layer

that prevents rapid chemistry and high conversion levels, while the second group focusses on stepwise extraction and conversion aimed at reaching higher conversion levels in shorter times, which offers the benefits of pure, separated product streams but at the penalty of a more complex process lay-out.

Several non-technical features of AMC, such as the handling of toxic metallic by-product streams or other problematic solid, liquid or gaseous effluents have so far received little attention in the evaluated literature. More encouraging is that life cycle assessment (LCA) tools are being increasingly used for quantifying the environmental footprint of AMC. However, it is unfortunate that in many cases only GWP is considered as the LCA impact category while, for example, land use, water use and resources depletion ought to be considered as well. A significant final point is that deployment of large AMC facilities presents challenges such as public acceptance, which have yet to be adequately addressed, in a world where CO₂ emissions mitigation is dearly needed while CCS/CCU can be perceived as technical drivers for continued use of fossil fuels.

As an overall final conclusion, it can be stated that deployment of AMC beyond TRL levels 5-6 needs a stronger (financial support) focus on technology that may be extensively deployed within less than 10 years, at TRL 8-9. Repeating the work from the 1990s is hardly productive: what does not work has been (and still is...) widely reported. It is quite clear by now which, very few, AMC approaches could be economically viable at an industrial kg/s CO_2 mineralisation scale in a single facility. As reported above, a first choice to be made is whether to produce either a low-value aggregate or a set of high-value pure carbonate and other materials. For the second choice, methods developed at ÅA seem most advanced.

As a second conclusion, it may be wise to decouple the operations of a CO_2 producer from that of a CO_2 mineralisation entity, connected via energy integration. The second entity would be responsible for the sales of carbonate and other products and the purchase of suitable rock feedstock as specialities while the former can benefit via avoiding costs for emitting CO_2 . Looking at current trends in waste processing, circular economies and markets for "green" products, the use of solid products from AMC should have a promising future.

A final caveat: the amounts of material that need to be handled are very large, making CO₂ emissions mitigation very visible. Fortunately, experience with mining activities and the state-of-the-art process technology can make this possible, especially in countries with significant suitable mine tailings resources.

Overall key findings and recommendations:

- A technology readiness level (TRL) above 6 has not been claimed (in the open literature) for Mg-based feedstock CO₂ mineralisation while for Ca-based materials a TRL level 9 has been claimed for a steelmaking slag-based process
- There has been scarcely any reporting on the economic viability of industrial scale deployment, even when considering the market value of by-product materials, primarily metals (Ni, Cr, PGMs, REEs), besides the carbonate products. Nonetheless, product markets that go beyond the use of construction materials are being developed more of this is becoming necessary within the circular economy and green urban regions concepts. A major economic driver, however, for CCU based on CO₂ mineralisation, seems to be the cost of CO₂ emissions rather than the profit that may be made with solid products sales.
- Costs estimated for CO₂ mineralisation processes operating at levels of many tons per day suffer from large error margins when based on lab-scale information for a kg CO₂ per day scale.

Therefore, demonstration of the technology at a tons per day level is dearly needed, which would see Mg-containing mining tailings carbonation progress towards TRL 9 during the coming 5-10 years. This cannot all be funded by governments: a strong and long-term commitment from private industry is needed.

- While Ca-based carbonated materials have markets in place and benefit from easier CO₂ mineralisation processing when compared to Mg-based materials, these are unlikely to offer a CO₂ sequestration potential that exceeds 1 Gt CO₂ per annum. On the other hand, while Mg-based feedstock amounts do offer a much larger potential that would have a significant climate change mitigation effect, the current markets for magnesium carbonate -based products is much smaller, even though current market prices are high.
- CO₂ mineral sequestration is preferably operated with (waste) heat integration, for example at the site where CO₂ is produced, and should preferably rely on zero-emission electricity. The energy use as heat and power per tonne CO₂ mineralised is an important process feasibility parameter, including crushing/grinding, mixing, pumping/compression/expansion, heating/cooling/drying and heat exchange, as well as transport of the rock, CO₂-containing gas and other solid products. However, most CO₂ mineralisation studies still do not consider energy use.
- Separation of CO₂ from a CO₂-containing gas stream is not needed for CO₂ mineralisation: this gives significant energy savings compared to CCS/CCU where such separation ("capture") is needed.
- A disadvantage of CO₂ mineral sequestration may be the large material streams involved, regardless of the fact that wastes and by-product streams at mining sites are processed and largely removed. Life cycle assessment (LCA) is nowadays a mature tool for quantifying the overall environmental footprint of *ex situ* CO₂ mineralisation. This should include the use of water and chemical additives besides the obvious features of global warming potential versus the use of energy.
- Social acceptance studies for large-scale CCU based on mineralisation are needed.
- For any identified feedstock rock resources, it is necessary to quantify how much CO₂ mineralisation potential and valuable metal by-products these can offer. Information in the literature is in most cases vague or imprecise with respect to the history of material sampled from a mining site, and whether it represents overburden, tailings, stockpiled low-grade ore, or something else, or whether it has been freshly mined or exposed to weathering for many years. In general, standardisation of analysis and characterisation methods is needed, including proper definitions of ores, leached ores, tailings, etc and the wet/dry processing and possible aging and weathering paths these went through.
- More internationally coordinated development of CCU (similar to CCS since the 1990s) is needed for example under the umbrella of IEA GHG activities. For example, legislation on CCU (similar to the 2009 EC directive on CCS) is lacking. And, besides the potentially negative emission technology (NET) BECCS for bioenergy (BE), also BECCU deserves consideration.

Mineral carbonation using mine tailings - A strategic overview of potential and opportunities

9 Appendices

Appendix A1: Mining operations and industrial mineral resources in Finland Appendix A2: Global rock / mineral resources Appendix A3: Review articles from 2016

Appendix A4: The ÅA routes

Mineral carbonation using mine tailings - A strategic overview of potential and opportunities

Mineral carbonation using mine tailings

A strategic overview of potential and opportunities

IEA/CON/21/274

APPENDIX A1-A4

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Appendix 1.1 Mining operations in mafic and ultramafic rocks in Finland

	Nature of mining operation	
	NI-43-101 or JORC compliant resource	assessment?
covered metal and mineral commodities	Cumulative reported metal production	
Potential and re	Secondary commodities recovered for beneficiation	
	Main metal and mineral commodities extracted for beneficiation	
	Geological setting and deposit name	

| [

Greenstone belts or other mafic volcanic terrains

				-	
Pantavaara-Kittila	ге		Fe 4.2 T	No	open pit
Porkonen	Fe		Fe 4000 kg	No	open pit
Tainiovaara	Ni	Cu, Co, PGE, S	Ni 262.99 t, Cu 22.54 t, S 653.71 t	No	open pit
Kangasjärvi	Zn, Au	Cu, Pb, Ag, S	Zn 4683.7 t, Au 3739.4 kg, Cu 80.58 t, S 34657.9 t	No	open pit
Haveri	Au	Cu, Fe	Au 4439.79 kg, Au t, Cu 6085.03 t	No	open pit + underground
Pampalo	Au		Au 6.23 t	Yes	open pit + underground
Hannukainen	Fe, Cu	Au, Co	Fe 1865241.53 t, Cu 14813.74 t, Au 212.97 kg	No	open pit + underground
Hannukainen	Fe, Cu	Au, Co	Fe 1865241.53 t, Cu 14813.74 t, Au 212.97 kg	Yes	
Pahtavaara	Au		Au 10.86 t	Yes	open pit + underground
Rautuvaara	Fe	Cu	Fe 5341879.08 t, Cu 26345.7 t	No	open pit + underground
Rautuvaara SW	Fe	Cu, Mn		No	open pit
Kittilä	Au	Ag	Au 30.95 t, Ag 404.3 kg	Yes	open pit + underground
Vihanti	Zn, Cu		Zn 1445122.67 t, Cu 128682.02 t	No	open pit + underground
Vihanti		Au, Pb, Ag, U, P, S	Pb 98327.27 t, Au 3267.13 kg, Ag 278.07 t, S 422643.88 t	No	open pit + underground
Mafic - ultramafic la	yered intrusive complexes				
Makola	Ż	Cu, Co, Fe, S	Ni 3051.31 t, Cu 1803.49 t	Yes	open pit + underground
Kovero-oja	Ni, Cu	Co, S	Ni 1840 t, Cu 1380 t	Yes	open pit + underground
Telkkälä	Ni	Cu, Co, S	Ni 7836.4 t, Cu 1989.04 t, S 20502.68 t	No	open pit + underground
Kylmäkoski	Ni	Cu, Co	Ni 2503.54 t, Cu 1887.44 t	No	open pit + underground
Vuorokas	Fе, V, Ті		Fe 458320 t, Ti 60607.87 t, V 2696 t	No	open pit
Enonkoski	Ni, Cu, Co		Ni 50486.89 t, Cu 14396.31 t	Yes	open pit + underground
Stormi	Ni, Cu	Co	Ni 51496.08 t, Cu 31963.55 t	Yes	open pit + underground
Kotalahti	Ni, Cu, Co	Pt, S	Ni 82079.62 t, Cu 32280 t	Yes	open pit + underground
Mustavaara	V, Fe, Mgt	Ħ	V 27484.8 t	Yes	open pit + underground
Hitura	Ni	Cu, Co, PGE, S	Ni 92623.39 t, Cu 35683.73 t, Co 544.25 t	Yes	open pit + underground
Otanmäki	Fe, V	Ті, S	Fe 8622538 t, V 64467.89 t, Ti 1923769.6 t, S 118137.91 t	Yes	open pit + underground
Kevitsa	Ni, Cu	Co, Au, Pd, Pt	Ni 78922 t, Cu 155396 t, Au 3518.45 kg, Pd 6.53 t, Pt 8.57 t, Co 3483 t	Yes	open pit
Kemi	Cr203		Cr2O3 14038861.67 t	Yes	open pit chrome
Ahmavaara	PGE, Ni, Cu, Pd, Pt	Au, Co		Yes	platinum group metal
Konttijärvi	PGE, Ni, Cu, Pd, Pt	Au		Yes	platinum group metal
Ophiolitic ultramafic	complexes				
Kylylahti	Cu, Zn	Ag, Au, Ni, Co	Cu 70659 t, Zn 12999 t, Ag 5.74 t, Au 3426 kg, Co 5702 t, Ni 2149 t	Yes	underground
Vuonos Cu	Cu, Co	Zn, Ni, Ag, Au, Fe, Se, S	Cu 117806.75 t, Co 7269.94 t, Ni 7074.33 t	No	open pit + underground
Vuonos Cu	Cu, Co	Zn, Ni, Ag, Au, Fe, Se, S	Ni 7074.33 t, Zn 68715.02 t, Fe 1141101.31 t, S 806053.96 t	No	open pit + underground
Vuonos-Ni	Ni, Co	Cu, Ag, Se	Ni 10939.4 t	No	open pit + underground
Luikonlahti	Cu, Co	Zn, Ni, S	Cu 64928.93 t, Co 7034.63 t, Ni 624.09 t, Zn 24740.23 t, S 1152049.78 t	No	open pit + underground
Outokumpu	Cu, Co	Ni, Zn, Ag, Au, Fe, S	Cu 956499.36 t, Co 54356.11 t, Zn 226648.49 t, S 6248199.07 t	Yes	underground

Appendix 1.1 Mining operations in mafic and ultramafic rocks in Finland (continued) Resource estimates and production figures

Geological setting and deposit name	Resources total	Reserves total	Total ore mined	Current status	Current operator or legacy owner	
Greenstone belts or o	ther mafic volcanic terrains	-				7
Pahtavaara-Kittilä	14 Mt @ Fe 30 %		14	Historic	Endomines Ov	
Porkonen	9 Mt @ Fe 30 %		15	Historic		
Tainiovaara	0.43 Mt @ Ni 0.5 %, Cu 0.03 %, Co 0.01 %		19984	Closed		
Kangasjärvi	0.3 Mt @ Zn 5.4 %, Au 0.3 ppm, Cu 0.06 %, Pb 0.02 %, Ag 5 ppm		91205	Closed	Cullen Resources Ltd	
Haveri	31.6 Mt @ Au 0.998 ppm		1559020	Closed		
Pampalo	806738 t @ Au 2.751 ppm		1932394	Operating	Endomines Oy	
Hannukainen	221 Mt @ Fe 32.192 %, Cu 0.171 %, Au 0.077 ppm	92.6 Mt @ Fe 32.203 %, Cu 0.	4563080	Closed		
Hannukainen	221 Mt @ Fe 32.192 %, Cu 0.171 %, Au 0.077 ppm	92.6 Mt @ Fe 32.203 %, Cu 0.	4563080	Under development		
Pahtavaara	4640000 t @ Au 3.2 ppm		5820321	Operating	Rupert Resources Ltd	
Rautuvaara	1.736 Mt @ Fe 46.78 %, Cu 0.2 %		11564405	Closed	Hannukainen Mining Oy	
Rautuvaara SW	4.5 Mt @ Fe 42.7 %, Cu 0.15 %, Mn 0.81 %			Closed	Hannukainen Mining Oy	
Kittilä	31966000 t @ Au 3.162 ppm	28925000 t @ Au 4.407 ppm	14817165	Operating	Agnico Eagle Finland Oy	
Vihanti	2.59 Mt @ U 0.028 %, Phos 3.24 % + 9.164 Mt @ Zn 0.36 %, Cu 0.34 %		27938832	Closed	Norrbotten Exploration AB	
Vihanti	2.59 Mt @ U 0.028 %, Phos 3.24 % + 9.164 Mt @ Zn 0.36 %, Cu 0.34 %		27938832	Closed	Norrbotten Exploration AB	
Mafic - ultramafic lay	sred intrusive complexes					
Makola	1 Mt @ Ni 0.8 %, Cu 0.42 %, S 8.4 %		412645	Closed	Muon Solutions Ov	
Kovero-oja	0.64 Mt @ Ni 0.4 %, Cu 0.33 %		46000	Closed	Dragon Mining Oy	
Telkkälä			605396	Closed	Outokumpu Mining Oy	
Kylmäkoski			689616	Closed		
Vuorokas	6.5 Mt @ Fe 32.5 %, Ti 3.297 %, V 0.26 %		1348000	Closed	Vuorokas Oy	
Enonkoski	1.178 Mt @ Ni 0.41 %, Cu 0.1 %, Co 0.007 %		6707515	Closed	Outokumpu Mining Oy	
Stormi	1.6 Mt @ Ni 0.44 %, Cu 0.29 %, Co 0.04 %		7577977	Closed	Dragon Mining Oy	
Kotalahti			12453647	Closed	Boliden AB	
Mustavaara	145.9 Mt @ V 1383 ppm, Fe 96110 ppm, Ti 5640 ppm		13648220	Closed	Strategic Resources	
Hitura	3064000 t @ Ni 0.538 %, Cu 0.187 %, S 2.451 %	1656000 t @ Ni 0.464 %, Cu 0	17177362	Closed	Belvedere Resources Ltd	
Otanmäki	14 Mt @ Fe 40 %, V 0.26 %, Ti 7.6 %		30629174	Closed		
Kevitsa	157.2 Mt @ Ni 0.229 %, Cu 0.337 %, Pd 0.091 ppm, Pt 0.142 ppm, Co 108.868 ppm, Au C	140.3 Mt @ Ni 0.239 %, Cu 0.	54573686	Operating	Boliden AB	
Kemi	100 Mt @ Cr2O3 29.341 %	48.3 Mt @ Cr2O3 25.9 %	54609224	Operating	Outokumpu Oy	
Ahmavaara	187.77 Mt @ Ni 0.069 %, Cu 0.175 %, Pd 0.825 ppm, Pt 0.17 ppm, Au 0.1 ppm			Under development	Gold Fields Arctic Platinum Oy	
Konttijärvi	75240000 t @ Ni 0.046 %, Cu 0.097 %, Pd 0.953 ppm, Pt 0.271 ppm, Au 0.073 ppm			Under development	Gold Fields Arctic Platinum Oy	
Ophiolitic ultramafic c	complexes					
Kylylahti	502000 t @ Cu 0.64 %, Zn 0.282 %, Au 1.231 ppm, Ni 0.247 %, Co 0.162 %		5433592	Closed	Boliden AB	
Vuonos Cu	0.76 Mt @ Cu 1.76 %, Co 0.14 ppm, Zn 1.33 %, Au 0.1 ppm, Ag 11 ppm		5489576	Closed	Mondo Minerals B.V.	
Vuonos Cu	0.76 Mt @ Cu 1.76 %, Co 0.14 ppm, Zn 1.33 %, Au 0.1 ppm, Ag 11 ppm			Closed	Mondo Minerals B.V.	
Vuonos-Ni	7465439 t @ Co 0.03 %, Se 3 ppm		5495761	Closed	Boliden AB	
Luikonlahti			6983164	Closed	Boliden Kylylahti Oy	
Outokumpu			29188315	Closed	Altona Mining Ltd	
			Fotal 326352385			

Appendix 1.1 Mining operations in mafic and ultramafic rocks in Finland

Appendix 1.2 Industrial mineral resources and mining operations in Finland Industrial mineral resources and mining one-rations in matir and uttramatic rooks

Industrial mineral resources an	d mining operations in mafi	ic and ultramafic rocks							
Deposit name	Alternative name	Resource type	Main metal and mineral commodities	Secondary commodities recovered for beneficiation	Resources total	Total ore mined (tonnes)	Cumulative reported metal production (tonnes)	Current status	Current operator or legacy owne
Jormua	Jormua	open pit	talc	Ni, Co		153624 T	lc 91615	Closed	
Pitkänperä	Mieslahti-Pitkänperä	open pit	talc	N	10 Mt @ Tlc 40 %	16 T	lc 8	Closed	Mondo Minerals B.V.
Lahnaslampi	Lahnaslampi	open pit	talc	N		17649290 T	lc 5595339	Closed	Mondo Minerals B.V.
Uutela	Uutela	open pit	talc	Ni, Co	5 Mt @ Tlc 50 %	2763335 T	lc 18158	Operating	Mondo Minerals B.V.
Punasuo	Lahnaslampi	open pit	talc	Ni		2879762		Operating	Mondo Minerals B.V.
Pehmytkivi	Horsmanaho	open pit	talc	Ni, Co		4270510 T	lc 75817	Closed	Mondo Minerals B.V.
Pihlajavaara	Pihlajavaara	open pit	talc			5579 T	lc 5579	Closed	Mondo Minerals B.V.
Repovaara	Repovaara	open pit	talc			716444 T	lc 328256	Closed	Mondo Minerals B.V.
Mieslahti	Mieslahti-Pitkänperä	open pit	talc	N	10 Mt @ Tlc 40 %	96794 T	lc 43283.5	Closed	Mondo Minerals B.V.
Horsmanaho	Horsmanaho	open pit	talc	Ni, Co		7 9898004 T	lc 2651648	Operating	Mondo Minerals B.V.
Karnukka	Karnukka	open pit	talc, magnesite			1100898		Operating	Mondo Minerals B.V.
Vasarakangas	Vasarakangas	open pit	talc, nickel	Co		1054604 T	lc 465909	Closed	Mondo Minerals B.V.
Lipasvaara	Lipasvaara	open pit	talc, nickel			1883654 T	lc 820627	Closed	Mondo Minerals B.V.
					Total 2500000 t	Total 42472514			
Industrial minerals in carbonati	te host rocks								
Deposit name	Alternative name	Resource type	Main metal and mineral commodities	Secondary commodities recovered	Resources total	Total ore mined (tonnes)	Cumulative reported metal production	Current status	Current operator or legacy owner
							(tonnes)		
Siilinjärvi	Siilinjärvi	open pit	apatite, phlogopite	Cal, Mica	999 Mt @ Phos 3.729 %	325671140 A	vpat 27659746, Cal 17545	Operating	Yara Suomi Oy
Sokli	Sokli	open pit	phosphorus pentoxide	Nb, Fe, U, Th, Ta, Zr, REE	123.3 Mt @ Phos 13.687 %	56720 P	hos 11344	Under development	Yara Suomi Oy
						Total 275777660 +			

Appendix 1.2 Industrial mineral resources and mining operations in Finland

im leistaubel C 1 vibeone	iaim bac sossilosos losos	clain i notice pa	and (continued)						
udustrial mineral resources in	silicate and other host rocks	s							
Deposit name	Alternative name	Resource type	Main metal and mineral	Secondary commodities	Resources total	Total ore mined	Cumulative reported	Current status	Current operator or legacy owner
		:	commodities	recovered		(tonnes)	metal production		
							(tonnes)		
metistiaarre	Yli-Lu osto	open pit	amethyst			0.1	ō	berating	private enterprise
ampivaara	Lampivaara	open pit	am eth yst			32.85 An	nt 18.85 Op	berating	Kaivosyhtiö Arctic Ametisti Oy
ännätsalo	Kännätsalo	open pit	beryl	Qtz, Feld		9319	ō	berating	Karelia Beryl Oy
vla-Aulis	Ala-Aulis	open pit	feldspar			1610816	ō	berating	Sibelco Nordic Oy Ab
uurakko	Juurakko	open pit	feldspar	Nb, Ta, Be, Li		18000 Fel	ld 18000, Qtz 18000 Cl	osed	
övböle	Lövböle	open pit	feldspar			1900 Fel	ld 532, Qtz 133 Cl	osed	
laapaluoma	Haapaluoma	open pit	feldspar			685462 Fel	ld 214807, Qtz 119387. Cl	osed	Perusmaa Ky
iitaniemi (Viitaniemi	open pit	feldspar, quartz			120600 Fel	ld 85377, Qtz 17026 Cl	osed	
emnäs	Lemnäs	open pit	feldspar, quartz, BeO			37800 Fel	ld 14805, Qtz 630, BeO Cl	osed	
aatiala	Kaatiala	open pit	feldspar, quartz, Nb, Be	Lİ		516188 Fel	ld 151542, Qtz 44040 Cl	osed	
ihlajavaara	Pihlajavaara	open pit	kaolin		1.2 Mt @ Kaol 30 %	383 Kai	ol 383 Cl	osed	Morenia Oy
apteeninautio	Kapteeninautio	open pit	kyanite		108.8 Mt @ Kya 13.7 %	20000	ō	osed	
vartsila	Kinahmi	open pit	quartz			12426	ō	berating	Sibelco Nordic Oy Ab
liekkam äki	Hiekkamäki	open pit	quartz			1345329 Qt	z 1058510 Cl	osed	
tistimaa	Ristimaa	open pit	quartz			1528271.99 Qt	z 759773.58 Ol	berating	SMA Mineral Oy
linahmi	Kinahmi	open pit	quartz			7383794 Qt	z 5543584.4 Ol	berating	Sibelco Nordic Oy Ab
üetyönmäki	Kietyönmäki	open pit	quartz, spodumene	Ta, Sn, Qtz, Nb	0.4 Mt @ LiO2 1.5 %, Sn 160 ppm, Ta 30 ppm	24 Qt	z 19 Hi	storic	Litiumlöydös Oy
łirvikallio	Hirvikallio	open pit	quartz, spodumene	Qtz	0.1 Mt @ LiO2 1.78 %	24 Qt	z 19 Hi	storic	
evalainen	Tevalainen	open pit	spectrolite			3685 Spi	ec 3685 O ₁	berating	private enterprise
ipasjärvi	Tipasjärvi	open pit	sulphur			809.9 S 2	175.36 Cl	bsed	
täsvaara	Rasivaara	open pit	sulphur, Fe	S		14 S 5	5.6 CI	osed	
Itravaara	Otravaara	open pit	sulphur, zinc			23882 S 9	1896.7 Cl	osed	

Appendix 1.2 Industrial mineral resources and mining operations in Finland

Total 13318760.84 t

Current operator or legacy owne Kuovila Limestone Oy Juuan Dolomiittikalkki Oy Nordkalk Oyj Abp Nordkalk Oyj Abp Nordkalk Oyj Abp Nordkalk Oyj Abp Salon Mineraali Oy Salon Mineraali Oy Vordkalk Oyj Abp Nordkalk Oyj Abp SMA Mineral Oy Current status Operating Operating Closed Closed Historic Historic Operating Closed Closed Operating Historic Operating Operating Operating Closed Operating Closed Operating Historic Operating 70962030.65 Cal 70163523.62, Wol 713 Operating Operating Historic Closed Closed 3647405 Dol 3718906, Cal 53695 3684589 Dol 3750220 394345 Dol 394345 **Cumulative reported** metal production (tonnes) 13700498 Cal 13731285 9000 Cal 9000 2790 Cal 2790 1143913 Dol 1148970 12000 Dol 12000 1234593 Cal 1234593 139560.6 Cal 139560.6 18000 Cal 18000 27 Cal 27 37350 Cal 37350 105583983 Cal 105583983 11568797 Cal 11593378 38655726 Cal 38648725 4403488 Cal 4397625 6311895 Cal 6312459 2825860 Dol 2845975 296039 Dol 6802744 8506458 Cal 8760884 122674 Dol 122674 122674 Dol 122674 276322 Dol 276322 11565 Cal 11565 450 Cal 450 Total ore mined (tonnes) 12.863 Mt @ Cal 77.4 % 9.6 Mt @ Cal 71.08 %, Mrbl 100 %, Wol 2.84 % 4.397 Mt @ Cal 69.378 %, Wol 3.37 %, Dol 1.29 ? 2.952 Mt @ Cal 82.26 % 87.81 Mt @ Cal 73.113 % + 10500 t @ Zn 1.43 % **Resources total** 5.736 Mt @ Cal 68.8 % 17 Mt @ Cal 76 % 17 Mt @ Cal 76 % Secondary commodities recovered Dol, Mrbl, Wol Wol, Dol calcite, zinc Cu, Pb, Ag, Fe calcite, zinc, wollastonite, dolc Pb, Cu, Ag dolomite Cal, Mrbl Mrbl Cal Nol Dol Main metal and mineral commodities calcite, dolomite ppendix 1.2 Industrial mineral resources and mining operations in Finland (continued dolomite dolomite dolomite dolomite dolomite dolomite dolomite calcite open pit open pit open pit open pit open pit underground mine Resource type open pit ndustrial minerals in (metamorphosed crystalline) carbonate rocks Alternative name Limberg-Skräbböle Ruokolanvaara Ruokojärvi Hermala Kuovila Reetinniemi Remo Järvenkylä Tytyri Äkäsjoensuu Hyypiämäki lllo Kalkkimäki Hyypiämäki Putkinotko halainen Siivikkala Ryytimaa Genböle Ankele Mustio Sipoo Förby Ahola Ahola Deposit name imberg-Skräbböle laa paniemi-kalkki Ruokojärvi Hermala-kalkki Valkjärvi Reetinniemi Ruokolanvaara Åkäsjoensuu Remonmäki lärvenkylä esterbacka lyypiämäki utkinotko ähteenoja Senböle halainen iivikkala Mustio nkele ytyri hola vhola ipoo örby ₽

Appendix 1.2 Industrial mineral resources and mining operations in Finland

Juuan Dolomiittikalkki Oy

Operati

dolomite Iolomite

open pit

Montola

Aontola

Aatara

Matara

open pit

Appendix 1.2 Industrial mineral resources and mining operations in Finland

Appendix 1.2 Industrial mi	ineral resources and mini	ing operations in Finla	¹ and (continued)						
udustrial minerals in (metam	orphosed crystalline) carbon	ate rocks (continued)							
Deposit name	Alternative name	Resource type	Main metal and mineral	Secondary commodities	Resources total	Total ore mined	Cumulative reported	Current status	Current operator or legacy owner
			commodities	recovered		(tonnes)	metal production		
							(tonnes)		
iikainen	Otamo	open pit	dolomite			4649929 D	Jol 4649929	Operating	Nordkalk Oyj Abp
yytimaa	Ryytimaa	open pit	dolomite	Cal		6972197 D	Jol 6972197	Operating	Nordkalk Oyj Abp
eppikangas	Leppikangas	open pit	dolomite		5 Mt @ Dol 100 %	744 D	Jol 27	Under development	Juuan Dolomiittikalkki Oy
alkkimaa	Kalkkimaa	open pit	dolomite		750 Mt @ Dol 100 %	7587735 D	ol 7888900	Operating	SMA Mineral Oy
1 atkusjoki	Matkusjoki	open pit	dolomite, calcite			791313 C	Jol 791313	Operating	Nordkalk Oyj Abp
antamaa	Rantamaa	open pit	dolomite, marble			33201 C	Jol 13104, Mrbl 20097	Closed	SMA Mineral Oy
'bbernäs	Ybbernäs	open pit	material for rock wool			1137070 R	twool 1093011	Operating	Paroc Oy Ab
ehlampi	Lehlampi	open pit	material for rock wool			1315846 R	twool 1115691	Operating	Paroc Oy Ab
outsenenlampi	Joutsenenlampi	open pit	material for rock wool			2677798 R	twool 2190893	Operating	Paroc Oy Ab
Austamäki	Mustamäki	open pit	material for rock wool			479850 R	twool 479850	Closed	Rudus Oy
1 etsäsian niemi	Metsäsianniemi	open pit	material for rock wool			497516 R	twool 497516	Closed	Paroc Oy Ab
'anh asuo	Vanhasuo	open pit	material for rock wool			672095 R	twool 635491	Operating	Paroc Oy Ab
allittu	Sallittu	open pit	material for rock wool			995537 R	twool 973412	Operating	Paroc Oy Ab
						Total POL POL			

Appendix A2: Global rock / mineral resources

In assessing the potential reactive mineral resources available for carbonation of CO_2 , it is instructive to note parallels with sequestration by injection in sedimentary basins. This conventional CCS approach has been the subject of extensive research, with numerous studies of national and global estimates of the dimensions and physical and chemical characteristics of potential repositories. This has been possible drawing on the detailed information and reservoir modelling acquired during petroleum and gas exploration, with the additional economic incentives associated with enhanced recovery and access to existing infrastructure. However, there will be many basins with favourable storage characteristics which can be excluded from consideration, being too remote from economically feasible exploration and production, or from industrial CO_2 emissions sources.

Explanatory note to Appendix A2

The compilation of mafic and ultramafic rocks in Appendix 2 is preliminary and far from complete; the enormity of the task of collecting and verifying data nationally, and from individual mining operations is beyond the scope of this review. Moreover, the focus of this review has been on the potential for CCUS with respect to tailings, rather than sequestration in reactive bedrock reservoirs. Ultimately, a useful global inventory of potentially reactive rocks and mine tailings for mineral carbonation also needs to be realistically constrained by meeting the following criteria:

1. Feasibility of reaction progress, from a mineralogical and chemical thermodynamic and reaction rate viewpoint. This requires both experimental mineral studies and where possible, evaluation of evidence for carbonation occurring through natural weathering processes in regolith environments and also in anthropogenic mine tailings

2. Accessibility, for example whether reactive materials are present as relatively permeable mine tailings or leaching of porous formations, or whether the process would incur energy penalties through the need for crushing intact rock (and whether this would be done in conjunction with existing mining operations, or exclusively for the purpose of carbonation).

3. Proximity to anthropogenic sources of CO_2 for effective greenhouse gas mitigation – both environmentally and economically

4. Identification of processing pathways and products for commercial carbonate-based products for industrial and construction, which provide the dual benefit of reducing emissions and additional value to mining and metallurgical operations.

The focus of this review has been on carbonation in mine tailings and more particularly, tailings from mining operations in Mg-rich geological environments. As discussed in the Chapters 2 and 3 of this report, the potential for *in situ* carbonate precipitation in tailings, whether abiotically or microbially mediated, has been investigated and is demonstrably significant in some abandoned and operating mines, as reviewed here in Chapter. Likewise, natural carbonate precipitation processes, notably calcium carbonate caliche and nodular cryptocrystalline magnesite, occur during weathering in tropical and arid environments and may also volumetrically significant, though rates of formation have not been quantified.

Weathering of serpentinites in tropical environments can also generate significant amounts of cryptocrystalline magnesite – the best known example being the Kunwara nodular magnesite deposit in northeastern Australia.

There are four broad categories of geological environments and processes within which Mg-rich silicate rocks maybe classed. The data in Appendix A2 are separated accordingly, where possible, even though the categories are not mutually exclusive:

1. Large igneous basaltic provinces, or large igneous provinces (LIPs)

These occur as extensive outpourings of basaltic lava (MgO contents approximately 4-8%), although early in Earth's history, komatiitic lavas with higher MgO contents (11-23%) were abundant. Large volume eruptions may occur within relatively short periods of time geologically (1-2 million years) and cover hundreds of thousands of square kilometers; individual flows maybe 10-100 meters thick but cumulatively theymay attain several kilometers total thickness large

2. Greenstone belts or other mafic terrains

These are characteristic of older terrains, in which many so-called greenstones may have originated as submarine or subaerial flood basalt provinces. Due to complex geological history, the original mineralogy is commonly hydrothermal alteration; for example olivine is typically serpentinzed. These terrains are typically highly mineralized, with Au, Ni, PGE being particularly significant.

3. Mafic-ultramafic layered intrusive complexes

These typically form sheet-like bodies that have intruded at various depths in the Earth's crust, typically in rifted environments during incipient breakup of diverging plate boundaries. Chemical and mineralogical differentiation during crystallization leads to compositional layering with accumulation of very Mg-rich phases (5-15%). Many of these intrusions are also economically significant, particularly for Ni, Co, Cr PGE. In continental settings, intrusions tend to have lower MgO contents and are characteristically associated with Fe, Ti and V and REE mineralization.

Most of the data in Appendix 2 relates to these kinds of intrusions and is substantially derived from a recent global review compiled by Smith and Maier (2021) continental plates or at oceanic spreading ridges.

4. Mafic-ultramafic ophiolitic complexes

These terrains represent fragments of oceanic crust and lithosphere, or in some cases deep continental lithosphere which have been tectonically emplaced into continental environments. Peridotites and serpentinites in these complexes may have MgO contents between 25-38%, if they represent residual compositions following extraction of other silicates during successive melting events. These terrains are also important with respect to Cu, Co, Ni mineralization and hydrothermal alteration has also resulted in the formation of asbestos and talc deposits. These terrains are therefore some of the most ideal for combi mining and mineral carbonation.

Within the tables, highlighting by bold text and gray shading refers to occurrences where there has been active mining and hence potential for establishing whether tailings are of sufficient volume and quality for CCU.

National or provincial estimates of maximum theoretical carbonation capacity are unfortunately rather crude; calculations are based on area of the geological complex multiplied by depth (with a rather generous maximum cutoff of 2 km), in turn multiplied by the approximate MgO percentage, if available (typically 8-15%), with a final approximation based on a density of 3 kg/m³ (which is also a rather high value, given that serpentinite typically has a density in the range 2.65-2.67 kg/m³.

Appendix 2.1 Afric	a (northern and western)								
Minera	I deposit jurisdiction and name	Potential and recomine mineral co	overed metal and mmodities	Ma	gnesium conte	ut	Dimensio	ns and estima potential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti 2. Greenstone belts or c	ic Provinces other mafic terrains			•					
3. Mafic-ultramafic lay€	ered intrusive complexes								
Algeria	In Allarene				88-70	90-63	20		
Algeria	In Tedeini				77-72	75-74	15		
Algeria	Laouni layered intrusions (three bodies)	Ni-Cu-(PGE)		9-14%	88-73	80-62	31	0.3	3
Algeria	Tin Zebane				78-71	78-73			
Benin/Togo	Kabyé Massif						1250	12	
Burundi	Mugina								
Burundi	Mukanda-Buhoro								
Burundi	Musongati	PGE-(Cu-Ni)		16-22%	90-76		60	3.5	60
Burundi	Nkoma								
Burundi	Nuange-Songa								
Burundi	Nyabikere								
Burundi	Rutovu	Fe-Ti-V							
Burundi	Waga	Laterite							
Cameroon	Mboutou Layered Gabbro				78-62	~ 62	20	Ч	
Cote D'Ivoire	Samapleu-Bounta	Ni-Cu-(PGE)		10%			× 3	0.2	0.3
Gabon	Monts de Cristal Complex (Kinguele)	PGE-(Cu-Ni)		10%	84-75		300	1.7	150
Morocco	Kettara	Cr-Ni			89-80		< 1.5		
Senegal	Sandikounda Layered Complex						> 50		
Sierra Leone	Freetown	PGE-(Cu-Ni)			72-56		910	7	
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									213.3

Appendix 2.2 Afri	ca (northeastern) + Arabia								
Miner	al deposit jurisdiction and name	Potential and rec mineral co	overed metal and mmodities	Ma	gnesium conter	Ŧ	Dimensio	ns and estima potential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalt	tic Provinces								
Ethiopia	Ethiopian LIP								
2. Greenstone belts or	other mafic terrains								
3. Mafic-ultramafic lay	ered intrusive complexes								
Egypt	Abu Ghalaga	Fe-Ti-V							
Egypt	Atud				77-76		1.2		
Egypt	El-Motaghairat (Kallalat)				86-71	83-57	4.5		
Egypt	Gabal Akab El Negum	Fe-Ti-V							
Egypt	Gabal Dahanib			16-20%	94-76	90-78	9	1.5	3.6
Egypt	Korab Kansi	Fe-Ti-V			86-68	73-72	100		30
Egypt	Shahira				83-82	84-80	20		6
Egypt	Um Ginud								
Egypt	Wadi Abu Fas	Fe-Ti-V							
Ethiopia	Bikilal	Ъ	181		76-64		350		105
Saudi Arabia	Al Ji'lani	Ni-Cu-(PGE)					42	9	
Saudi Arabia	Jabal Shai						4	£	
Saudi Arabia	Jabal Tirf				71-60	~ 67	20	< 1.5	
Saudi Arabia	Wadi Kamal (Khamel)	Ni-Cu-(PGE)					< 200	۳ م	60
Somalia	Dibrawein (~ 30 intrusions)								
Somalia	Dudub							0.23	
Somalia	Gul Sakar								
Somalia	Hamar								
Somalia	Rakdasafaka							1.2	
Yemen	Suwar-Wadi Qutabah Complex	Ni-Cu-(PGE)			< 75	69-57	250	> 2	75
4. Mafic-ultramafic op	hiolitic complexes								
Egypt	Gabal Imleih				83-81		45	0.5	6
Oman	Oman ophiolite								
Total estimate									285.6

Appendix 2.3 Afric	a (southern and central)								
Minera	deposit jurisdiction and name	Potential and recc mineral cor	wered metal and nmodities	Ma	gnesium conte	nt	Dimensic	ons and estime potential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
South Africa	Karoo basalt province								
2. Greenstone belts or c	other mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Angola	Hamutenha	Ni-Cu-(PGE)					6.8		
Angola	Oncocua	Ni-Cu-(PGE)					< 10		
Botswana	Lechana				83-81	86-83			
Botswana	Molopo Farms	PGE-(Cu-Ni)		13%	87-84	89-62	13000	3.2	5100
Botswana	Moshaneng Complex						35		
Botswana	Selkirk(-Takwane)	Ni-Cu-(PGE)	4.5	7-8%			9		1.5
Botswana	Tsetseng Complex (six bodies)						< 15	4	
Botswana	Xade						> 3,000	4	
Madagascar	Andriamena intrusions	ŗ	~ 8-10	9-11%			2	0.12	
Madagascar	Ranomena	ŗ	0.25	9-11%	93-92	91-90	0.2		
Mozambique	Atchiza				87-86	68-65	330		
Mozambique	Tete			8-9%	82-60	74-49	800	ß	450
Namibia	Cape Cross						35		
Namibia	Doros				75-54		17	> 0.5	
Namibia	Etengua				65-63		< 10		
Namibia	Grootfontein Mafic Body	Fe-Ti-V					250		
Namibia/Angola	Kunene	Fe-Ti-V			79-58		2500		600
Namibia	Messum						35	> 2.4	
Namibia	Ohamaremba	Ni-Cu-(PGE)			78-65		2	0.75	0.3
Namibia	Ombuku (two bodies)	Ni-Cu-(PGE), Cr					28 + 0.1		6
Namibia	Otjitambi						< 10		
South Africa	Budd	magnesite						0.7	

Appendix 2.3 Afric	a (southern and central) continued								
Mineral	deposit jurisdiction and name	Potential and recc	overed metal and	Ma	gnesium conter	ıt	Dimension	ıs and estima	ited carbonation
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
South Africa	Bushveld	PGE-(Cu-Ni)	3,733	7.5-13%	88-77		100,000	6	60000
South Africa	Bushveld	PGE-(Cu-Ni)	6,646						
South Africa	Bushveld	PGE-(Cu-Ni)	2,274						
South Africa	Bushveld	PGE-(Cu-Ni)	346						
South Africa	Bushveld	PGE-(Cu-Ni)	50.9						
South Africa	Central								
South Africa	Core Zone							2	
South Africa	Elandshoek	asbestos							
South Africa	Elephant's Head								
South Africa	Emmenes								
South Africa	Handsup(-Mundt's Concession?)	asbestos							
South Africa	Heidelberg			4.8			~1		
South Africa	Helvetia Body	Ni-Cu-(PGE)			78-70			0.45	
South Africa	Hillside	verdite stones							
South Africa	Kaapsehoop	asbestos							
South Africa	Kalkkloof	asbestos					15		
South Africa	Koedoe						15	0.75	
South Africa	Koster (several bodies)						0.45 dia	0.12	
South Africa	Lindeques Drift			4.8			11 (length)	0.2	
South Africa	Losberg				86-82	91-84	20.5	0.12	
South Africa	Magaliesberg						1 (dia)	0.29	
South Africa	Mambula	Fe-Ti-V	22				25		
South Africa	Messina							> 10	
South Africa	Magnesite						16 (length)		
South Africa	Morgenson								
South Africa	Mount Ayliff (Tabangulu, Ingeli, Tonti)	PGE-(Cu-Ni)	0.47	14%	87-72		800	1.2	390
South Africa	Msauli(-Havelock)	asbestos					7 (length)		
South Africa	Mundt's Concession(-Handsup?)	asbestos							

Annendix 2 3 Afric	a (southern and central) continued								
		Potential and a second	المتم امتحيت امتحين					and a start of	tad souther state
ININER	deposit jurisdiction and name	Potential and reco	vered metal and	INIA	gnesium conter	Ľ	nimensior	is and estima	ited carbonation
luriediction or mining		Main metal and	Total are mined				Areal	Maximum	Theoretical
district	Deposit name	mineral	(Mt)	MgO (%)	Fo _{olv}	En _{opx}	extent	thickness	reactive rock mass
		commodities	12121				(km²)	(km)	(Mt)
South Africa	New Amalfi				70-3	75-31	15 (width)	0.44	
South Africa	Pioneer				92-91			Ч	
South Africa	Richmond						6 (length)	0.2	
South Africa	Rosentuin						11 (length)	0.17	
South Africa	Sawmill								
South Africa	Schikfontein (formerly Kaffirskraal)	Fe-Ti-V					1.6		
South Africa	Ship Hill	magnesite						0.65	
South Africa	Stella	PGE-(Cu-Ni)					18	1	
South Africa	Stolzburg	asbestos				89-87	15	1.2	
South Africa	Thole							0.2	
South Africa	Trompsburg	Fe-Ti-V			74-69	75-70	2500	2	
South Africa	Tugela Rand					87-76	50	1.9	
South Africa	Uitkomst	Ni-Cu-(PGE)	407 (+ 6.23 Cr)		90-80	90-50	9 (length)	0.85	ß
South Africa	Usushwana	PGE-(Cu-Ni)		8%			210	7.5	
South Africa	Zandspruit						0.5		
Tanzania	Block 1	Ni-Cu-(PGE)			87-82		2	0.9	
Tanzania/Burundi	Kapalagulu	PGE-(Cu-Ni)		15%	85-81		> 20	1.3	12
		Ni-laterite	20						
Tanzania	Kabanga (Main)	PGE-(Cu-Ni)		12-15%	90-76	88-80	> 2 (dia)	0.5	0.3
Tanzania	Kabanga (North)	Ni-Cu-(PGE)	21.3 (indicated)	12-15%	89-78		0.15 (dia)	0.1	0.3
Tanzania	Luhuma	Ni-Cu-(PGE)					с С		
Zimbabwe	Chimbadzi Hill	Fe-Ti-V-(P)			60-50		8.05		
Zimbabwe	Great Dyke	PGE-(Cu-Ni)	44000	16%			5,000	> 3.3	480
Zimbabwe	Great Dyke	ບັ	10000						
Zimbabwe	Madziwa (several bodies)	Ni-Cu-(PGE)	12	8%			1,200		300
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									67346.4

Appendix 2.4 Aust	ralia + Oceania + Antarctica								
Minera	deposit jurisdiction and name	Potential and recc mineral cor	overed metal and mmodities	Ma	gnesium conte	int	Dimensio	ns and estima potential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	(%) MgO	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
Western + Central Austi	alia Yilgarn + Pilbara								
	Warakurna LIP								
2. Greenstone belts or c	ther mafic terrains								
Western Australia (Yilga	ırın + Pilbara)								
	Mount Keith	N							
3. Mafic-ultramafic laye	red intrusive complexes								
Western Australia (Yilga	ırn + Pilbara)								
Australia	Andover	Ni-Cu-(PGE)		10-11%			140	2.1	87
Australia	Atley Complex						100	2	60
Australia	Barrambie Complex	Fe-Ti-V	39.7				100	1.7	25.5
Australia	Bullock Hide						9	< 0.5	
Australia	Coobina	Cr-V	1.5					0.2-0.6	
Australia	Dingo	Ni-Cu-(PGE)		8-12%			2.2	< 0.5	0.3
Australia	Gnanagooragoo (Range Bore)	PGE-(Cu-Ni)					70 (diameter)	ъ	
Australia	Jimberlana	PGE-(Cu-Ni)		8-12%	80-75	83-74	006	5.5	540
Australia	Lady Alma Complex	Fe-Ti-V	180					2	
Australia	Maitland	PGE-(Cu-Ni)					14	2	
Australia	Mapa							> 0.4	
Australia	Millindinna								
Australia	Mount Thirsty			13%				2	
Australia	Mount Scholl	Ni-Cu-(PGE)	0.5	10-11%			18	2	9.6
Australia	Munni Munni	Ni-Cu-(PGE)		8-12%			225	> 5.5	135
Australia	Narndee	PGE-(Cu-Ni)			80-49		600	9	
Australia	North Whundo	Ni-Cu-(PGE)					2		
Australia	Opaline Well						ß	0.5	
Australia	Radio Hill	Ni-Cu-(PGE)	0.54	11.5%			3.6	1.2	12
Australia	Ruth Well	Ni-Cu-(PGE)							
Australia	Sherlock	Ni-Cu-(PGE)	16				18	Ч	6
Australia	Windimurra	Fe-Ti-V	210		90-35		2,500	11	1500
Australia	Yalgowra							2	
Australia	Youanmi	Fe-Ti-V	185				500	4	300

Appendix A2: Global rock/ mineral resources

Appendix 2.4 Aust	ralia + Oceania + Antarctica (continued)								
Minera	l deposit jurisdiction and name	Potential and reco mineral cou	overed metal and mmodities	Ma	;nesium contei	nt	Dimension	is and estima otential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Western Australia (Kim	berley)						•		
Australia	Alice Downs	Ni-Cu-(PGE)							
Australia	Armanda	Ni-Cu-(PGE)					3.7	0.7	
Australia	Big Ben	PGE-(Cu-Ni)					100	2	
Australia	Black Hills Yard	Ni-Cu-(PGE)					100	0.3	
Australia	Bow River	Ni-Cu-(PGE)					16		
Australia	Bulldust Flat	Ni-Cu-(PGE)							
Australia	Corkwood	Ni-Cu-(PGE)					0.45	0.2	
Australia	Eastmans Bore	PGE-(Cu-Ni)					6 (length)	0.95	
Australia	Eileen Bore	Ni-Cu-(PGE)							
Australia	Fletcher Creek	Ni-Cu-(PGE)					4.5	0.3	
Australia	Frog Hollow	Fe-Ti-V					8	0.8	
Australia	Hart	Fe-Ti-V	470				> 250 (length)	0.5	
Australia	Keller Creek	Ni-Cu-(PGE)					0.5	0.3	
Australia	Lamboo	PGE-(Cu-Ni)	1.5 (cr)				60	1.5	27
Australia	McIntosh	Ni-Cu-(PGE)		8%	78-68		84	9	36
Australia	Norton	Ni-Cu-(PGE)					14		
Australia	Ord Crossing	Ni-Cu-(PGE)							
Australia	Panton	PGE-(Cu-Ni)	14.3	8-9%			28	1.6	12
Australia	Salt Lick Creek			6.6-10.5%	84-81	83-79	11	7	m
Australia	Savannah (formerly Sally Malay)	Ni-Cu-(PGE)	3.85				2		
Australia	Springvale	PGE-(Cu-Ni)					78	2	
Australia	Toby			7-8%			240		9
Australia	Wateranga				74-42	86-51	28	> 0.5	9
Australia	West Robin Soak	Ni-Cu-(PGE)					0.16	0.1	
Australia	Wilagee	PGE-(Cu-Ni)					20	1.3	

Appendix 2.4 Aust	ralia + Oceania + Antarctica (continued)								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium contei	ıt	Dimensions	s and estima otential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal I extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Central Australia							-		
Australia	Cavenagh Range						324	1.8	
Australia	Claude Hills	Ni-Cu-(PGE)	4.5				4		
Australia	Ewarara				88-86	89-83	8	0.3	0.6
Australia	Gosse Pile					83-78	12		
Australia	Hinkley						92	ŝ	
Australia	Kalka	PGE-(Cu-Ni)		7-8%		85-75	40	5	21
Australia	Mantamaru (Jameson, Bell Rock, Blackstone)	PGE-(Cu-Ni)		10-13%	64-62		3400 (original	< 10	
Australia	Michael(-Latitude) Hills						132	4	
Australia	Morgan Range						50	>1	
Australia	Mordor	PGE-(Cu-Ni)			78-74	~ 77	35	1.2	12
Australia	Murray Range						25		
Australia	Mt Davies (N and S)				91-83	93-73	72	4.2	
Australia	Nebo-Babel (Musgrave Block)	Ni-Cu-(PGE)	392	11.70%	74-70	77-49	5.5 (strike)	0.5	0.9
Australia	Ngunala	Ni-Cu-(PGE)					210		
Australia	Nova Bollinger intrusion	Ni-Cu-(PGE)	13.1	8.80%	83-80		2.9	0.45	0.3
Australia	Pirntirri Mulari	PGE-(Cu-Ni)		10-13%	88-82		5 (diameter)	ŝ	c
Australia	Saturn						10 (diameter)		
Australia	Walter Hill						12	9	
Australia	The Wart			10-13%	83-78		10	2	9
Australia	Wingellina	PGE-(Cu-Ni)		10-13%	88-77		36	< 2.5	21
Eastern Australia									
Australia	Bucknalla (formerly Westwood)	PGE-(Cu-Ni)			83-69		10	0.8	2.1
Australia	Eulogie Park						6 (diameter)	0.9	
Australia	Somerset Dam			6-8%			4	0.5	4.8
Total estimate									2837.1

Appendix 2.4 Aust	ralia + Oceania + Antarctica (continued)								
Minera	deposit jurisdiction and name	Potential and recc mineral cor	overed metal and mmodities	Mag	nesium conter	Ŧ	Dimension	s and estima otential(km	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{alv}	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
New Zealand Aoteraroa									
New Zealand	Blue Mountain				82-74		1.5	> 0.8	0.3
New Zealand	Tapuaenuku						35	3.5	
New Zealand	White Hill Intrusions			11-13%			10 (length)	< 0.7	£
Antarctica									
Antarctica	Butcher Ridge			6.40%			3000	∞	3000
Antarctica	Dais (Basement Sill)			6.40%		86-66	50 (length)	0.5	4.8
Antarctica	Dufek	PGE-(Cu-Ni)		8-13%			> 6600	8.8	7500
Antarctica	Mount Egerton			6.40%		83-70		0.25	
Antarctica	Muren			7-8%			> 2	1.3	0.6
Antarctica	Utpostane			13%			25	с	19.5
Total estimate									10528.2
4. Mafic-ultramafic oph	iolitic complexes								
Eastern Australia	Hondon of condou (con of council				00 00			5	ĊĊ
Oceania					0000		0	t	0
New Caledonia									
New Zealand									
Aoteraroa									
New Zealand	Greenhills	PGE-(Cu-Ni)		11-13%	92-86		14		4.5
New Zealand	Lone Stag			11-13%					
New Zealand	Pahia Layered Series	PGE-(Cu-Ni)		11-13%	82-70		7		2.1
New Zealand	Riwaka	Ni-Cu-(PGE)		8.3%			130		

Appendix 2.5 North	h America (Canada)								
Minera	l deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	int	Dimension	s and estima otential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	(%) OBM	Foolv	En _{opx}	Areal extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Canada Ontario Quebe									
1. Large Igneous Basalti	ic Provinces								
2. Greenstone belts or (other mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes								
Canada	Agnew	PGE-(Cu-Ni)		8%	72-59	70-67	50	2.1	30
Canada	Bell River Complex	PGE-(Cu-Ni)		8-13%			1300	9	780
Canada	Big Mac	Fe-Ti-V					120		
Canada	Big Trout Lake	PGE-(Cu-Ni)					> 60 (length)	> 0.6	
Canada	Bird River (inc. Euclid Lake)	Ni-Cu-(PGE)	~ 15				20 (length)	0.8	4.8
Canada	Black Thor	Fe-Ti-V	137.7		94-80		8 (strike)		19.2
		Ni-Cu-(PGE)							
Canada	Bravo	Ni-Cu-(PGE)	18.5	20%			< 50	0.2	2
Canada	Bridges				71-66	75-71	20	1.5	9
Canada	Butler West and East	Fe-Ti-V							
Canada	Coldwell	PGE-(Cu-Ni)	97.4		63-26	56	350	< 2.5	150
		PGE-(Cu-Ni)	32.42						
Canada	Crystal Lake	Ni-Cu-(PGE)			79-51			0.9	
Canada	Dore Lake Complex	Fe-Ti-V					390	7	
Canada	Double Eagle (2 bodies)	ბ	20.5				1	0.7	0.3
Canada	Double Eagle (2 bodies)	Ċ	85.9						1.2
		Ni-Cu-(PGE)	6.9						
Canada	East Bull Lake	PGE-(Cu-Ni)		8%	65-59	71-64	30	0.85	9
Canada	Ferguson Lake	Ni-Cu-(PGE)	19.4				85	< 0.6	30
Canada	Fox River	PGE-(Cu-Ni)		19%			540	2	600
Canada	Franklin Sill			11.00%	87-70		< 100 (length)	0.15	4.8
Canada	Grader	Fe-Ti-V		5-6%			2	> 0.2	0.3
Canada	Hele	Ni-Cu-(PGE)					40	0.13	
Canada	Hettasch				73-50		200	> 0.8	
Canada	Highbank Lake-Fishtrap	Fe-Ti-V					690		

Appendix 2.5 Nortl	h America (Canada) continued								
Minera	l deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	ignesium conte	ut	Dimensio	ns and estima potential(km	ited carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Canada	Kamiskotia Complex	-			81-77		170	>4	
Canada	Kanichee	Ni-Cu-(PGE)					0.7	0.6	
Canada	Kiglapait			8%	72-36		560	8.4	300
Canada	Lac des lles Complex (several bodies)	PGE-(Cu-Ni)	88	> 8.3%		82-67	50 (diameter)		60
Canada	Lac Édouard	Ni-Cu-(PGE)	0.069		80-77				
Canada	Lac Fabien	Fe-Ti-V	> 250		70-30	70	40	4.5	21
Canada	Lac Kennedy	Ni-Cu-(PGE)			86-76				
Canada	Lansdowne House	Ni-Cu-(PGE)	14.6						
		Fe-Ti-V							
Canada	Legris Lake	PGE-(Cu-Ni)					25	> 0.2	
Canada	Lynn Lake intrusions	Ni-Cu-(PGE)							
Canada	Mayville	Ni-Cu-(PGE)	9.2				10 (length)	1.1	3
Canada	Menarik Complex	ŗ					9	0.5	
Canada	Michikamau	Ni-Cu-(PGE)				70-60	400	3.5	
Canada	Montcalm	Ni-Cu-(PGE)	3.56				85	>1	2.7
Canada	Muskox	PGE-(Cu-Ni)		13-16%			125 x 11 (north	× 8	600
Canada	Mulcahy Lake (one of four intrusions)						63	7	
Canada	Newark Island			10-12%	60-10		150	£	06
Canada	River Valley	Ni-Cu-(PGE)		8%	74	80-60	100	0.9	21
Canada	Saturday Night	Ni-Cu-(PGE)							
Canada	Seagull	PGE-(Cu-Ni)			83-50		85	0.8	
Canada	Sept Iles	Fe-Ti-V		5-6%	75-21		5000	9	1500
Canada	Shakespeare	Ni-Cu-(PGE)					14 (length)	0.43	
Canada	Sudbury	Ni-Cu-(PGE)	1648	3.60%		85-53	1620	m	450
Canada	Sunday Lake	PGE-(Cu-Ni)					2	0.37	
Canada	Thunder	Ni-Cu-(PGE)			86-56		0.8	0.5	
Canada	Thunderbird	Fe-Ti-V							
Canada	Tigalak			4-5%			80		
Canada	Voisey's Bay	Ni-Cu-(PGE)	124.4	8%	81-40		6.25	1	1.5
Total estimate									4683.8

Appendix 2.5 North	ר America (Canada) continued								
Minera	l deposit jurisdiction and name	Potential and rec mineral co	overed metal and mmodities	Ma	ıgnesium conte	nt	Dimensio	ns and estima potential(km	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
4. Mafic-ultramafic oph	iolitic complexes								
Canada Cordillera Britis	h Columbia								
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or (other mafic terrains								
3. Mafic-ultramafic lay	ered intrusive complexes								
Canada	Axelgold	Fe-Ti-V	5.4				540		
4. Mafic-ultramafic oph	iolitic complexes								
Canada NW Territories	Nunavit								
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or (other mafic terrains								
3. Mafic-ultramafic lay	ered intrusive complexes								
4. Mafic-ultramafic oph	iolitic complexes								

Appendix 2.6 North	ר America (USA)								
Minera	l deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium contei	ŧ	Dimensio	ons and estima potential(kn	ated carbonation ז ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
USA Cordillera									
1. Large Igneous Basalti 2. Greenstone helts or o	c Provinces wher mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes								
USA	Bear Creek (plus several MU bodies)				90-87			> 0.5	
USA	Lady of the Lake	PGE-(Cu-Ni)		15.40%			2.5		1.2
USA	Salt Chuck	PGE-(Cu-Ni)	0.3	10%			< 11		3
USA	Skymo				88-80		20		
USA	Stillwater	PGE-(Cu-Ni)	~ 150	12.5%	79-63	86-76	1,500	6.5	1125
4. Mafic-ultramafic oph	iolitic complexes								
USA Mid-continent									
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or c	other mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes								
USA	Bovine Igneous Complex (BIC) (+ Little BIC)	Ni-Cu-(PGE)		8.10%	83-77		0.44	0.75	0.3
USA	Duluth	Ni-Cu-(PGE)	4400	8.4%	66-47	80-60	5000	4.5	2520
USA	Echo Lake (+ Bluff, Haystack, Skinny)	PGE-(Cu-Ni)			62-59		> 18	>1	
USA	Nellie				85-56		2500	> 4.4	
USA	Potato River				63-31		< 120	3.6	
USA	Sonju Lake	PGE-(Cu-Ni)		8.4%			> 10	1.2	3
USA	Tamarack	Ni-Cu-(PGE)			84-82		50	> 0.75	
4. Mafic-ultramafic oph	iolitic complexes								
USA Atlantic									
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or o	other mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes								
Canada	St. Stephen	Ni-Cu-(PGE)	>1		85-61	71-50	24		7.2
USA	Moxie	Ni-Cu-(PGE)			88-20	74-54	1200		
USA	Palisades Sill				72-52		150	0.34	7.5
USA	Pleasant Bay			4-7%	12-1		169	ε	6
USA	Vinalhaven (> 100 mafic/alkaline plutons)						128	1	
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									3673.2

Appendix 2.7 North	n Atlantic								
Minera	l deposit jurisdiction and name	Potential and recov mineral com	vered metal and imodities	Ma	gnesium conte	ŧ	Dimension	s and estima otential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
 Large Igneous Basalti Greenstone belts or c 	c Provinces other mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes								
Canada	Baffin Island Northern Sill						0.35		
Canada	Baffin Island Southwestern Sill						0.22		
Greenland	Amikoq	PGE-(Cu-Ni)					25 (length)	0.15	1.2
Greenland	Fiskenæsset	PGE-(Cu-Ni) + Fe-Ti-V	50-100				500 (strike)	0.55	60
Greenland	llimaussag	REE	437		17-1		136	Ч	
Greenland	Imilik						62		
Greenland	Kap Edvard Holm	PGE-(Cu-Ni)		13.3%	85-66		360	7.5	300
Greenland	Kap Gustav Holm				79-68			2.3	
Greenland	Klokken				52-2		7.5	0.7	
Greenland	Kruuse Fjord	PGE-(Cu-Ni)		8.5%	82-46		< 260	> 5	126
Greenland	Lilloise				87-43		32	2.8	
Greenland	Motzfeldt	REE	200-500				140	> 1.7	
Greenland	Noe-Nygaard				77-72		10		
Greenland	Nordre Aputitëq						5		
Greenland	Nunarssuit						1125	ε	
Greenland	Patulajivit								
Greenland	Qôroq	REE					105		
Greenland	Ujarassuit Nunat				92-85		0.08		
Greenland	Skaergaard	PGE-(Cu-Ni)	23		80-58		70	3.5	60
Iceland	Austurhorn (Hvalnesfjall gabbro)				72-60		11	0.8	
Iceland	Lysuskard (Lýsuskarð)						ε		
Iceland	Midhyrna								
Iceland	Reydarfjall (Reyðarártindur)						4.5		
Iceland	Slaufrudal (Slaufrudalur)						15		
Iceland	Vesturhorn						19		
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									547.2

Appendix 2.8 Europ	oe (southern + central + Britain)								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	nt	Dimensio	าs and estima ootential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or o	other mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Czech Republic	Ransko	Ni-Cu-(PGE)			85-79	82-80	10		
France	St-Jean-du-Doigt (Poul Rodou layered gabbros)						200	> 1.5	
Germany	Harzburg				90-78		10		3
Ireland	Dawros				92-80	92-76	1		
Italy	Ivrea-Verbano Zone Mafic Complex	Ni-Cu-(PGE)					35 (length)	00	21
Italy (Sardinia)	Monte Plebi						0.5	> 0.05	
Italy	Sondalo						40		
Portugal	Beja	Ni-Cu-(PGE)			88-54		265		75
Scotland	Belhelvie						18		
Scotland	Ben Buie (+ Corra Bheinn, Bheinn Bheag)				86-84		16	0.9	4.5
Scotland	Centre 3 (Ardnamurchan)						< 30		
Scotland	Cuillin			10-12%	90-77		8 (diameter)		15
Scotland	Insch					71-44			
Scotland	Loch Ailsh	PGE-(Cu-Ni)					10		
Scotland	Loch Borralan	PGE-(Cu-Ni)					26	0.4	
Scotland	Morven-Cabrach				44-43			7	
Scotland	Rum	PGE-(Cu-Ni)		10-12%	90-82		25	0.75 (ELS)	6
Scotland	Shiant Isles Main Sill				83-5			0.17	
Spain	Aguablanca	Ni-Cu-(PGE)	15.7	12%	88-79		10	> 0.5	4.8
Switzerland	Mont Collon				79-75		14	> 0.4	
Wales	Mynydd Penarfynydd (3 bodies)							0.15	
Wales	St David's Head (inc Carn Llidi)						Ч	0.57	
4. Mafic-ultramafic oph	iolitic complexes								
Slovakia	Kovice								
Total estimate									129.3

Appendix 2.9 Euro	oe (Fennoscandia) Finland								
Minera	l deposit jurisdiction and name	Potential and recc mineral cor	overed metal and mmodities	Ma	gnesium conte	ent	Dimensio	ns and estima potential(km	ted carbonation ¹³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or c	other mafic volcanic terrains								
Finland	Hannukainen	Fe, Cu	4563080						
Finland	Hannukainen	Fe, Cu	4563080						
Finland	Haveri	Au	1559020						
Finland	Kangasjärvi	Zn, Au	91205						
Finland	Kittilä	Au	14817165						
Finland	Pahtavaara	Au	5820321						
Finland	Pahtavaara-Kittilä	Fe	14						
Finland	Pampalo	Au	1932394						
Finland	Porkonen	Fe	15						
Finland	Rautuvaara	Fe	11564405						
Finland	Rautuvaara SW	Fe							
Finland	Tainiovaara	N	19984						
Finland	Vihanti	Zn, Cu	27938832						
3. Mafic - ultramafic lay	ered intrusive complexes								
Finland	Ahmavaara	PGE, Ni, Cu, Pd, Pt							
Finland	Akanvaara	Cr-V		8-9%			50	3.3	24
Finland	Enonkoski	Ni, Cu, Co	6707515						
Finland	Hautajärvi								
Finland	Heimonvuori	Ni-Cu-(PGE)			83-65		0.005		
Finland	Hitura	N	17177362						0.3
Finland	Hyvinkää						20		
Finland	Junttilanniemi	Ni-Cu-(PGE)						0.6	
Finland	Kaipola						10		
Finland	Kärppäsuo								
Finland	Kauhajärvi	Fe-Ti-V		6-8%	61-21	68-67	9	> 0.4	0.3
Finland	Kemi	Cr203	54609224	< 10%	83-82	~ 80	30	2	6
Finland	Kevitsa	Ni, Cu	54573686		89-77	84-73	16	2.2	6
Finland	Koillismaa Complex (several blocks)	PGE-(Cu-Ni)	23.2				350	< 2	06
Finland	Koillismaa Complex (several blocks)	PGE-(Cu-Ni)	23.6						
Finland	Koillismaa Complex (several blocks)	Fe-Ti-V	13.4						
Finland	Koitelainen	Cr-V		8-9%	85-77		750	3.2	660

Appendix 2.9 Euro	be (Fennoscandia) Finland continued								
Minera	l deposit jurisdiction and name	Potential and recc mineral cor	ivered metal and mmodities	Ma	gnesium conte	ŧ	Dimensio	ons and estima potential(kn	ited carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Finland	Koivusaarenneva	Fe-Ti-V	44	6-8%		57-51	2.4	-	0.6
Finland	Konttijärvi (Portimo)	PGE, Ni, Cu, Pd, Pt	75	9-10%			0.18	0.31	0.3
Finland	Kotalahti	Ni, Cu, Co	12453647	9-10%			0.26	> 0.9	0.3
Finland	Kovero-oja	Ni, Cu	460000						
Finland	Kuohatti	Ni-Cu-(PGE)			82-80	97-75	0.2	0.12	
Finland	Kylmäkoski	iN	689616						0.3
Finland	Lapinlahti						44		9
Finland	Laukunkangas	Ni-Cu-(PGE)	7.9				0.2	0.8	0.3
Finland	Luikujärvi				75-67		0.5		
Finland	Luusniemi				75-62		9		
Finland	Makola	ï	412645						0.3
Finland	Mustavaara	V, Fe, Mgt	13648220						
Finland	Naistenrako	Ni-Cu-(PGE)	0.03		77-65		0.03		
Finland	Narkaus (Portimo; six blocks)	PGE-(Cu-Ni)		9-10%			23.4	0.8	5.4
Finland	Niinimäki	Ni-Cu-(PGE)	3.2		83-77		1	0.3	
Finland	Otanmäki	Fe, V	30629174				20	0.8	ß
Finland	Penikat	PGE-(Cu-Ni)		< 10%		82-67	50	2.4	30
Finland	Perämaa	Fe-Ti-V		6-8%			150		
Finland	Peuratunturi						0.3		
Finland	Porrasniemi						2 (length)	0.4	
Finland	Rytky	Ni-Cu-(PGE)	1.54	9-10%	85-78		0.5	< 0.4	0.3
Finland	Särkiniemi	Ni-Cu-(PGE)	0.29	8%	75-72		0.02	> 0.12	
Finland	Sotkavaara	PGE-(Cu-Ni)					3.75	< 0.45	
Finland	Stormi	Ni, Cu	7577977						0.3
Finland	Suhanko (Portimo)	PGE-(Cu-Ni)	187	9-10%			35	0.5	5.1
Finland	Telkkälä	ï	605396						0.3
Finland	Törmälä	Ni-Cu-(PGE)	0.12		85-74		0.008	0.004	
Finland/Sweden	Tornio/Kukkola	Cr-V					ŝ	< 0.5	
Finland	Tsohkoaivi(-Kelottijärvi)							0.1	
Finland	Tsuomasvarri						∞		
Finland	Vuorokas	Fe, V, Ti	1348000						
Finland	Ylivieska	Ni-Cu-(PGE)			85-62		18		4.5

Appendix 2.9 Euroș	be (Fennoscandia) Finland continued								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	nt	Dimensio	ons and estima potential(kn	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	(%) OBM	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
4. Ophiolitic ultramafic	complexes								
Finland	Horsmanaho	talc, Ni		25-38%					
Finland	Jormua complex			25-38%					
Finland	Kylylahti	Cu, Zn	5433592	25-38%					1.8
Finland	Lahnaslampi	talc		25-38%					
Finland	Luikonlahti	Cu, Co	6983164	25-38%					2.3
Finland	Nuttio complex			25-38%					
Finland	Outokumpu	Cu, Co	29188315	25-38%					9.8
Finland	Vuonos Cu	Cu, Co	5489576	25-38%					1.8
Finland	Vuonos-Ni	Ni, Co	5495761	25-38%					1.8
Total estimate									867.1

Appendix 2.9 Euroș	oe (Fennoscandia) Norway + Sweden								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium contei	ıt	Dimensio	ons and estime potential(km	ited carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Norway									
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or c	ther mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Norway	Bjerkreim-Sokndal	Fe-Ti-V-P		4-6%	77-62		230	7.5	
Norway	Čoalbmejávri	PGE-(Cu-Ni)			83-80	83-71	2	0.35	
Norway	Skoganvárre	PGE-(Cu-Ni)			82-77	82-80	1	0.5	
4. Mafic-ultramafic oph	iolitic complexes								
Norway	Fongen-Hyllingen				75-0		160	9	
Norway	Hasvik			8%	78-74		12	1.7	5.7
Norway	Honningsvåg (group of 5 intrusions)				89-76	80-77		> 2	
Norway	Kvalfjord				84-77		35		
Norway	Lille Kufjord				82-71		S	1.5	
Norway	Melkvann (two lobes)				82-80		100		
Norway	Nordre Brumandsfjord				79-76		50		
Norway	Råna	Ni-Cu-(PGE)	43		69-06	85-54	70	< 3.8	
Norway	Reinfjord	PGE-(Cu-Ni)		16-22%	85-77		10	0.2	0.9
Norway	Rognsund				74-64		50	0.9	
Sweden									
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or c	ther mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Europe Fennoscandia									
Sweden									
Sweden	Bottenbäcken (several outcrops)	Ni-Cu-(PGE)							
Sweden	Hoting	Ni-Cu-(PGE)					100		
		Fe-Ti-V							
Sweden	Kläppsjö	Ni-Cu-(PGE)			74-10		21	ŝ	
Sweden	Kleva	Ni-Cu-(PGE)					12		
Sweden	Näsberg (Näsberget)	PGE-(Cu-Ni)					40	4	
Sweden	Notträsk	Ni-Cu-(PGE)					20		
Sweden	Rörmyrberget	Ni-Cu-(PGE)	0.7	13.00%	90-76		0.98	0.35	0.3
Sweden	Rymmen				83-72	84-60	Ŋ		
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									6.9

Appendix A2: Global rock/ mineral resources
Appendix 2.10 Russ	sia (Fennoscandia)								
Mineral	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	nt	Dimension	ıs and estima otential (km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or o	ther mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Russia	Burakovsky (Burakovskii)	ర	200		86-78	82-59	630	8	360
Russia	Fedorova Tundra	Ni-Cu-(PGE)			66-60	82-55	100?	4?	
Russia	Imandra (Imandrovsky)	Cr-V				75-55	1500	3.5	
Russia	Kivakka (Oulanka Complex)	PGE-(Cu-Ni)			84-83	82-72	~ 15.5	2	
Russia	Kiy Island						800		
Russia	Khibina (Khibiny)	P-REE					1327	15	
Russia	Kolvitsa					81-66	60 (length)	2	
Russia	Koulumaoiva								
Russia	Lukkulaisvaara (Oulanka Complex)	PGE-(Cu-Ni)		12-13%		77-74	44	4.6	66
Russia	Matkalsky (Matkalskii)								
Russia	Medvedevsky (Medvedevskii)	Fe-Ti-V							
Russia	Monchegorsk Complex	PGE-(Cu-Ni)	27.8	5-8%	92-80	86-70		2.7	
Russia	Mt Generalskaya	Ni-Cu-(PGE)					5.25	1.7	
Russia	Pados-Tundra	ت		14.00%	91-85	91-85	13	2.1	10.5
Russia	Panski Tundra	PGE-(Cu-Ni)			66-60	82-55	> 250	4	
Russia	Pilgujärvi	Ni-Cu-(PGE)	36 (Pechenga)				4.5	0.6	
Russia	Pyrshin						100	> 1.5	
Russia	Ruiga				86-75	78-77	20	0.81	
Russia	Tolstik						10	0.1	
Russia	Tsipringa (Oulanka Complex)						~ 40		
Russia	Volch'i- & Moncha Tundra			5-8%			122.5		30
Russia	Zhemchuzhnyi (Zhemchuzhnaya)								
Russia	Kopansky (Kopanskii)	Fe-Ti-V							
Russia	Kusinsky (Kusinsko)								
4. Mafic-ultramafic ophi	iolitic complexes								
Total estimate									466.5

Appendix 2.10 (con	itinued) Russia (Urals) + Ukraine								
Mineral	l deposit jurisdiction and name	Potential and reco mineral cor	wered metal and nmodities	Ma	gnesium content		Dimensio	ns and estima potential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or o	other mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Russia	Annensky								
Russia	Artyukhovsky								
Russia	Astakhovsky								
Russia	Bychkovsky								
Russia	Elansky (Elanskii/Elanskoe)	Ni-Cu-(PGE)					120		
Russia	Elinsky	Ni-Cu-(PGE)							
Ukraine	Fedorivka-Korosten	Fe-Ti-P			42-32		m	0.32	
Russia	Ikoretsky								
Russia	Lipov Kust (Pioneer)	Ni-Cu-(PGE)					> 60	~ 1.2	
Russia	Mamonsky (Mamonskii)	Ni-Cu-(PGE)							
Russia	Mokhovskoy								
Russia	Peskovatsky								
Russia	Podkolodnovsky								
Russia	Shiryaevsky	Ni-Cu-(PGE)						~ 6	
Russia	Shishovsky								
Russia	Sukhoi Yar								
Russia	Troitsky								
Russia	Uvarovsky								
Russia	Vyazovsky	PGE-(Cu-Ni)					80	~ 0.7	
Russia	Yubi Ley								
4. Mafic-ultramafic ophi	iolitic complexes								
Russia	Nurali	IJ					~ 70	1.5	
Russia	Sarany (N & S) (+ poorly studied massifs of Teologorsk Tserkovov)	J					~ 2	0.24	
Russia	Voikar-Syninski (Syn'inskii/Synya)						2000	6	

Appendix 2.10 (con	tinued) Russia (Siberia)								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	nt	Dimensic	ons and estima potential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{alv}	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
Russia	Noril'sk 1	Ni-Cu-(PGE)	33		81-74		30	0.2	1.5
Russia	Kharaelakh	Ni-Cu-(PGE)	3230		81-78		70	0.07	1.5
2. Greenstone belts or o	ther mafic terrains								
3. Mafic-ultramafic laye	red intrusive complexes								
Russia	Argydzhek	PGE-(Cu-Ni)							
Russia	Azartov								
Russia	Bolsheatalyk						10	4	
Russia	Burlaksky (Burlakski)	PGE-(Cu-Ni)			86-79	80-63	16	2.5	
Russia	Bulka			24%	78-72	76-65	100	> 1	72
Russia	Chineysky	PGE-(Cu-Ni)		5.8%	77-73	68-53	130	2.5	45
Russia	Deneshkin Kamen (Denezhkin Kamen)								
Russia	(Yoko/loko-)Dovyren (Dovirensky)	Ni-Cu-(PGE)		14.5^%	89-73	80-56	65	3.5	66
Russia	Dukuk	Ni-Cu-(PGE)			80-66	74-66		0.7	
Russia	Epilchik (3 bodies)	PGE-(Cu-Ni)					~ 25		
Russia	Golumbei	PGE-(Cu-Ni)							
Russia	ll'Deus	Ni-Cu-(PGE)							
Russia	Kachkanar	Fe-Ti-V	9300		93-85				
Russia	Kharlovo	Fe-Ti-V	3500				12		
Russia	Kingash(-Verkhnii)	PGE-(Cu-Ni)	219				2		
Russia	Kobez								
Russia	Koksharovska (+ Ariadninsky & Shoumninsky)	Fe-Ti-V					34		
Russia	Kondyor (Kondor) (+ poorly studied plutons of Chad, Feklistov, Sybah, Inagli)	PGE-(Cu-Ni)	5 (t)		95-90		~ 36		
Russia	Kuchesh								
Russia	Kumba								
Russia	Kuvalorog(sky)	Ni-Cu-(PGE)			85-80		30		
Russia	Kytlym	PGE-(Cu-Ni)					725		
Russia	Lower Derbin								

Appendix A2: Global rock/ mineral resources

Appendix 2.10 (con	tinued) Russia (Siberia)								
Minera	deposit jurisdiction and name	Potential and reco mineral cor	ivered metal and nmodities	Ma	gnesium conter	H.	Dimensio	ns and estima ootential(km	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo _{olv}	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Russia	Lucha	Ni-Cu-(PGE)	4 Ni, 1 Cu	-			250		
Russia	Lukinda	Ni-Cu-(PGE)					48		
Russia	Lysogorsk								
Russia	Maloatalyk						12	2	
Russia	Malyi Zadoi	PGE-(Cu-Ni)							
Russia	Maristyi (+ several poorly-studied massifs)								
Russia	Mazhalyk								
	Meteshikha (+ poorly studied plutons of								
Russia	Burlakovskii, Burlya, Furai, Ostraya Sopka,			11.60%			48		15
	Vodorazdel'nyi)								
	Nizhne-Derbinsk (+ poorly studied plutons of								
Russia	Ashtatski, Azertakski, Konzulski, Medvezhi,	PGE-(Cu-Ni)			84		4	0.4	
	Tubilski)								
Russia	Nizny Tagil	PGE-(Cu-Ni)			94-88		47	> 10	
Russia	Ognit (Medek)	PGE-(Cu-Ni)					2		
Russia	Pavda								
Russia	Pravotarlashkin								
Russia	Seglebir	Ni-Cu-(PGE)					36		
Russia	Shaman (Shamansky)								
Russia	Shumikha	PGE-(Cu-Ni)							
Russia	Srednyaya Ters'	PGE-(Cu-Ni)							
Russia	Tartai	PGE-(Cu-Ni)		11-17%	90-83		1.5		
Russia	Tokty-Oi	PGE-(Cu-Ni)							
Russia	Uktus	PGE-(Cu-Ni)			96-68		50		
Russia	Ul'degitsky								
Russia	Ust'depsky						350		
Russia	Veselyi (+ poorly studied Petropavlovsk)								
Russia	Volkovsky	PGE-(Cu-Ni)	11.3				135	2.5	
Russia	Zapevalikha	PGE-(Cu-Ni)							
Russia	Zhelos	PGE-(Cu-Ni)							
4. Mafic-ultramafic oph	iolitic complexes								
Russia	Kaigadat								
Total estimate									234

Appendix A2: Global rock/ mineral resources

Appendix 2.11 Asia	I (China)								
Minera	I deposit jurisdiction and name	Potential and recc mineral cor	wered metal and nmodities	Mag	nesium conten	1	Dimensio	ns and estima potential(km	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	(%) OBM	Foolv	En _{opx}	Areal extent (km ²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalti	c Provinces								
2. Greenstone belts or (other mafic terrains								
3. Mafic-ultramafic laye	ered intrusive complexes	Eo.Ti.V	Ċ				0.65	-	
China	Baima	Fe-Ti-V	1497		74-55		7.	- T	12
China	Baimazhai	Ni-Cu-(PGE)		17.9%	8		0.1	0.064	ł
China	Beiba	Fe-Ti-V					150		
China	Bijigou	Fe-Ti-V			79-67		500	S	
China	Dalongkai						0.025	> 0.1	
China	Dawusunangou	Fe-Ti-V		8-9%	64-47		4	1	0.9
China	Erhongwa	Ni-Cu-(PGE)		10.3%	89-81		16.5		4.8
China	Fanshan	P-Fe	63.8				30	> 0.73	9
China	Haladala	Fe-Ti-V			73-65	84-67	25		
China	Hongge	Fe-Ti-V	4572		86-70		60	> 1.3	24
China	Huangshandong	Ni-Cu-(PGE)	> 50	7.3-10%	84-59		4.2	>1	1.2
China	Huangshannan	Ni-Cu-(PGE)	30				4	0.6	0.3
China	Jinbaoshan	PGE-(Cu-Ni)			84-82		S	0.15	
China	Limahe	Ni-Cu-(PGE)	< 3	21%	86-77		0.16	0.3	
China	Mazaertag	Fe-Ti-V		6-8%	73-71		0.13	0.3	
China	Niumaoquan	Fe-Ti-V	0.35	> 7.3%	< 76		2.7		
China	Panzhihua	Fe-Ti-V	1333	12%	81-77		30	2	19.8
China	Piqiang	Fe-Ti-V	120	7-9%	79-61		16.7		4.5
China	Poyi	Ni-Cu-(PGE)	1.3 Ni, 0.22 Cu	15.0%	91-83		~ 1.8	2.6	1.8
China	Quruqtagh (5 bodies)	Ni-Cu-(PGE)			83-71	1.	5, 2, 10, 12, 2	0	
China	Shangzhuang (not Shangzhuang in Lajisan Belt)	Fe-Ti-V	20		81-63		0.6		
China	Taihe	Fe-Ti-P	810		~ 71		9	1.2	
China	Tudun	Ni-Cu-(PGE)	0.0018 (Ni+Cu)		< 85		0.98		
China	Wangjiangshan	Ni-Cu-(PGE)			76-60		120	2.5	
China	Wajilitag	Fe-Ti-V	100		76-67		15	0.27	
China	Xiadong				97-93		3.5		
China	Xiangshan	Ni-Cu-(PGE)	0.04 Ni, 0.02 Cu		< 81.9		10		
China	Xiaohaizi				75-69		18	0.75	
China	Xiarihamu	Ni-Cu-(PGE)	157	9.8%	90-84	90-75	~ 0.8	0.5	0.3
China	Xinjie	PGE-(Cu-Ni)		14.0%	88-61	76-72	11	1.2	5.4
China	Zhubu	Ni-Cu-(PGE)			84-81		0.3	0.6	
Total estimate									315

Appendix 2.11 Asi	a (central and northeastern)								
Miner	al deposit jurisdiction and name	Potential and recommended mineral commended	overed metal and mmodities	Ma	gnesium conte	ıt	Dimensio	ns and estime potential(km	ited carbonation ו ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Iran	Ghazan-Khanik	Fe-Ti-V			50-40	87-57			
Iran	Qareaghaj	Fe-Ti-V		8%	63-41	40-36	12		3
Japan	Asama Complex (several bodies)			7.50%	89-78	~ 74	'n	0.46	0.3
Japan	Õura Complex			9-11%	91-82		23	4	
Kazakhstan	Chelkar						< 75		
Mongolia	Bayantsagaan						9	> 1.2	
Mongolia	Dulaan	Ni-Cu-(PGE)			78-73		4		
Mongolia	Khairkhan (Hairhan)	PGE-(Cu-Ni)			77-74	73-64	70		21
Mongolia	Marinkin	Ni-Cu-(PGE)					11	0.7	
Mongolia	Nomgon	Ni-Cu-(PGE)			79-75		9.5		£
Mongolia	Oortsog	Ni-Cu-(PGE)			77-76		2.5		
Mongolia	Rudniy	Ni-Cu-(PGE)							
Mongolia	Zaoblachnyi								
South Korea	Macheon						45	0.9	
Sri Lanka	Kandy						24	0.3	
Vietnam	Khao Que				21-18		30		
Vietnam	Nui Chua (also Tri Nang, Nui Yen Chu)	PGE-(Cu-Ni)		7-11%	87-75		55		15
4. Mafic-ultramafic opl	hiolitic complexes								
Pakistan	Chilas			6.3%	83-75		< 12,000		
Pakistan	Jijal	PGE-(Cu-Ni)			92-89	90-72	150	11	
Total estimate									42.3

Appendix 2.12 Lati	n America								
Miner	al deposit jurisdiction and name	Potential and reco mineral cor	wered metal and mmodities	Ma	gnesium conte	t	Dimensio	ns and estima potential(km	ted carbonation 1 ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	(%) MgO	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
1. Large Igneous Basalt	ic Provinces			-					
 Greenstone belts or Mafic-ultramafic lay. 	other matic terrains ered intrusive complexes								
Argentina	Las Aguilas (several in the San Luis Province)	Ni-Cu-(PGE)		13.7%	84-82		< 200	< 2	150
Argentina	Fiambalá	Ni-Cu-(PGE)		> 11%	91-90	89-59	36	2.8	24
Argentina	Jaboncillo Valley (several in the Sierras Valle Fertil	(1		> 8%	82-78	80-77			
Argentina	Virorco (several in the San Luis Province)	Ni-Cu-(PGE)				74-70	1.5	5	
Bolivia	Rincon del Tigre	PGE-(Cu-Ni)		9-10%	< 88		720	4.6	420
Brazil	Americano do Brasil	Ni-Cu-(PGE)	3.1		88-78		36		6
Brazil	Bacuri	ა	8.8		90-76	93	55	1	15
Brazil	Barro Alto								
Brazil	Brejo Seco	Ni-Cu-(PGE)			89-80		31	3.5	
Brazil	Caboclo dos Mangueiros	Ni-Cu-(PGE)	200				1		0.3
Brazil	Campo Alegre de Lourdes	Fe-Ti-V	100				22		9
Brazil	Campo Formoso	PGE-(Cu-Ni)					40	1.4	
		ŗ							
Brazil	Cana Brava						40 (length)	2.5	
Brazil	Canindé	Fe-Ti-V			80-70	79-73	55		
Brazil	Carreira Comprida						116		
Brazil	Fazenda Mirabela	Ni-Cu-(PGE)	0.726		88-86		7	> 3	3
Brazil	Fazenda Palestina						9		
Brazil	Ipanema	PGE-(Cu-Ni)					< 0.55	0.13	
Brazil	Jacurici Complex	Ⴆ	4.5		92-85	94-88	3.5	0.3	0.3
Brazil	Lago Grande	PGE-(Cu-Ni)			86-82	85-81	20	1.2	7.2
Brazil	Luanga	PGE-(Cu-Ni)	142	11.5%	86-79	90-77	21	3.6	13.5

Appendix 2.12 Latir	א America (continued)								
Minera	deposit jurisdiction and name	Potential and reco mineral co	overed metal and mmodities	Ma	gnesium conte	nt	Dimensio	ns and estima potential(km	ted carbonation ³ + Mt)
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Foolv	En _{opx}	Areal extent (km²)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Brazil	Mamão	Ni-Cu-(PGE)					> 4 (length)	0.14	
Brazil	Mangabal (I & II)	Ni-Cu-(PGE)			83-78	85-67	4.5	0.35	0.3
Brazil	Monto do Carmo	Au	0.013				52		
Brazil	Morro do Leme	Ni-Cu-(PGE)			93-91		> 2 (length)	> 0.25	
Brazil	Morro da Mata	Laterite	14.3				202		60
Brazil	Morro Sem Boné (plus satellite bodies)	Ni-Cu-(PGE)					6 (length)	0.4	
Brazil	Niquelândia	PGE-(Cu-Ni)			76-63		800	ъ	
Brazil	Peixe	Fe-Ti-V					30		
Brazil	Rio Crixás				63-7	57-17	196		
Brazil	Rio Jacaré	Fe-Ti-V	2				84	1	
Brazil	São Domingos						39		
Brazil	Taquaral								
Brazil	Tróia	PGE-(Cu-Ni)							
Brazil	VE3				85-83		19		
Brazil	Vermelho	Laterite	220		91-86		14	0.5	4.2
Venezuela	Mochila Complex (12 bodies)	PGE-(Cu-Ni)					< 45	(Mochila sout	h)
4. Mafic-ultramafic oph	iolitic complexes								
Total estimate									712.8

Appendix A3: Review articles from 2016

Selected (recent) references to additional information regarding global mineral carbonation potential

Ref	Information	Comment
[1]	Table 3. Australia's mineral resources and potential of its mining waste for carbon capture and storage (CCS) by mineral carbonation	Carbonation capacity not estimated, but estimates of world production capacity of various mineral resources provided
[2]	Table 1. Example of worldwide super-large sites potentially available for ex situ mineral carbonation with an attempt of prioritization.	Examples of worldwide source sink matching. Distances between source and sink estimated.
[3]	Table 3. Global abundance and carbonation potential of industrial wastes.	Overall global mineral carbonation potential estimated, but not for natural minerals / mine tailings
[4]	Supplementary information 7. Estimated material suitability (CO2 (Mt) converted to alkalinity per 1 Mt of tailings), Annual tailings production (ATPX) and annual CDR [large scale CO ₂ removal] capacity of selected commodity- hosting silicate deposit types.	Combined with Figure 1, the supplementary material gives an good overview of global mine tailings potential for mineral carbonation.

[1] Azadi, M., Edraki, M., Farhang, F., Ahn, J. 2019, "Opportunities for Mineral Carbonation in Australia's Mining Industry" *Sustainability* 11(5); 1250, doi: 10.3390/su11051250

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[3] Woodall, C.M., McQueen, N., Pilorgé, H., Wilcox, J. 2019 Utilization of mineral carbonation products: current state and potential, *Greenh Gas Sci Technol.* 9; 1096–1113 doi: 10.1002/ghg.1940

[4] Bullock, L.A., James, R.H., Matter, J., Renforth, P., Teagle, D.A. 2021. Global Carbon Dioxide Removal Potential of Waste Materials from Metal and Diamond Mining. *Front. Clim.*, 28 July 2021 https://doi.org/10.3389/fclim.2021.694175

Appendix A4: The ÅA routes

Research at Åbo Akademi Univ. (ÅA) in Turku, Finland since 2005 has resulted in five different varieties of what is referred to in the literature referred to as the "ÅA route". In most cases the first or, less commonly, the second variety of these routes is referred to. The preferable input rock is serpentinite, containing primarily serpentine, $3MgO\cdot2SiO_2\cdot2H_2O$, or $Mg_3Si_2O_5(OH)_4$ besides some other species, primarily iron oxides/silicates.

In short, the first route implies extraction of Mg from serpentinite using ammonium sulfate (AS) flux salt in a rotary kiln at 400 - 450°C, giving water-soluble magnesium sulfate MgSO₄ which, after removal of iron oxyhydroxide FeOOH is converted into magnesium hydroxide Mg(OH)₂. The latter is carbonated to give magnesite MgCO₃ in a pressurised fluidised bed (PFB) reactor at 500 – 520 °C, at a CO₂ partial pressure of 20 bar. (Pressurisation is needed since MgCO₃ is not stable above approx. 410 °C at atmospheric pressure CO₂; a higher temperature than that is needed for sufficiently fast chemical kinetics.) Residence times for the two process steps are 30 min and 10-15 min, respectively; note that for raising the pH in the aqueous solutions for FeOOH and Mg(OH)₂ precipitation, the ammonia NH₃ released as vapour from the rotary kiln can be used. Recovery of (moist) AS from the solutions after Mg(OH)₂ precipitation is accomplished using mechanical vapour concentration and drying. After separation from silica product, unreacted rock is returned to the extraction step. The development was reported in the doctoral theses of Fagerlund¹ and Nduagu² and appended papers in 2012. Combined, this gives the first, ÅA1 route as schematically depicted in Figure 1.



Figure 1: The first ÅA route, based on "dry" extraction of magnesium and "dry" carbonation

Detailed studies addressed the processes in the kiln ³ and the suitable geochemistry/mineralogy/ petrology of magnesium silicate rock for this process ⁴. Approximately 30-35% of the heat requirements for the extraction step can be covered by the heat from the carbonation reactor. Followup work focussing on energy integration was reported in the theses by Romão ⁵ and Slotte⁶ (with appended publications). The latter considered processing of CO₂-containing gas without preseparation of CO₂ and also included LCA.

For cases where the disadvantages of complexity cannot motivate heat recovery from the carbonation step in a PFB, the carbonation process step can be carried out in an aqueous solution. This gives the process scheme as simplified in Figure 2, i.e. the ÅA2 route. The extraction of magnesium and production of aqueous MgSO₄ is identical to that described above for route ÅA1. However, it is not

possible to carbonate MgSO₄ unless in alkaline solution for which again, the ammonia vapours from the magnesium extraction kiln can be used. After raising the pH to pH = 10.2 - 10.5 the solution allows for reaction with CO₂ from a flue gas, giving a magnesium carbonate hydrate (MCH) MgCO₃·3H₂O a.k.a. nesquehonite. Otherwise, as with the ÅA1 route an aqueous solution of AS is obtained that needs to be processed to give AS as a (moist) powder for re-use.



Figure 2: The second ÅA route, based on "dry" extraction of magnesium and "wet" carbonation

For two case studies, namely a lime kiln and a natural gas – fired power plant (NGPP) a comparison of the routes has been published ⁷, while a summary of the results obtained at ÅA with the ÅA1 and ÅA2 routes up to 2017 ⁸ also introduces also the use of membrane separation methods, as outlined below.

Following the proof-of-concept work for the ÅA1 and ÅA2 routes, focus on the recovery of AS salt resulted in assessments based around membrane separations and electrodialysis, as recently summarised in the doctoral thesis by Koivisto ⁹:

- The aqueous solution containing dissolved sulfates of Mg, Fe and contaminants, after removal of unreacted rock and silica, contains a significant amount of dissolved ammonium bisulfate, ABS. This derives from decomposition of the excess AS (typically 15-20% depending on rock iron content) in the kiln, giving ABS and ammonia vapour. Separating HSO₄⁻ from SO₄²⁻, an ABS stream can be removed and returned to the furnace for Mg extraction¹⁰.
- The aqueous solution after carbonation of MgSO₄ with added NH₃ and CO₂-containing gas is an alkaline solution containing mainly AS. This can be processed using bipolar membrane electrodialysis (BMED) into three streams 1) more concentrated AS, facilitating water removal, 2) water and 3) an NH₄OH solution ¹¹.
- A conventional use of BMED for an aqueous AS solution would give sulphuric acid H₂SO₄ and an NH₄OH solution as products. The first can be mixed with AS to give an ABS / AS mixture.

As an outcome, a third, ÅA3 route was designed as schematically shown in Figure 3. It includes optional reverse osmosis (RO) membrane (pre-) separation for the removal of water from the process flows.



Figure 3: The third ÅA route, route ÅA3, based on "dry" extraction of magnesium and "wet" carbonation, improved with membrane separation methods

The above considerations led to work on extraction of Mg from serpentinite in an aqueous solution (at ambient or near ambient temperatures) containing a mixture of ABS and AS ¹². Thus, in parallel with the above ÅA3 route a fourth ÅA4 route was suggested as shown in Figure 4.



Figure 4: The fourth ÅA route, route ÅA4, based on "wet" extraction of magnesium and "wet" carbonation, improved with membrane separation methods

This relies fully on BMED to produce the sulfuric acid for producing the ABS to be used with AS for Mg extraction using aqueous solutions, and the NH₄OH solution for raising the pH for the MgSO₄ solution in which the carbonation shall take place with the CO₂-containing gas.

As noted, the PFB carbonation reactor as part of the first ÅA route may not produce sufficient heat for primarily the extraction of Mg from serpentinite at 400-450°C. A special case, though, occurs if high CO_2 concentrations in the gas to be processed would motivate the use of a PFB carbonation reactor. Then membrane-based technologies and considerations given above can be combined with the use of a PFB carbonator. This gives the most recent (2020) fifth ÅA4 process route as depicted in Figure 5.



Figure 5: The fifth ÅA route, route ÅA5, based on "wet" extraction of magnesium and "dry" carbonation, improved with membrane separation methods

More detail, including a discussion on which ÅA route if preferable for given CO_2 emission process characteristics is given elsewhere ¹³.

While the ÅA1 and ÅA5 routes give magnesite as the carbonate product, the ÅA2, ÅA3 and ÅA4 routes give nesquehonite. One application developed and tested at ÅA, presented this year in the doctoral thesis of Erlund ¹⁴ is the use of magnesium carbonate hydrate (MCH) for seasonal or diurnal TES (thermal energy storage). This suits the temperature range 0 - 60 °C based on the chemical conversion MgCO₃·3H₂O (s) + 1 MJ/kg heat $\leftarrow \rightarrow$ MgCO₃(s) + 3H₂O(g). Silica gel mixed with the MCH can absorb/ desorb the water vapour during the heat storage/discharge stages.¹⁵

The maturity of all ÅA routes is still low (TRL = 5), not having been tested outside the laboratory. However, current work involves taking at least one of the selected routes to an industrial-scale setting.

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