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Analysis of the potential for negative CO_2 emission mine sites through bacteria-mediated carbon mineralisation: Evidence from Australia

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Abstract

Carbon mineralisation has the potential to sequester and safely store large amounts of carbon dioxide (CO_2). However, this technology has not seen the same level of development as geological storage in sedimentary reservoirs. This is primarily because early work on carbonation of minerals focused on high temperature and pressure process routes, which are cost-prohibitive to accelerate the reaction from geological to industrial time scales. Bacteria-mediated carbon mineralisation of mine tailings [1] overcomes this impediment because it occurs at ambient temperature and standard pressure and the rock is already crushed. With abundant mafic and ultramafic rock, a highly developed mining sector, and a warm climate that promotes fast carbonation reactions, Australia presents an optimal region to develop this technology. We assess the mineralisation potential of Australia's existing and future nickel mine tailings and estimate that this carbon sink could sequester up to 2,171 Megatons (Mt) of CO_2.

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1. Introduction

Over the last several decades, there has been growing concern that the increased concentration of carbon dioxide (CO_2) in the atmosphere may have detrimental effects on the environment and the economy [2,3]. In 1958, geochemist Charles David Keeling began to record measurements of the carbon dioxide concentration at the Mauna Loa Observatory, Hawaii. Yearly average concentration levels on the 'Keeling curve' have since risen sharply from 315 parts per million (ppm) in 1958 to averaging 402.24 ppm in August 2016 [4]. The level of 400 ppm has been considered to be a critical barrier for taking action to mitigate anthropogenic climate change. In 2015, the 21st yearly session of the Conference of the Parties (COP21) in Paris produced an agreement to reduce greenhouse gas emissions and keep the global average increase in surface temperature from climbing over 2°C, as compared to pre-industrial levels. This agreement was ratified by more than 190 countries [5].

Prior to COP21, participating countries were invited to initiate or intensify the domestic preparation of their respective Intended Nationally Determined Contributions (INDCs). The INDCs entail each country's specific emission reduction goals, describing how those will contribute to achieving the objectives of the then upcoming COP21 meeting in Paris [6]. The Australian Government submitted their INDCs in August 2015 with targets covering all facets of the economy and committed to reduce greenhouse gases (GHGs) by 26-28 % by 2030, relative to 2005 levels [7]. Australia faces an especially challenging undertaking because the emissions reductions must not impeed the expected growth in the economy of more than 2 % per annum, as outlined in the *'Pathways to Deep Decarbonisation in 2050'* report [8].

This report is part of the global *Deep Decarbonization Pathways Project* (DDDP), which outlines how countries can decarbonize their economies. Among the proposed pathways for Australia, one of the key technologies identified is carbon capture and storage (CCS). In said report, CCS is foremost described as the process of capturing CO_2 at point sources (e.g., power plants), transporting it and finally injecting it into an appropriate rock formation that is suitable for the long-term geological (stratigraphic) storage of CO_2 [8]. The *Novel CO_2 Capture Task Force Report* [9] provides details about how CO_2 in Australia could be temporarily and permanently absorbed and stored to meet the nation's decarbonisation goals. In addition to the 'traditional' CCS methods, this report also mentions a role for mineral carbonation.

The Australian Novel CO_2 Capture Taskforce states that passive or accelerated carbon mineralisation technology (carbon geosequestration) may *'genuinely and permanently sequester the necessary quantities of CO_2 for centuries'* [9]. Carbon mineralisation involves a naturally occurring reaction of CO_2 with magnesium- and calcium-containing rocks (mafic and ultramafic rocks) to form carbonate minerals (similar to chalk) which are composed of calcium carbonate, thereby storing CO_2 in a stable and benign form [9]. The energy economics to accelerate the slow rate of passive carbonation reactions present a serious obstacle [10], resulting in the methods being unequivocally dismissed in various reports [8,9] as a viable means to contribute to the decarbonisation of the Australian economy. However, a developing technology that uses naturally occurring soil bacteria (Cyanobacteria) to induce the carbon mineralisation process without the need of external energy sources, overcomes many of these obstacles [11].

Utilizing mineral waste from ultramafic mine sites for carbon mineralisation has been documented previously [12-15]. However, when estimating the CO_2 mineralisation rates, generally small sample sets have been used. More recently, complementary laboratory experiments and reactive transport modeling have been deployed to investigate and quantify the carbonation rate in mine tailings [16].

Although these strategies have proven effective in laboratory-scale studies, [1] pilot projects are necessary to evaluate strategies for accelerating carbon mineralisation, which if successful and cost effective could be incorporated into tailings storage facility design with the purpose of sequestering CO_2.

Power et al. (2014) discuss these strategies and propose two scenarios for pilot projects, which if implemented at the mine-scale could render some mining operations carbon-neutral. They also provide estimates of the operational costs of the proposed scenarios on a dollar per tonne of CO_2 basis to assess the economic feasibility of carbon mineralisation strategies [1].

In this paper, we assess the potential of the biological carbon mineralisation process described by Power et al. [1] to sequester CO_2 across Australia. The area of focus is on a subsample of Australian nickel mines, which present optimal geological preconditions as a mineral feedstock (mafic and ultramafic host rock). We first estimate the total

sequestration potential of a subset of mines based on their past production. Next, we extrapolate these results to the entire population of Australian nickel mines. After adjusting for differences in carbon mineralisation rates by ultramafic/mafic rock source, we estimate the Australia-wide carbonation potential based on existing nickel mines, though platinum group metals, chrysotile asbestos, diamond, chromite, and talc mines can also enhance carbon mineralisation. Finally, we will estimate potential CO_2 sequestration, based on past production and known Australian reserves. The key questions that are dealt with in this paper are the following:

- What is the total available mafic and ultramafic mineral feedstock from both past and future mine production?
- What is the potential of bacterially mediated carbon mineralisation to sequester CO_2 across nickel and other ultra-mafic/mafic mines in Australia?
- What is the yearly uptake potential of carbon dioxide through bacterially mediated carbon mineralisation?

2. Methods

2.1. Study area: mafic and ultramafic nickel mine sites

Using Geoscience Australia's Archean, *i.e.,* mafic and ultramafic magmatic, events map (Figure 1), the
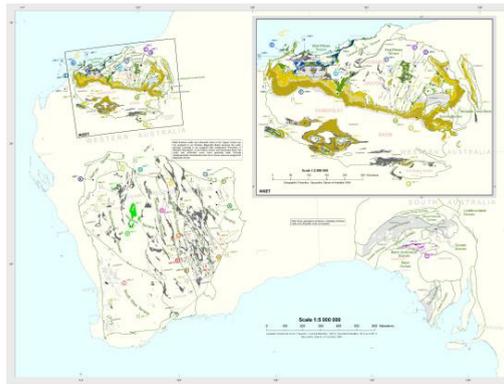

Figure 1. Map of Australia's Archean mafic and ultramafic magmatic events [18]

continental scale of carbon mineralization that could be realized from events producing rock units that cover 100's of km^2 can be appreciated. For example, a single rock unit 20 km^2 by 50 m in depth would hold in excess of 10^{10} metric tons of ultramafic rock that could sequester 1 Gt of carbon (Table 1, Reactions 1 - 5).

Table 1. Chemical reactions [17]

Silicate weathering: $Mg_3Si_2O_5(OH)_4 + 3\ H_2SO_4 \rightarrow 3\ Mg^{2+} + 2\ Si(OH)_4 + H_2O + 3\ SO_4^{2-}$	(1)
Carbon Mineralisation: $5\ Mg^{2+} + 4\ CO_3^{2-} + 2\ OH^- + 5\ H_2O \rightarrow Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$	(2)
Photosynthesis: $HCO_3^- + H_2O \rightarrow CH_2O + O_2 + OH^-$	(3)
Carbon dioxide equilibrium with water: $CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$	(4)
Carbonate ion formation: $HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$	(5)

Ultramafic rock typically contains a high percentage (up to 50 %, by weight) of magnesium oxide. Ophiolite belts, which are comprised of an abundance of magnesium as serpentine [$Mg_3Si_2O_5(OH)_4$], olivine (Mg_2SiO_4) and brucite [$Mg(OH)_2$] represent the best feedstock for carbon mineralisation [19]. Mafic and ultramafic mine sites are a valuable feedstock for carbon mineralisation and there is potential to be used to offset CO_2 emissions that are generated by the mining industry. It has been documented that passive carbonation is already occurring at various mine sites (for example, Mount Keith, Australia, Clinton Creek, Canada and Diavik, Canada) [1]; however, the potential remains largely untapped.

Currently, we do not know the amount of mine tailings that are generated annually from the production of nickel, platinum group elements, chrysotile asbestos, diamond, chromite and talc. However, data for individual ore deposits is available; for instance, the nickel mine at Mount Keith in Western Australia produces approximately 11 Mt of tailings each year. The complete carbonation of the tailings could sequester approximately 4 Mt of CO_2 every year, which represents 10 times the annual emissions of Mount Keith [1]. Although passive carbonation is ongoing at the Mount Keith mine site, and accounts for roughly 11% of total GHG emissions per annum, the core potential remains untapped [20].

2.2. Focus: Nickel mine sites

Nickel mines are the area of concentration in this paper, as they present optimal feedstock (mafic and ultramafic rocks) and both active and abandoned sites can be found in large numbers across Australia. As of September 2016, the Australian Mine Atlas lists 129 mines (historic, operational, planned) as well as 207 deposits containing nickel [21]. Australia is one of the largest nickel producers in the world with a production of 246 kt and holds approximately one quarter of the world's estimated economic nickel resources, which equated to 81 Mt in 2014 [22].

Nickel can commonly be found in two main ore types: sulfide and laterite ores. Sulfide often includes copper and/or cobalt and sometimes also precious metals such as gold, platinum or palladium (PGMs). Laterite ores are formed near Earth's surface after extensive weathering and occur near the equator or in arid regions such as southern Africa or Western Australia [23]. In the past, most nickel production was derived from sulfide ores, due to lower cost and less complex processing requirements compared to laterite ores. In terms of resources, however, approximately 60% of Ni reserves are found in laterites whereas 40% are contained in sulfide-bearing ore [23].

2.3. Approach

The approach for estimating sequestration potential starts with an assessment of past nickel ore production across some of the largest mine sites in Australia (Figure 2).
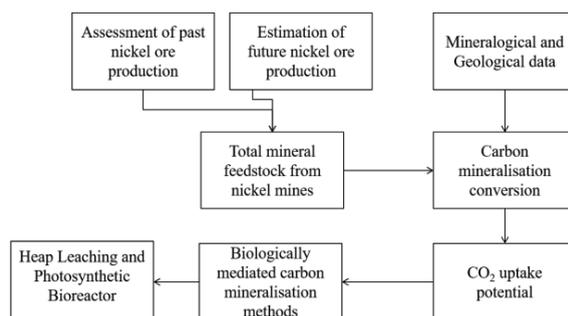

Figure 2. Outline of the process leading to the calculation of the CO_2 sequestration potential of nickel mines across Australia; heap leaching and photosynthetic bioreactor

The list has been composed with the aid of the detailed research report about the sustainability of mining in Australia [23]. The mineralogical and geological data have been assessed in detail, in order to determine the potential for biologically mediated carbon mineralisation. Total mineral feedstock values from the sample dataset were extended to include the remainder of Australia's nickel production. It includes estimates of future production of nickel ores; both for the selected mine sites as well as the remainder of Australia's nickel production. Since estimates of future potential are based on less precise estimates of mineralogy and geology, we have elected to select the more conservative estimates to avoid overstating the carbon mineralisation potential.

The carbon mineralisation conversion table (Table 2) translates the mineral feedstock into sequestration potential of carbon dioxide within various magnesium carbonate minerals. It lists various mafic and ultramafic minerals that yield differing feedstock-to-product ratios. For example, brucite, which is a highly reactive mineral, can sequester

one ton of CO_2 for every 1.33 ton of mineral feedstock if the mineral product has a CO_2:MgO ratio of 1:1. Contrastingly, production of artinite and pokrovskite, which have lower CO_2:MgO ratios, would require carbonation of 2.65 tons of brucite to sequester one ton of CO_2 (Table 2).

Table 2. Carbon mineralisation conversion table [reproduced from 24]

Mineral/ Formula	CO_2:MgO Ratio	Serpentine $Mg_3Si_2O_5(OH)_4$	Brucite $Mg(OH)_2$	Forsterite Mg_2SiO_4	Diopside $CaMgSi_2O_6$	Enstatite $Mg_2Si_2O_6$
Magnesite, $MgCO_3$	1:1	2.10	1.33	1.60	2.46	2.28
Hydromagnesite, $(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Dypingite, $Mg_5(CO_3)_4(OH)_2 \cdot {\sim}5H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Pokrovskite, $Mg_2(CO_3)(OH)_2$	1:2	4.20	2.65	3.20	3.28	4.56
Artinite, $Mg_2(CO_3)(OH)_2 \cdot 3H_2O$	1:2	4.20	2.65	3.20	3.28	4.56
Nesquehonite, $MgCO_3 \cdot 3H_2O$	1:1	2.10	1.33	1.60	2.46	2.28
Lansfordite, $MgCO_3 \cdot 5H_2O$	1:1	2.10	1.33	1.60	2.46	2.28

Combining the conversion table with the previously identified mineral feedstock for both past and future production will then give a range of the amount of CO_2 that could potentially be sequestered across Australia's nickel mine sites. The last step will look into methods for absorbing the estimated amounts of CO_2 utilizing heap-leaching and a photosynthetic bioreactor to accelerate carbon mineralisation.

2.4. Ultramafic feedstock from nickel mines: estimations

The first element for determining the CO_2 sequestration potential is the past production of nickel at various mine sites across the country. Based on data from Mudd [23] with regards to nickel mines in Australia, key mine sites have been selected. The data from these selected mine sites have been enriched with publicly available information from the peer-reviewed literature as well as company annocements [25-40]. In a second step, the remainder ore from Australian nickel production (past and future) was estimated.

Table 3 lists nickel sulfide mines and nickel laterite mines separately. While nickel production from sulfide mines has made up the vast majority of past production, laterite mines have approximately double the reserves compared to sulfide mines. Therefore, our calculations predict that nickel from lateritic mines will make up the majority of future Australian nickel production [23].

The selected sulfide and laterite nickel mines comprise of a total of 23 mine sites, most of which are found in Western Australia. This list represents some of the largest and most important nickel mines in Australia that have adequate mineralogical and geological data available to estimate sequestration potentials. These mine sites have produced 3,812 kt of nickel and approximately 372 Mt of ore. The estimated reserves of the selected mine sites equate to 23,316 kt of nickel, which translates into 3,202 Mt of nickel ore.

The lower half of Table 3 lists past nickel production for the remainder of Australian mine sites, which totals 3,347 kt of nickel (as per 2015) and an estimated ore production of 438 Mt. Furthermore, Geoscience Australia has estimated the Economic Demonstrated Reserves (EDR) of nickel to be 19,000 kt, whereas the Subeconomic Demonstrated Reserves (SDR) are estimated to be 4,000 kt [41]. These are Economic Demonstrated Resources (EDR) measures that are established and either analytically demonstrated, or can be assumed with a reasonable certainty that extraction would be profitable under predefined investment assumptions. Subeconomic Demonstrated Resources (SDR) is comparable to EDR regarding certainty of occurrence. However, financial viability of SDR might only be reflected in the future [41]. Since the 'Selected nickel mines' section covers the main nickel projects in Australia, the EDR and SDR are considered to be included therein and will not be additionally listed as mining and sequestration potential. Only the Inferred Resources (IR) are listed separately, as they present resources for which quantitative estimates are based on a broad knowledge of the geological character of the deposit. Therefore, there are either none or only few samples or measurements [42]. It is assumed for the purpose of this paper that the nickel concentration for the inferred resources is 0.5 %, which is lower than past production as concentration is declining over time [23].

Table 3. Production and reserves of mafic and ultramafic feedstock from nickel mines

	Past nickel production (kt nickel)	Ø Nickel concentration (%)	Past ore production (Mt ore)	Total Reserves (kt nickel)	Ø Nickel concentration (%)	Total Reserves (Mt ore)
Selected nickel mines						
Nickel sulfide mines	3,434	1.02	336	8,271	0.67	1,210
Nickel laterite mines	378	1.06	36	15,189	0.76	1,992
Total selected mines	**3,812**	**1.02**	**372**	**23,316**	**0.73**	**3,202**
Remainder of Australia						
1967 – 2007 (Mudd)	1,857	0.76[*]	243			
2008 – 2015 (OCE)	1,490	0.76[*]	195			
Economic Demonstrated Resources (Included in 'Selected nickel mines')				19,000		
Subeconomic Demonstrated Resources (Included in 'Selected nickel mines')				4,000		
Inferred Resources				17,800	0.50[*]	3,560
Total remainder of Australia	**3,347**		**438**	**17,800**	**0.50**	**3,560**
Total Australia	**7,159**		**810**	**41,116**		**6,762**

* assumed concentration

2.5. Carbon sequestration potential

The geologic setting, production rates, reserves and mineralogy of key Australian sulfidic and laterite-hosted nickel mines (23 locations across Australia) are quite well defined. Therefore, the sequestration potential for past production as well as the reserves for these sites could be estimated using publicly available data. Where mineralogical data were not available, the information for a 'typical' mine type (based on the existing sulfide and laterite mine data) was applied.

The estimated mafic and ultramafic feedstock established in Table 3 will serve as a base for the calculations of carbon sequestration potential. The uptake potential is dependent on the subtype of feedstock (Table 2). In order to estimate the carbon sequestration potential from nickel mining, the mafic and ultramafic feedstock established in Table 3 were used to calculate the carbonation yields, using the conversion factors provided by Power et al., ([24]; see Table 2), which range from 1.66 tons (for brucite) to 2.85 tons (for enstatite) to fix one ton of CO_2 as dypingite or hydromagnesite, which commonly form in Australian mine tailings (e.g., [16]). This project focuses on dypingite and hydromagnesite as target carbonates because they are more stable than lansfordite or nesquehonite, and their formation can be bacterially mediated [10,14,43].

For the remainder of Australia, both past production and reserves, the mineralogical setting has yet to be defined. Therefore, a mix of the aforementioned profiles (sulfide and laterite) was assumed. The ratios applied for the *'Remainder of Australia'* section are 0.9 sulfide to 0.1 laterite (for past production) and 0.3 sulfide to 0.7 laterite (for estimated reserves of the inferred resources). This was adjusted for the fact that future production of nickel will likely stem predominantly from laterite mine sites, as there is a greater abundance of these resources to be exploited [23]. The CO_2 sequestration capacity assumes complete carbonation of the mineral feedstock.

A total of 2,171 Mt of CO_2 could be sequestered considering past production and future production of both the selected mine sites as well as the inferred resources. Nickel sulfide mine sites make up the largest portion of the sequestration potential from past production of the selected mine sites, with approximately 111 Mt of CO_2, while lateritic mine sites hold a potential of 12 Mt of CO_2. An additional 148 Mt of CO_2 could be sequestered from the past production of the remainder of Australia's nickel mines, totaling at 271 Mt of CO_2. The past to future production sequestration ratio is 1:7, with 271 to 1,900 Mt of CO_2.

Table 4. CO_2 sequestration potential from nickel mines feedstock

	Past ore production	Total Reserves	Sequestration from past production	Sequestration from future production
	(Mt ore)	(Mt ore)	(Mt CO_2)	(Mt CO_2)
Selected sulfide and laterite nickel mines				
Nickel sulfide mines	336	1,210	111	421
Nickel laterite mines	36	1,992	12	492
Total selected mines	**372**	**3,202**	**123**	**913**
Remainder of Australia				
1967 – 2007 (Mudd)	243		82	
2008 – 2015 (OCE)	195		66	
Inferred Resources (IR)		3,560		
Total remainder of Australia	**438**	**3,560**	**148**	**987**
Sequestration (Mt CO_2)			**271**	**1,900**
Total sequestration (Mt CO_2)				**2,171**

2.6. Annual CO_2 uptake estimations

A direct biotechnological approach to carbon mineralisation could be devised at mine sites by combining heap leaching, which has been used for centuries to extract metals from sulfidic low-grade ore and a photosynthetic bioreactor [1,44]. Briefly, this could be done by placing the ore on a liner and inoculating with acid generating bacteria and nutrients. Sulfidic material provides ideal conditions for acid-generating microbes, such as *Acidithiobacillus spp.* that accelerate the generation of sulfuric acid for mineral dissolution and metal leaching [1,44]. For example, leaching 7500 tons of ultramafic mine tailings, could release enough magnesium to sequester approximately 2,800 tons of CO_2 per year, in a 0.12 km^2 photosynthetic bioreactor.

3. Results

Leading up to the COP21 in Paris as of November 2015, the Australian government had pledged to reduce its overall GHGs by 26 to 28 % in 2030 compared to 2005 levels [7]. As of 2014, Australia emitted a total of approximately 523 Mt of CO_2 equivalent gases (CO_2e), whereas 2005 emissions amounted to 519 Mt of CO_2e [45]. Therefore, in order to reach its pledge, the annual CO_2e would have to be reduced to 376 CO_2e, which represents a reduction of approximately 150 Mt (or 28 %) of CO_2e by 2030. Assuming linearity, an average additional reduction of approximately 11 Mt of CO_2e per annum would have to occur over the following 14 years in order to reach the goals stated at the COP21. In other words, a total amount of roughly 1,115 Mt of CO_2 would need to be reduced in total from 2016 to 2030.

While the Australian government will be working on a suite of solutions in order to achieve the pledged goals, bacterially mediated carbon mineralisation could be a substantial contributor. Based on the current data for Australia there is potential for sequestering more than 2,000 Mt of CO_2 utilizing past and future feedstock. If bioreactors were used to accelerate this bacteria-mediated mineralisation process to full potential by 2030, this would result in more than 10x the required reductions.

4. Discussion

Carbon mineralisation has been identified by the Australian Novel CO_2 Capture Task Force Report as being one of few technologies that have the potential to sequester and safely store large amounts of CO_2 for centuries. Australia

is an optimal region for further developing this technology due to the abundance of mafic/ultramafic rock and mineral waste that is rich in magnesium [9].

Using mine waste as a feedstock possesses several additional benefits. First, as the rocks are crushed and ground, their high reactive surface area presents an optimal material for carbon mineralisation reactions. Furthermore, they provide an incentive for mining companies to market their reduced carbon footprint.

To accelerate the rate of naturally-occurring carbon mineralisation, most processes rely on very high pressure and temperature and the process costs associated with these increased reaction kinetics have rendered these processes economically unviable. Bacteria-mediated carbon mineralisation overcomes eliminates the need for much of the energy required to generate the high pressures and temperatures required to mediate the reaction.

Although this study demonstrates how bacterially-mediated carbon mineralisation of mine tailings has the potential to overcome the previous energy economics objections, this study has not demonstrated its economic viability, especially given the current price of carbon. Economists concur that carbon is currently undervalued [46]; while the 'social cost of carbon' is estimated at USD 200 according to Pindycks [46], there are dozens of different market prices in the form of national carbon floors or cap and trade systems with a proliferation of announcements in 2016 from both emerging and developed countries. Ernst and Young [47] predict that beginning in 2020, companies are likely to be "carbon constrained in all the major emitting and emerging countries" and expect a global carbon market to appear. A global carbon market will remove much of the uncertainty in the benefits of the process. Future and ongoing work strives to integrate the costs associated with these processes.

Acknowledgements

References

[1] Power I, McCutcheon J, Harrison A, Wilson S, Dipple G, Kelly S, Southam C, Southam G. Strategizing carbon-neutral mines: A case for pilot projects. Minerals 2014; 2:399-436.

[2] Linnenluecke M, Smith T, McKnight B. Environmental finance: A research agenda for interdisciplinary finance research. Economic Modelling 2016; 59:124-130.

[3] Winn MI, Kirchgeorg M. The siesta is over: A rude awakening from sustainability myopia. New perspective in research in corporate sustainability 2005; 3:232-258.

[4] Scripps Institute of Oceanography. The Keeling curve. https://scripps.ucsd.edu/programs/keelingcurve/. 2016.

[5] Adoption of the Paris agreement. United Nations Office at Geneva. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Geneva; 2015.

[6] Intended Nationally Determined Contributions (INDCs). Adoption of the Paris agreement. United Nations Framework Convention on Climate Change. http://unfccc.int/focus/indc_portal/items/8766.php. 2015.

[7] Australia's Intended Nationally Determined Contribution to a new Climate Change Agreement. Australian Government. http://www4.unfccc.int/submissions/INDC/Published%20Documents/Australia/1/Australias%20Intended%20Nationally%20Determined%20 Contribution%20to%20a%20new%20Climate%20Change%20Agreement%20-%20August%202015.pdf. 2015.

[8] Denis A, Jotzo F, Ferraro S, Jones A, Kautto N, Kelly R, Skarbek A, Thwaites J. Pathways to Deep Decarbonisation in 2050 - Initial Project Report. Melbourne: Climateworks Australia; 2014.

[9] Burgess J, Jeffery L, Lowe A, Schuck S, Flentje W. Novel CO_2 capture task force report. Docklands: Global CCS Institute; 2011.

[10] Zevenhoven R, Fagerlund J, Songok JK. CO_2 mineral sequestration: developments toward large-scale application. Greenhouse Gases: Science and Technology 2011; 1:48-57.

[11] Power I, Wilson SA, Thom J, Dipple GM, Gabites J, Southam G. The hydromagnesite playas of Atlin, British Columbia, Canada: A biogeochemical model for CO_2 sequestration. Chemical Geology 2009; 260:286-300.

[12] Beinlich A, Austrheim H. In situ sequestration of atmospheric CO_2 at low temperature and surface cracking of serpentinized peridotite in mine shafts. Chemical Geology 2012; 332-333:32-44.

[13] Wilson SA, Raudsepp M, Dipple GM. Verifying and quantifying carbon fixation in minerals from serpentine-rich mine tailings using the Rietveld method with X-ray powder diffraction data. American Mineralogist 2006; 91:1331-1341.

[14] Pronost J, Beaudoin G, Tremblay J, Larachi F, Duchesne J, Hébert R, Constantin M. Carbon sequestration kinetic and storage capacity of ultramafic mining waste. Environmental Science & Technology 2011; 45:9413-9420.

[15] Power I, Wilson SA, Thom J, Dipple G, Southam G. Biologically induced mineralization of dypingite by cyanobacteria from an alkaline wetland near Atlin, British Columbia, Canada. Geochemical Transactions 2007; 8:1-16.

[16] Wilson SA, Harrison AL, Dipple GM, Power IM, Barker SLL, Ulrich Mayer K, Fallon SJ, Raudsepp M, Southam G. Offsetting of CO_2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining. International Journal of Greenhouse Gas Control 2014; 25:121-140.

[17] McCutcheon J, Wilson SA, Southam G. Microbially accelerated carbonate mineral precipitation as a strategy for in situ carbon sequestration and rehabilitation of asbestos mine sites. Environmental Science & Technology 2016; 50:1419-1428.

[18] Hoatson DM, Jaireth S, Whitaker AJ, Champion DC, Claoué-Long JC. Australian Archean Mafic-Ultramafic Magmatic Events, Sheet 1 of 2 (1:5 000 000 scale map). Canberra: Geoscience Australia; 2009.

[19] Metz B, Davidson O, De Coninck H, Loos M, Meyer L. IPCC special report on carbon dioxide capture and storage. New York: Cambridge University Press; 2005.

[20] WMC Resources Ltd.. Annual Sustainability report 2004. Melbourne; 2005.

[21] Australian Mines Atlas. Geoscience Australia. http://www.australianminesatlas.gov.au/. 2016.

[22] Nickel. Geoscience Australia. http://www.ga.gov.au/scientific-topics/minerals/mineral-resources/nickel#heading-3. 2014.

[23] Mudd GM. Nickel sulfide versus laterite: The hard sustainability challenge remains. Proc. "48th Annual Conference of Metallurgists" 2009.

[24] Power I, Harrison A, Dipple G, Wilson S, Kelemen P, Hitch M, Southam G. Carbon mineralization: From natural analogues to engineered systems. Reviews in Mineralogy & Geochemistry 2013; 77:305-360.

[25] Genesis of Kambalda Nickel Deposits. Mincor Resources NL. http://www.mincor.com.au/kambalda_nickel_operations/genesis_of_kambalda_nickel_deposits.phtml/. 2016.

[26] Six Mile Ni deposit, Yakabindie Station. Mineral Database. http://www.mindat.org/locdetailed-122762.html/. 2016.

[27] Keays RR, Jowitt SM. The Avebury Ni deposit, Tasmania: A case study of an unconventional nickel deposit. Ore Geology Reviews 2013; 52:4-17.

[28] Barnes SJ. Cotectic precipitation of olivine and sulfide liquid from komatiite magma and the origin of komatiite hosted disseminated nickel sulfide mineralisation at Mt Keith and Yakabindie Western Australia. Economic Geology 2007; 102:299-304.

[29] Mason R, Hodkiewicz P, Barrett D, Buerger R. Structural geology of the Emily Ann Nickel Deposit and implications for the mining process. Fifth International Mining Geology Conference 2003.

[30] Hoaston DM, Blake DH. Geochronology of the mafic-ultramafic intrusions. Australian Geological Survey Organisation 2000; 246:163-172.

[31] Black Swan Geology. Poseidon Nickel Ltd.. http://poseidon-nickel.com.au/black-swan/black-swan-geology/. 2015.

[32] Standing JG. Structural Geology in unfamiliar terrane; Controls on laterite-hosted nickel mineralisation at Ravensthorpe, W.A. Structural Geology and Resources 2012; 56:155-158.

[33] Frick LR, Lambert DD, Hoatson DM. Re-Os dating of the Radio Hill Ni-Cu deposit, west Pilbara Craton, Western Australia. Structural Australian Journal of Earth Sciences 2001; 48:43-47.

[34] Hoatson DM, Wallace DA, Sun SS, Macias LF, Simpson CJ, Keays RR. Petrology and platinum-group-element geochemistry of Archaean layered mafic-ultramafic intrusions, west Pilbara Block, Western Australia. AGSO Bulletin 1992; 242:319.

[35] Cawse Extended - Geology. TNG Limited. http://www.tngltd.com.au/projects/jv_projects_cu_au_ni/cawse_extended_geology.phtml/. 2008.

[36] Syerston Scandium Feasibility Study Update. CleanTeQ Holdings Limited. http://cdn.ceo.ca.s3-us-west-2.amazonaws.com/1b965k3-1515124.pdf/. 2016.

[37] Elias M, Donaldson MJ, Giorgetta NE. Geology, mineralogy, and chemistry of lateritic nickel-cobalt deposits near Kalgoorlie, Western Australia. Economic Geology 1981; 76:1775-1783.

[38] Resources and Energy Quarterly. Australian Government. http://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Resources-and-energy-quarterly.aspx/ . 2014.

[39] Fiorentini M, Beresford S, Barley M, Duuring P, Bekker A, Rosengren N, Cas R, Hronsky J. District to camp controls on the genesis of komatiite-hosted nickel sulfide deposits, Agnew-Wiluna Greenstone Belt, Western Australia: Insights from the multiple sulfur isotopes. Economic Geology 2012; 107:781-796.

[40] Clayton W, Stott H, Mazzuchelli RH. Maggie Hays nickel mineralization, Lake Johnson district, Western Australia. CRC Leme 2005; 2:1-3.

[41] Year Book Australia 2012. Australian Bureau of Statistics. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1301.0~2012~Main%20Features~Mineral,%20oil%20and%20gas%20resources~151. 2012.

[42] National Classification System for Identified Mineral Resources. Geoscience Australia. http://www.australianminesatlas.gov.au/aimr/class.html. 2015.

[43] Power I, Wilson S, Small DP, Dipple GM, Wan W, Southam G. Microbially mediated mineral carbonation: Roles of phototrophy and heterotrophy. Environmental Science & Technology 2011; 45:9061-9068.

[44] Power IM, Dipple GM, Southam G. Bioleaching of ultramafic tailings by *Acidithiobacillus* spp. for CO_2 sequestration. Environ. Sci. Technol. 2010; 44:456-462.

[45] National Greenhouse Gas Inventory. Australian Government. http://ageis.climatechange.gov.au/Chart_KP.aspx?OD_ID=61556544518&TypeID=2. 2014.

[46] Pindyck RS. Pricing carbon when we don't know the right price: Despite the unknowns, we should begin to tax carbon. Regulation 2013; 36:43-46.

[47] The future of global carbon markets: Key findings. Ernst & Young Global Limited. http://www.ey.com/gl/en/services/specialty-services/climate-change-and-sustainability-services/the-future-of-global-carbon-markets_key-findings/. 2013.