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Potential for offsetting diamond mine carbon emissions through mineral carbonation of processed kimberlite: an assessment of De Beers mine sites in South Africa and Canada

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Abstract

De Beers kimberlite mine operations in South Africa (Venetia and Voorspoed) and Canada (Gahcho Kué, Victor, and Snap Lake) have the potential to sequester carbon dioxide (CO₂) through weathering of kimberlite mine tailings, which can store carbon in secondary carbonate minerals (mineral carbonation). Carbonation of ca. 4.7 to 24.0 wt% (average = 13.8 wt%) of annual processed kimberlite production could offset 100% of each mine site's carbon dioxide equivalent (CO₂e) emissions. Minerals of particular interest for reactivity with atmospheric or waste CO₂ from energy production include serpentine minerals, olivine (forsterite), brucite, and smectite. The most abundant minerals, such as serpentine polymorphs, provide the bulk of the carbonation potential. However, the detection of minor amounts of highly reactive brucite in tailings from Victor, as well as the likely presence of brucite at Venetia, Gahcho Kué, and Snap Lake, is also important for the mineral carbonation potential of the mine sites.

Keywords Mineral carbonation · Carbon mineralization · Carbon sequestration · Carbonate · Kimberlite · Diamond mining

Introduction

There is enormous untapped potential for offsetting diamond mine carbon dioxide (CO_2) emissions through carbonation of processed kimberlite. Mineral carbonation, also referred to as carbon mineralization, is the storage of CO_2 in stable carbonate minerals (e.g. Power et al. 2013, 2014a, b and references

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therein). The formation of secondary carbonate alteration minerals, many of which form at low temperatures and pressures and sequester substantial quantities of atmospheric CO_2 , is a well-recognized pathway for storing carbon in mafic and ultramafic rocks, such as basalts, peridotites, and serpentinites (e.g. Hansen et al. 2005; Wilson et al. 2006, 2009a; Matter and Kelemen 2009; Power et al. 2014a, b). Limited studies have

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been conducted on kimberlites (e.g. Sader et al. 2007; Wilson et al. 2009b, 2011), but it is expected that atmospheric carbon is currently being, or could be, sequestered in these rocks through both natural (e.g. in situ alteration of kimberlite pipes) and artificially enhanced (e.g. accelerated carbonation rates in processed kimberlite) formation of secondary carbonates. Determining the origin(s) of carbonate minerals in kimberlite pipes and in processed kimberlite (e.g. primary magmatic and high temperature hydrothermal carbonates versus low temperature, secondary carbonates) is critical in order to understand the carbonation rates and enhanced carbonation potential of kimberlite. Furthermore, it is important to be able to trace the sources of incorporated carbon (i.e. atmospheric carbon versus recycled magmatic or bedrock carbon; Wilson et al. 2009a, 2011, 2014), in order to understand carbon cycling in kimberlites and ultimately to prove that atmospheric CO_2 is being sequestered. It is also important to conduct field work and mineralogical analyses to determine the silicate and hydroxide mineralogy of kimberlite as a step toward understanding the carbonation potential of various mine sites. This is particularly important because kimberlites are known to be heterogeneous in composition, both within a mine site (i.e. different rock facies) and between mine sites (e.g. Field et al. 2008).

Although on-going low temperature alteration reactions have been observed in kimberlite pipes (e.g. in the Attawapiskat region of Canada; Sader et al. 2007), and it is well recognized that processed kimberlite is highly suitable for carbon sequestration (e.g. the Carmex Project; Bodénan et al. 2014), only a handful of studies have previously investigated carbonation of processed kimberlite at specific diamond mines. These studies have focused on mining operations in the Canadian sub-Arctic, with detailed mineralogical, stable isotope, and radiocarbon work only having been carried out at Diavik (e.g. Wilson et al. 2009b, 2011) and detailed hydrogeochemical modelling only having been done at Ekati (Rollo and Jamieson 2006). Carbonation of processed kimberlite at Diavik is rapid: two orders of magnitude faster than the natural rate as measured in Artic and sub-Arctic river catchments (Wilson et al. 2011), even under unfavorable conditions (i.e. subaqueous storage in a cold climate). Deliberately accelerating carbonation of the processed kimberlite produced annually at Diavik has the potential to offset up to ten times the mine's carbon emissions (Wilson et al. 2011).

The De Beers Group of Companies operates a number of mines in South Africa and Canada (Figs. 1 and 2). The goal of this study is to summarize information on the mineralogical diversity of processed kimberlite from four mine sites: Venetia in South Africa and Gahcho Kué (a 51% joint venture with Mountain Province Diamonds), Victor, and Snap Lake in Canada. This study was conducted under the auspices of Project Minera, which is a De Beers initiative that is investigating the potential to offset diamond mine carbon emissions through mineral carbonation of processed kimberlite. Thus, here

we also describe the scope of Project Minera and report on preliminary calculations which indicate that there is potential to accelerate carbonation of processed kimberlite at De Beers mines in South Africa and Canada to achieve carbon offsets.

De Beers research and development – Project Minera

Project Minera, a research and development (R&D) initiative run by De Beers Group Services (Johannesburg) in collaboration with partners at De Beers mine sites, is currently investigating the potential to store large volumes of CO₂ at diamond mines through the mineralization of processed kimberlite. The project aims to accelerate carbon extraction from the atmosphere or point sources of CO₂, storing carbon in processed kimberlite at a speed that could offset anthropogenic carbon emissions, to deliver carbon-neutral mining at one or more De Beers operations. In a May 2017 press release, De Beers publically announced this R&D project and stated a goal of achieving a carbon-neutral mining operation within 5 to 10 years (https:// www.debeersgroup.com/en/news/company-news/companynews/de-beers-pioneers-research-programme-to-make-carbonneutral-mini.html). The R&D project is managed by an in house team of De Beers staff, who are working in collaboration with academics at universities and research institutions in Canada. Australia, the UK, the USA, and South Africa.

As shown in Fig. 3, De Beers envisions a five step approach to implementing mineral carbonation technologies at a diamond mine. Step 1 is to assess mine emissions, which De Beers does as part of environmental monitoring and reporting at its mine sites (e.g. De Beers Report to Society 2016, http://www. debeersgroup.com/en/building-forever/RTS2016.html). Step 2 is to assess passive (unintentional) carbon storage and additional storage potential in processed kimberlite at mine sites. The sample analysis presented in this study was obtained as part of this Step 2 assessment work, which is on-going. Step 3 is to implement technologies that can increase carbon storage in processed kimberlite in tailings storage facilities. Pilot work to assess various technologies that could potentially be employed at De Beers mine sites began in 2017 and will continue into 2018. Step 4 is to monitor carbon storage amounts over time. Finally, Step 5 is to rehabilitate tailings following normal procedures. The steps followed by De Beers align with the general approach (developed by academics, e.g. Power et al. 2013, 2014a, b and references therein) for assessing mineral carbonation (or carbon mineralization) at mine sites, which is shown in Fig. 4.

Field localities and sampling

Field work and sampling were conducted at Venetia Mine, Limpopo Province, South Africa, and Gahcho Kué Mine,



Northwest Territories, Canada, to begin assessing the CO_2 sequestration potential of processed kimberlite at these sites. Samples of kimberlite material were collected at the processing plants, fine processed kimberlite containments (Fig. 5), ore stockpiles, and coarse processed kimberlite impoundments. Samples were selected for the initial mineralogical analysis that is presented in this study. Recently deposited fine processed kimberlite from the tailings storage facilities at Victor and Snap Lake mines was sampled by De Beers staff.

Analytical methods

Powder X-ray Diffraction (XRD)

All samples were dried under ambient conditions for at least 24 h prior to being pulverised using a ring mill. Samples were then milled for 7 min under anhydrous ethanol using a McCrone Micronizing Mill. Following drying and disaggregation, micronized samples were prepared for analysis in back-loading cavity mounts and loaded against frosted glass to reduce the effects of preferred orientation. Samples from Venetia, which are particularly rich in smectite, were Ca-exchanged by agitation on a shaker table for 24 h while suspended in a solution of 1 M CaCl₂. Ca-exchanged samples were rinsed three times with MilliQ water to prevent formation of chloride salts as an artefact of this treatment during drying.

Samples from Venetia and Victor were analyzed in the Monash X-ray Platform at Monash University. XRD patterns for Venetia and Victor samples were collected using a Bruker D8 Advance Eco X-ray Diffractometer equipped with a LYNXEYE XE 1D Position Sensitive Detector. Data acquisition for Venetia samples was done using a long, fine-focus Co X-ray tube whereas data for Victor were collected using Cu radiation. Both tubes were operated at 40 kV and 25 mA. All patterns were collected over a 2θ range of $3-80^{\circ}$ with a step size of 0.02° /step and a dwell time of 1 s/step. Samples from Gahcho Kué and Snap Lake were analyzed in the Department of Earth, Ocean, and Atmospheric Sciences at The University of British Columbia. XRD patterns were collected using a Bruker D8



Fig. 2 Map showing De Beers mine sites in Canada





Focus X-ray Diffractometer equipped with a LYNXEYE 1D Position Sensitive Detector. The long, fine-focus Co X-ray tube was operated at 35 kV and 40 mA. Mineral identification from all patterns was performed using either DIFFRAC.EVA V.2 or V.4 (Bruker AXS) with reference to standard patterns from either the ICDD PDF-2 or PDF-4+ database.

Rietveld refinement approach

Quantitative phase analysis was done using two modified versions of the Rietveld method (Rietveld 1969; Hill and Howard 1987; Bish and Howard 1988). Rietveld refinement of powder

Fig. 5 Photographs of fine processed kimberlite at Venetia(a, b) and Gahcho Kué (c, d)

diffraction data typically requires that all phases within a given sample be highly crystalline and have well-known crystal structures (Bish and Howard 1988). Turbostratic disorder in clay minerals, such as the serpentine polymorphs and smectites (chiefly saponite) found in processed kimberlite, results in severe anisotropic peak broadening in powder XRD patterns. Peak profiles for disordered clay minerals must be modelled using alternative approaches to traditional Rietveld refinement.

Here, we have employed two such methods. Samples from Victor, which contain high abundances of serpentine minerals and low abundances of smectite, were analyzed using the method of Wilson et al. (2006). This method uses a Pawley phase



(Pawley 1981) for structureless pattern fitting of the serpentine peaks and the introduction of an internal standard so that the disordered phase can be treated as though it were amorphous for the purposes of quantification. An in-house fluorite (CaF_2) standard was added to each of the Victor and Snap Lake samples at an abundance of 10 wt% prior to micronizing.

Samples from Venetia and Gahcho Kué, which contain high abundances of both serpentine and smectite, were refined using the Poorly Ordered or No Known Crystal Structure (PONKCS) method (Scarlett and Madsen 2006). This method was also applied to one sample from Snap Lake; however, although smectite was present in this sample, it was not quantified owing to it being present at trace abundance. The PONKCS method allows for quantification of multiple disordered phases using structureless pattern fitting. PONKCS models were prepared from 50:50 wt% mixtures of (1) lizardite sourced from The University of British Columbia and NIST 676a α-Al₂O₃ and (2) Ca-exchanged SWy-2 obtained from Clay Minerals Society Source Clay Repository and NIST 676a α -Al₂O₃. Unit-cell parameters and space groups were obtained from Mellini and Viti (1994) for lizardite and Viani et al. (2002) for Ca-montmorillonite as a proxy for Ca-saponite. Peaks for these two clay phases were fitted using the Pawley method (Pawley 1981), without reference to atomic scattering information, to refine a calibrated mass, M, value for the unit cell of each phase.

Rietveld refinements for samples from all four mines were carried out with the program TOPAS v.5 (Bruker AXS) using the fundamental parameters approach (Cheary and Coelho 1992). Background functions were typically modelled using third-order Chebychev polynomials with an additional 1/*x* function. A default Brindley radius of 0.00025 mm and a packing density of 0.4 were used to correct for microabsorption contrast amongst all phases (Brindley 1945). A spherical harmonics correction (Järvinen 1993) was used to model anisotropic peak shape for lizardite and smectite during calibration of Pawley and PONKCS phases as well as during refinement of XRD patterns from De Beers samples.

The detection limit for most minerals was typically ~ 0.1 wt% for the XRD patterns used in this study. We have previously calibrated similar refinement procedures to synthetic samples of kimberlite mine tailings with known abundances of the minerals that are found in natural samples (Wilson et al. 2009b). This approach provides information about the magnitude of relative errors on refined mineral abundances. For mineralogically similar samples, relative errors on mineral abundances are typically 5–20% for minerals present at greater than 5 wt% abundance, with relative and absolute error generally decreasing for minerals present at higher abundance. Relative errors increase, and are in the range of 5–50%, for most common minerals found in

kimberlite when they are present between 1 and 5 wt% abundance. For minerals present at abundances <1 wt%, relative errors may increase further; however, the magnitude of absolute (wt%) errors are typically small.

BET surface area analysis

Surface areas of kimberlite residues were determined by multipoint Brunauer–Emmett–Teller (BET; Brunauer et al. 1938) with N_2 adsorption using a Quantachrome Autosorb-1 surface area analyzer at The University of British Columbia. This provides an estimate of the reactive surface area of a processed kimberlite sample.

Analytical results

Mineralogy and surface areas of processed kimberlite samples

Qualitative and quantitative mineralogical results for the four De Beers mines analyzed in this study are provided in Tables 1 and 2. Table 1 gives a general indication of the relative abundances of silicate, oxide, hydroxide, and carbonate minerals present in processed kimberlite from Venetia, Gahcho Kué, Victor, and Snap Lake mines in addition to those previously published by Wilson et al. (2009b) for Diavik. Rietveld refinement results highlight the mineralogical diversity of processed kimberlite (Table 2). This mineralogy depends on the original composition of a kimberlite facies, its alteration history following emplacement, and ultimately mineral processing, as well as the lithology of the surrounding country rock. Consequently, the mineralogy of processed kimberlite can vary substantially from one deposit to another and between facies within a single pipe (Table 2). Although we report quantitative mineral abundances for only a small sample set from each mine (i.e. four samples each from Venetia and Victor, two from Gahcho Kué, and one from Snap Lake), this dataset nevertheless highlights the variability of kimberlite mineralogy that results from different emplacement and alteration histories.

Samples from the four De Beers mines are typically dominated by phyllosilicate minerals, with phyllosilicate abundances varying from an average value of 37.7 wt% (n = 4) for processed kimberlite from Victor to values of 68.6 wt% (n = 4) for Venetia, 71.6 wt% (n = 1) for Snap Lake, and 85.8 wt% (n = 2) for Gahcho Kué. Serpentine minerals and smectites, respectively, are present at average abundances of 19.0 wt% and 36.6 wt% at Venetia and of 38.0 wt% and 13.1 wt% at Gahcho Kué. Smectite was not detected in samples from Victor and is only present at trace abundance in the one sample analyzed from Snap Lake. Serpentine minerals are present at an average abundance of 36.4 wt% in the two samples from Victor and 32.1 wt% in the single sample from Snap Lake.

Table 1 Qualitative mineralogy
and mineral surface areas for
select diamond mine sites

Mineral group	Venetia	Gahcho Kué	Victor	Snap Lake	Diavik
Tectosilicates					
K-feldspar		m ^a		m	
Plagioclase		t		М	m
Quartz	m	t	t	m	t
Phyllosilicates					
Chlorite		m	t	М	
Mica	М	М	t	М	m
Serpentine	М	М	М	М	М
Smectite	М	М		t	m
Talc		М		m	
Inosilicates					
Amphibole	m	t			
Clinopyroxene	М		t		t
Orthopyroxene			t		
Orthosilicates					
Garnet					t
Olivine	t		М		М
(Hydr)oxides					
Brucite			t		
Spinels	t		t		
Carbonates					
Calcite	m	m	М	m	m
Dolomite		t	М	m	
Magnesite			t		
Siderite			t		
BET surface area (m ² /g)	13.8	46.2	21.4	24.7	48.0

^a M, major; m, minor; t, trace

Primary silicate minerals, such as forsterite, diopside, and enstatite were detected in some samples; however, this is strongly site specific. In samples from Gahcho Kué and Snap Lake, none of these phases are present at abundances that are measurable using the conditions of XRD data collection employed here. In samples from Venetia, diopside was quantified at an average abundance of 20.5 wt%. The four samples from Victor, which have experienced less hydrous alteration than samples from the other mines, contain 21.0 wt% forsterite, 1.4 wt% diopside, and 1.5 wt% enstatite on average.

Processed kimberlite samples from Victor also contain brucite at an average abundance of 0.2 wt%. Brucite may also be present near the detection limit, which is typically <0.1 wt% for the XRD patterns used in this study, in the samples from Venetia and Gahcho Kué; however, this requires confirmation with microscopy. It is worth noting that brucite has been observed previously in XRD patterns from Venetia (Stripp et al. 2006).

The XRD crystallographic approach to quantitative mineralogy does not give a direct measurement of elemental C abundance within carbonate minerals in a sample. However, the amount of C stored within gangue and newly formed carbonate minerals can be estimated by stoichiometry. The total abundance of carbonate minerals is highly variable for processed kimberlite from the different mines. Average carbonate mineral abundance is 3.5 wt% for Venetia, 2.9 wt% for Gahcho Kué, and 36.2 wt% for Victor. Carbonate minerals were detected at 8.2 wt% in the one sample from Snap Lake. Calcite is the sole carbonate phase quantified at Venetia, whereas both calcite and dolomite are present at Gahcho Kué and Snap Lake. Calcite and dolomite are present at very high abundance at Victor, reflecting emplacement of the kimberlite in limestone (e.g. van Straaten and Kopylova 2013). Magnesite and either siderite or ankerite are also present at <2 wt% abundance each in the processed kimberlite from Gahcho Kué. Nesquehonite (MgCO₃·3H₂O), the hydrated Mg-carbonate mineral which commonly forms by reaction of ultramafic mineral wastes with atmospheric CO₂ (e.g. Wilson et al. 2006, 2009a, 2009b), may be present near detection in samples from Venetia and Gahcho Kué; however, further characterization work is needed owing to overlap of the most intense peaks of nesquehonite with a minor peak of plagioclase.

BET surface area is an indication of reactive surface area and is commonly employed in mineral dissolution and precipitation studies (e.g. Thom et al. 2013). Kimberlites included in this study had BET surface areas ranging from 13.8 to 48 m²/ g. These high surface areas reflect the presence of clay minerals (e.g. smectites, serpentine minerals). In the case of nonclay minerals, particle size data and electron microscopy may be used to estimate surface areas based on grain size and crystal morphologies.

Potential for CO₂ offsets at De Beers mines

The maximum CO_2 sequestration capacity of the annual kimberlite tailings produced at each mine site was estimated using the Ca, Mg, Fe, and Mn content in silicate, oxide, and hydroxide minerals assuming that they are liberated and available to bind with CO_2 on a mole-per-mole basis.

Mineral group	Venetia				Gahcho Kué		Victor				Snap Lake
Mineral (wt%)	VEN-CRD-A1	VEN-CRD-B1	VEN-FRD-1A	VEN-FRD- 1A_washed	17GK-fPK-01a (Weathered)	17GK-02 (less Weathered)	16VM-OC	16VM-RC	16VM-OF	16VM-RF	17SL-fPK-01a
Tectosilicates K-feldspar					5.2	9.1					3.3
Plagioclase	0.8	2.0			0.7	1.3					10.7
Quartz	0.6	2.3	0.8	0.4	0.6	1.6	0.2		1.5	1.0	6.2
rnynosincates Chlorite	tr? a	tr?	tr?	tr?	4.7	6.6	0.6	0.5	1.1	1.2	17.9
Mica (Phlogophite)	15.8	13.4	10.9	11.5	14.0	18.8			0.7	1.0	12.0
Serpentine	26.2	14.1	17.8	18.1	33.7	42.3	35.0	32.3	46.5	31.7	32.1
Smectite Talc	25.6	30.2	44.5	46.1	17.1 18.5	9.0 7.0					tr? 9.6
Inosilicates											
Amphibole (Tremolite)	6.2	7.8	3.7	3.6	1.9						
Clinopyroxene (Diopside)	19.0	26.1	19.3	17.5			1.4	0.9	1.6	1.8	
Orthosilicates							4. 1	1.9	1.0	7.1	
Garnet											
Olivine							19.4	21.6	14.5	28.4	
(Hyur)oxides	0	0,1	0-1	0	0-7	0-1					
Brucite	tr./	tr'/	tr'/	tr'/	ц./ С П	tr'/	7.0	0.2	0.2	0.3	
Spinels (Magnetite) Carbonates	1.1	0.4	0.1		0.7	1.5	1.5	1.5	1.5	0.0	
Calcite	4.7	3.5	3.0	2.8	2.4	2.1	14.5	18.4	9.8	12.9	2.9
Dolomite Maonesite					0.6	0.8	23.7 1.8	20.5 1.8	20.2	18.5 0.8	5.4
Nesquehonite	tr?	tr?	tr?	tr?	tr?	tr?					
Juctific	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
R_w (%) b	7.6	7.4	7.2	7.3	5.0	5.5	9.8	9.4	9.7	10.5	6.6
X ² °	2.1	2.0	2.1	2.2	2.0	2.1	1.9	1.8	1.9	2.1	2.8
d d	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.4
^a tr? denotes a mineral phas	e that may or may	y not be present at	trace abundance								

 Table 2
 Rietveld refinement results highlighting the mineralogical diversity of processed kimberlite

S762

 $^{\rm b}\,R_{\rm wp}$ is the weighted pattern index, a function of the least-squares residual, in units of %

 $^{\rm c}\chi^2$ is the unitless reduced chi-squared statistic for the least-squares fit $^{\rm d}$ d is the unitless Durbin–Watson statistic, a measure of serial correlation

Bulk geochemical and mineralogical data for Venetia and Victor (Table 2) were used to calculate the maximum sequestration potential for these mines. For the other mines, where bulk geochemical data of the processed kimberlite samples are not yet available (for example, only two samples from Gahcho Kué have been analyzed to date, and these represent weathered kimberlite from the top of the pipe), the kimberlite conversion factor from Wilson et al. (2009b) was used as an approximation. This maximum carbon sequestration value, along with the total carbon dioxide equivalent (CO₂e) emissions for each mine site, was used to estimate the maximum CO₂ sequestration capacity (% carbonation) that would be required to offset 100% of the CO₂e emissions at each mine site (Table 3). The results indicate that carbonation of ca. 4.7 to 24.0 wt% (average = 13.8 wt%) of the annual processed kimberlite production could offset 100% of each mine site's CO₂e emissions. In addition, many of the mine sites have substantial historical tailings with additional CO₂ storage capacity, although this has not yet been quantified. Overall, there is more than enough capacity to completely offset each mine site's CO₂e emissions through mineral carbonation of processed kimberlite.

Discussion and conclusions

Because kimberlites display considerable mineralogical diversity (see Tables 1 and 2), detailed characterization of processed kimberlite samples is essential in order to assess the mineral carbonation potential of specific diamond mine sites, as well as the technologies that could potentially be employed to enhance carbonation. Despite their mineralogical diversity, all of the processed kimberlite samples presented in this study contain abundant minerals with carbonation potential (Tables 1 and 2). Minerals of particular interest for reactivity with carbon dioxide include serpentine, olivine (forsterite), brucite, and smectite. The most abundant minerals, such as serpentine, provide the bulk of the carbonation potential. However, the presence of minor and trace minerals is also important, particularly brucite, which is easily carbonated under low pressure and temperature conditions (e.g. Harrison et al. 2016, 2017).

The serpentine polymorphs are of particular interest owing to their high Mg content, large surface areas, and relatively fast dissolution rates, which make them good feedstocks for carbonation reactions (e.g. Power et al. 2013, 2014a, b). Amongst the phyllosilicates, only the serpentine minerals have been considered in detail as feedstocks for carbonation reactions (e.g. Power et al. 2013). Mg-rich smectites, such as the saponite commonly found in kimberlite, have received very little attention for their use in carbonation reactions. However, recent work on Mg-rich kerolite and stevensite (in the sense of Brindley et al. 1977) in carbonate microbialites reveals that they are commonly replaced by carbonate minerals at low temperatures (Burne et al. 2014; Zeven et al. 2015). Previous studies have explored carbonation of the smectite mineral montmorillonite, which contains sheets of octahedrally co-ordinated Al and Mg. This work has been done in the context of injection of dry or variably wet supercritical CO₂ (scCO₂) into sedimentary reservoirs. Under the high pressure and temperature conditions used for geologic sequestration of scCO₂ in sedimentary rock, CO₂ becomes intercalated within the interlayer galleries of montmorillonite (e.g. Loring et al. 2012; Schaef et al. 2012). However, to our knowledge, similar studies have not been performed on Mg-Fe bearing saponite, which contains brucite-like sheets of Mg and Fe, and which is compositionally more similar to kerolite/stevensite. Therefore, there may also be potential for mineral carbonation technologies to target reactions involving smectite minerals, although this

Table 3 Estimated CO₂ sequestration capacity of processed kimberlite at De Beers mines in South Africa and Canada

	Venetia (2016) ^a	Voorspoed (2016) ^b	Gahcho Kué (March–September 2017) ^b	Victor (2016) ^a	Snap Lake (2015) ^b
Ore mined (Mt)	3.89	3.26	1.13	3.24	1.04
Ore treated (Mt)	4.74	3.13	0.91	2.99	1.1
Total CO ₂ e emissions (Mt)	0.21	0.067	0.084	0.053	0.12
Estimated maximum CO_2 sequestration capacity - ore mined (Mt)	1.24	1.48	0.51	0.95	0.47
Carbonation required to achieve 100% CO ₂ e offset - ore mined (%)	17.0	4.5	16.4	5.6	25.4
Estimated maximum CO_2 sequestration capacity – ore treated (Mt)	1.51	1.42	0.41	0.88	0.5
Carbonation required to achieve 100% CO_2 e offset - ore treated (%)	13.9	4.7	20.3	6.0	24.0

^a Calculated from Ca, Mg, Fe, and Mn content in silicate and oxide minerals

^b Based on Diavik conversion values (see Wilson et al. 2009b)

Note that 2016 data (January to December) are used for Venetia, Voorspoed, and Victor. 2015 data (January to December) are used for Snap Lake, which was put on care and maintenance at the end of 2015. 2017 data (March to September) are used for Gahcho Kué, which achieved commercial production in early March

requires further study. Other phyllosilicate minerals, such as phlogopite, talc, and chlorite, are not sufficiently reactive to contribute appreciably to the carbonation potential of processed kimberlite (e.g. Brantley 2003).

Olivine (forsterite), which lacks silica polymerization, has been widely used as a feedstock mineral for carbonation reactions. Therefore, the presence of substantial olivine at Victor is considered favorable for carbonation potential. Pyroxene (inosilicate) minerals are also found at some sites, particularly Venetia, and these also have been considered for use in CO₂ sequestration. However, their slow dissolution rates make them less suitable for mineral carbonation, particularly at ambient conditions (e.g. Power et al. 2013). Therefore, although pyroxene minerals contribute to overall carbonation potential of certain mine sites, they are not likely to be targeted using low cost carbonation approaches that are likely to be employed in the near future (e.g. Power et al. 2014a, b). Brucite is a highly reactive phase that carbonates rapidly at ambient conditions, and it is known to play an important role in carbon mineralization in mining environments (e.g., Assima et al. 2013; Bea et al. 2012; Harrison et al. 2013; Wilson et al. 2010, 2014). Therefore, the presence of brucite at some mine sites is considered highly favorable and more work should be done to look for the presence of brucite, even at low concentrations, at diamond mine sites.

The surface areas of the processed kimberlite also vary (Table 1). The samples with the highest surface areas are likely to be easiest to carbonate, provided that the reactive surface area is associated with minerals such as serpentine, olivine, brucite, and possibly smectite.

Overall, the new mineralogical results from De Beers mine sites sampled concur with the previous research at Diavik (Wilson et al. 2009b) that enhanced mineral carbonation of processed kimberlite has the potential to offset the total carbon emissions at each mine site (Table 3). The estimates of carbonation capacity in Table 3 are based on bulk chemical data and mineral content data for Venetia and Victor and, for the other sites, are based on estimates of kimberlite carbonation capacity by Wilson et al. (2009b) based on data for Diavik. These estimates should be refined following further studies to assess the variability of tailings compositions at each site.

Future research directions

Power et al. (2013, 2014 and references therein) have demonstrated that carbonation rates in ultramafic mine wastes are highly variable and controlled by factors such as: (1.) the nature of ore, gangue, and alteration mineralogy; (2.) mineral processing and mine design; (3.) tailings handling and storage; (4.) local climate; and (5.) biology. Additional research, particularly on historical tailings, is required to assess what factors may be limiting carbonation reactions at the De Beers mine sites assessed in this study. Once the factors limiting carbonation have been identified, then technologies to accelerate carbonation can be identified and tested, first at the laboratory-scale and then at pilot scales on the mine sites.

Laboratory-scale studies (e.g. Power et al. 2013, 2014a, b and references therein) indicate that carbonation rates of ultramafic mine tailings can be increased by targeting ratelimited reactions, such as CO_2 supply and mineral dissolution. Technologies that could be employed to enhance carbonation include CO_2 injection and biotechnologies, such as bioreactors (e.g. McCutcheon et al. 2014). In addition, making simple, low-cost physical changes to processed kimberlite storage, such as depositing thinner layers of tailings (e.g. Wilson et al. 2014), could also enhance carbonation rates.

Future research at De Beers mine sites will start with comprehensive mineralogical characterization of a larger suite of samples, to ensure that the full range of processed kimberlite compositions has been considered. In particular, this will enable the carbonation potential estimates provided in Table 3 to be refined. Future analysis of carbonate minerals will also include fingerprinting methods, for example stable isotope and radiocarbon analyses, that will assist with tracing sources of carbon. Future research will also focus on determining the degree of any passive ("unintentional") carbonation of processed kimberlite that has already occurred, and on quantifying the additional CO₂ sequestration storage potential present in historical tailings, which may be substantial at some of the longeroperating mine sites. Tapping into the full carbonation potential of processed kimberlite (i.e. achieving 100% of the theoretical mineral carbonation) is not likely to be economically or practically achievable in the near future. However, carbonating even a small percentage of processed kimberlite could lead to substantial offsets or even carbon-neutral mining operations.

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