Kinetics-informed global assessment of mine tailings for CO_2 removal

Liam A. Bullock*, Aidong Yang, and Richard C. Darton

Department of Engineering Science, Parks Road, University of Oxford, Oxford, United Kingdom

*Corresponding author (liam.bullock@eng.ox.ac.uk)

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Supplementary Table A. Assessed deposit types and associated tailings mineralogies, selected based on their average whole rock E_{pot} (Bullock et al., 2021) and C_{pot} values. Typical grain size of each tailings material also shown (typical processed size for extraction of commodity and storage in tailings pond). Full reference list for typical modal mineralogies, commodity to tailings ratio calculations, and typical grain size examples, given below (Supplementary Table C).

Tailings material	Typical modal mineralogy (after Bullock et al., 2021)	Mean whole rock E_{pot} (g CO_2/kg)	Mean whole rock C_{pot} (g CO_2/kg)	Typical grain size (µm)
Asbestos serpentinite	Srp (91%), Opq (5%), Ol (2%), Cpx (1%), Qz-Cal-Brc (1%)	649	432	75
Cr layered	Chr (57%), Opx (36%), Cpx (7%)	282	234	250
Cr podiform	Chr (44%), Ol (42%), Cpx (14%)	366	239	250
Cu porphyry	Pl (30%), Cpx-Opx (30%), Amp (10%), Bt-Ms (10%), Qz (10%), Cal (5%), Opq (5%)	194	92	120
Cu VMS	Pl (30%), Amp (20%), Bt-Ms (15%), Qz (10%), Chl (10%), Cpx-Opx (5%), Py (5%), Cal (5%)	188	102	100
Diamond kimberlite	Ol (20%), Srp (20%), Bt-Ms (20%), Opq (15%), Cpx-Opx (10%), Cal (10%), Ap (5%)	558	358	75
Ni sulphide	Ol (50%), Chr (20%), Cpx-Opx (20%), Py (5%), Opq (5%)	660	436	200
Olivine dunite	Ol (90%), Cpx-Opx (5%), Srp (5%)	619	411	100
Pb-Zn skarn	Qz (30%), Or (20%), Cal (10%), Pl (10%), Amp (10%), Bt-Ms (10%), Py (5%), Opq (5%)	546	351	220
PGM layered mafic intrusion	Opx (50%), Pl (15%), Cpx (10%), Ol (10%), Bt-Ms (5%), Py (5%), Opq (5%)	417	274	75
Talc serpentinite	Serp (53%), Ol (13%), Chl (20%), Tlc (10%), Amp (2%), Opq (2%)	722	479	200
Ti anorthosite	Pl (50%), Opx (20%), Opq (15%), Ol (10%), Ap (2%), Or (2%), Qz (1%)	218	131	200

Modal mineralogies adjusted for commodities extracted at grades of over 10% (Cr), assuming 80% removal efficiency of targeted ore minerals based on beneficiation studies (see Bullock et al., 2021 and references therein). Mean E_{pot} (EW potential) and C_{pot} (carbonation potential) calculated based on mean whole rock geochemistry of each deposit type and E_{pot} and C_{pot} formulae of Renforth (2019) and Bullock et al. (2021). Grain size values shown are quoted average particle sizes, or maximum sieve size where >90% of material passed (see Supplementary Table C for literature sources).

Supplementary Table B. Effects of mineral compositional (and end member) variations on dissolution rates under unimproved conditions (W_r^{Neut}).

Mineral group	Average W_r^{Neut}	Maximum W_r^{Neut}	Minimum W_r^{Neut}	End member	General formula	Average W_r^{Neut}	Maximum W_r^{Neut}	Minimum W_r^{Neut}
Clinopyroxene	-11.12	-10.8	-12.4	Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	-11.63	-10.9	-12.4
				Diopside	$CaMgSi_2O_6$	-10.95	-10.8	-11.09
Orthopyroxene	-11.6	-11.0	-12.5	Bronzite	$(Mg,Fe)_2[SiO_3]_2$	-11.5	-11.0	-12.0
				Enstatite	$Mg_2Si_2O_6$	-11.75	-11.0	-12.5
Plagioclase	-11.6	-9.58	-14.61	Albite	$NaAlSi_3O_8$	-11.03	-9.58	-11.83
				Andesine	$(Na,Ca)(Si,Al)_4O_8$	-11.07	-10.12	-11.69
				Anorthite	$CaAl_2Si_2O_8$	-12.11	-10.14	-14.61
				Oligoclase	$(Na,Ca)(Si,Al)_4O_8$	-11.96	-	-
Serpentine	-11.6	-9.79	-12.4	Lizardite	$Mg_3Si_2O_5(OH)_4$	-12.4	-	-
				Chrysotile	$Mg_3Si_2O_5(OH)_4$	-11.49	-9.79	-12.0
Mica	-	-	-	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$	-12.07	-11.9	-12.24
Amphibole	-	-	-	Hornblende	$Ca_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$	-12.51	-11.73	-13.0
Olivine	-	-	-	Forsterite	Mg_2SiO_4	-10.04	-9.6	-10.57
Chlorite	-	-	-	Clinochlore	$Mg_5Al(AlSi_3O_{10})(OH)_8$	-12.52	-	-
Clay	-	-	-	Talc	$Mg_3Si_4O_{10}(OH)_2$	-12.0	-	-
Inosilicate	-	-	-	Wollastonite	$CaSiO_3$	-9.8	-8.0	-11.6

Mineral groups and associated calculated W_r values represent average of presented end member compositions, with the exceptions of amphibole (hornblende only), mica (biotite only), chlorite (clinochlore only), olivine (forsterite only), clay (talc only) and inosilicate (wollastonite only).

Sources of published dissolution rates used in this study

W_r from published rates achieved under pH conditions of 3-4 and 6-8, using BET-measured surface area

Amphibole (hornblende): Sverdrup (1990); Palandri and Kharaka (2004); Golubev et al. (2005); Bandstra et al. (2008).

Biotite: Nickel (1973); Sverdrup (1990); Zhang (1990); Acker and Bricker (1992); Swoboda-Colberg and Drever (1993); Zhang et al. (1993, 1996); Kalinowski and Schweda (1996); Frogner and Schweda (1998); Palandri and Kharaka (2004); Golubev et al. (2005); Bandstra et al. (2008).

Chlorite (clinochlore): May et al. (1995); Johnson et al. (2001); Palandri and Kharaka (2004); Bandstra et al. (2008).

Olivine (forsterite): Eriksson (1982); Grandstaff (1980, 1986); Siegel and Pfannkuch (1984); Blum and Lasaga (1988); Wogelius and Walther (1991); Pokrovsky and Schott (2000); Rosso and Rimstidt (2000); Palandri and Kharaka (2004); Bandstra et al. (2008).

Plagioclase: Bailey (1974); Chou and Wollast (1984, 1985); Manley and Evans (1986); Holdren and Speyer (1987); Schweda (1989); Casey et al. (1991); Amrhein and Suarez (1992); Welch and Ullman (1993, 2000); Oxburgh et al. (1994); Oelkers and Schott (1995); Stillings and Brantley (1995); Stillings et al. (1996); Taylor et al. (2000); Carroll and Knauss (2001); van Hess et al. (2002); Palandri and Kharaka (2004); Bandstra et al. (2008).

Pyroxene: Grandstaff (1977); Schott et al. (1981); Sverdrup (1990); Knauss et al. (1993); Chen and Brantley (1998); Palandri and Kharaka (2004); Golubev et al. (2005); Bandstra et al. (2008).

Serpentine (lizardite and chrysotile): Hume and Rimstidt (1992); Palandri and Kharaka (2004); Bandstra et al. (2008); Thom et al. (2013); Zhang et al. (2019).

Talc: Lin and Clemency (1981); Nagy (1995); Palandri and Kharaka (2004); Bandstra et al. (2008).

Wollastonite: Xie (1994); Palandri and Kharaka (2004); Bandstra et al. (2008).

Supplementary Table C. Sources of information for modal mineralogies, commodity production to tailings production ratios and typical grain sizes for each potentially suitable tailings material type.

Tailings type	Modal mineralogy examples	Production and tailings data	Typical grain size examples
Asbestos serpentinite	Boschi et al. (2006); Yalçin and Bozkaya (2006); Khedr and Arai (2010); Teixeira et al. (2010); Buyukkahraman and Coban (2013); Bhilisse et al. (2014); Punturo et al. (2015); Ferenc et al. (2016); McCutcheon et al. (2017); Apollaro et al. (2018)	Wilson et al. (2006; 2009); Pronost et al. (2011); Oskierski et al. (2013); Power et al. (2014); McCutcheon et al. (2017); Lechat et al. (2016); Statista (2019)	Carbon Capture and Storage (Second Edition) (Rackley, 2017)
Cr layered	Page (1979); Barnes and Naldrett (1985); Manyeruke et al. (2005); Holwell and McDonald (2006); McIntosh (2017)	Bolaños-Benítez et al. (2018); Statista (2019)	Chrome ore beneficiation plant, Sukinda region, India (Das, 2015)
Cr podiform	Zhou et al. (1996); Mosier et al. (2012)	Bolaños-Benítez et al. (2018); Statista (2019)	Chrome ore beneficiation plant, Sukinda region, India (Das, 2015)
Cu porphyry	Quan et al. (1987); Carten et al. (1988); Ulrich and Heinrich (2002); Shen et al. (2009); Ochoa-Landín et al. (2017); McFall et al. (2018)	Henderson (2013); Ndlovu et al. (2017); Rio Tinto (2019); Statista (2019)	Bahuerachi Cu coarse tailings, Mexico (Hu et al., 2017)
Cu VMS	Larson (1984); Gemmell and Large (1992); Bullock et al. (2017); Patten et al. (2017); Martin et al. (2018)	Henderson (2013); Ndlovu et al. (2017); Rio Tinto (2019); Statista (2019)	Las Cruces project tailings, Spain (European Commission, 2009)
Diamond kimberlite	Machin (2000); Becker and Le Roex (2006); Dongre and Tappe (2019)	Wilson et al. (2009); Power et al. (2014); Statista (2019)	Kimberlite Tailings: A Road Construction Material (Swami et al., 2007)
Ni sulphide	Marston et al. (1981); Barnes et al. (1992); Scoates and Mitchell (2000); Maier et al. (2008)	WMC Resources Ltd (2005); Power et al. (2014); Pietek and Kurylak (2017); Statista (2019)	Moa river nickel tailings dams, Cuba (Rodríguez et al., 1998)
Olivine dunite	Friend et al. (2002); Søndergaard (2019)	Niranjana Minerals (2006; 2013); Kremer et al. (2019)	Landoy dunite mine sludge waste, Spain (Pasek Minerales, 2021)
Pb-Zn skarn	Harris and Einaudi (1982); Somarin (2004); Liu et al. (2012)	Emsbo et al. (2010); Statista (2019)	Kursun et al. (2017) Pb-Zn tailings from Balıkesir Balya region, Turkey
PGM layered mafic intrusion	Page (1979); Barnes and Naldrett (1985); Manyeruke et al. (2005); Holwell and McDonald (2006); McIntosh (2017)	Ndlovu et al. (2017); Statista (2019)	South African mine tailings (Amponsah-Dacosta, 2017)
Talc serpentinite	Boschi et al. (2006); Yalçin and Bozkaya (2006); Khedr and Arai (2010); Teixeira et al. (2010); Buyukkahraman and Coban (2013); Bhilisse et al. (2014); Punturo et al. (2015); Ferenc et al. (2016); McCutcheon et al. (2017); Apollaro et al. (2018)	Munro (1992); Industrial Minerals (2015)	Eastern Finland talc deposits (European Commission, 2009)
Ti anorthosite	Duchesne (1999)	Korneliussen et al. (2000); Mindat.org (2016); USGS (2021)	Tellnes Mine tailings, Norway, USGS Report (Schulz et al., 2017)

Modal mineralogies of each deposit type devised from available information in sources presented. Tailings estimates based on mean, maximum and minimum ratios of known annual commodity production to known tailings production for site examples from sources presented. Typical grain size values shown are quoted average particle diameter sizes, liberated mineral sizes (from in-situ) or maximum sieve size where >80% of material passed.

Supplementary Table D. Targeted mineral dissolution extent and timescales under EW conditions (10 µm grain size and average published W_r determined at pH 3-4).

Mineral	Dissolution (%) after 1 year	Dissolution (%) after 70 years	Time for complete mineral dissolution (years)
Amphibole	0.1	8.4	2405
Biotite	0.3	16.7	1172
Chlorite	0.04	2.8	7406
Clinopyroxene	3.8	99.9	76
Olivine	70.6	100*	3
Orthopyroxene	0.06	4.0	5081
Plagioclase	0.9	52.4	315
Serpentine	34.1	100*	8
Talc	0.08	5.8	3491

* Full dissolution achieved before 70 years. For shrinking core model used here, molar volume of mineral converted to one mol Si basis.

Supplementary Table E. Estimated annual and cumulative production (Mt) of suitable tailings for host countries for the years 2030-2100.

	2030	Min. 2030	Max. 2030	2050	Min. 2050	Max. 2050	2100	Min. 2100	Max. 2100
Angola	25.72	3.11	42.81	514.40	62.14	856.20	1800.39	217.49	2996.71
Australia	16.39	12.87	20.11	327.86	257.41	402.25	1147.50	900.92	1407.87
Austria	0.20	0.03	0.45	4.09	0.53	9.07	14.31	1.86	31.73
Botswana	41.79	5.05	69.57	835.90	100.98	1391.33	2925.63	353.43	4869.66
Brazil	9.12	5.67	13.97	182.33	113.50	279.38	638.14	397.25	977.83
Canada	221.67	23.94	550.58	4433.41	478.74	11011.63	15516.94	1675.60	38540.72
China	14.33	9.31	21.40	286.61	186.28	427.94	1003.12	651.97	1497.81
Congo	9.64	1.17	16.05	192.90	23.30	321.08	675.15	81.56	1123.77
Finland	2.48	1.93	2.99	49.66	38.64	59.80	173.81	135.26	209.29
France	0.33	0.08	0.52	6.60	1.53	10.49	23.11	5.36	36.72
Greece	3.73	0.09	10.68	74.54	1.89	213.56	260.88	6.60	747.46
Guinea	0.48	0.06	0.80	9.64	1.17	16.05	33.76	4.08	56.19
India	0.69	0.16	1.10	13.82	3.21	21.96	48.36	11.22	76.85
Italy	1.47	0.06	4.08	29.50	1.22	81.58	103.25	4.28	285.53
Japan	10.19	0.28	29.04	203.75	5.63	580.85	713.13	19.72	2032.96
Kazakhstan	0.16	0.04	0.26	3.29	0.76	5.23	11.52	2.67	18.30
Lesotho	3.21	0.39	5.35	64.30	7.77	107.03	225.05	27.19	374.59
Mexico	0.76	0.02	2.16	15.11	0.38	43.29	52.88	1.34	151.51
Norway	17.63	0.45	50.50	352.54	8.92	1010.07	1233.88	31.23	3535.26
Others	29.02	23.47	34.32	580.41	469.34	686.38	2031.42	1642.68	2402.32
Pakistan	0.13	0.03	0.21	2.61	0.61	4.15	9.14	2.12	14.52
Russia	720.83	54.74	1946.13	14416.51	1094.72	38922.55	50457.78	3831.52	136228.94
Sierra Leone	1.77	0.21	2.94	35.36	4.27	58.86	123.78	14.95	206.02
South Africa	1061.43	42.86	3054.19	21228.65	857.24	61083.82	74300.28	3000.33	213793.37
South Korea	0.25	0.06	0.39	4.91	1.14	7.81	17.20	3.99	27.33
Spain	3.78	0.10	10.82	75.54	1.91	216.44	264.40	6.69	757.56
Taiwan	2.01	0.05	5.77	40.29	1.02	115.44	141.01	3.57	404.03
Tanzania	0.96	0.12	1.61	19.29	2.33	32.11	67.51	8.16	112.38
Turkey	0.76	0.02	2.16	15.11	0.38	43.29	52.88	1.34	151.51
United States	101.67	5.22	291.05	2033.31	104.34	5820.91	7116.59	365.20	20373.18
Zimbabwe	148.61	9.48	421.29	2972.25	189.64	8425.83	10402.88	663.76	29490.41

Suitable tailings – countries that host asbestos serpentinite, talc serpentinite, diamond kimberlite, Ni sulphide, olivine dunite and PGM layered mafic intrusion tailings.

Tailings of minor CDR potential (e.g., Cu porphyry and VMS, Cr podiform and layered intrusion, Ti anorthosite) not included in production tonnages here.

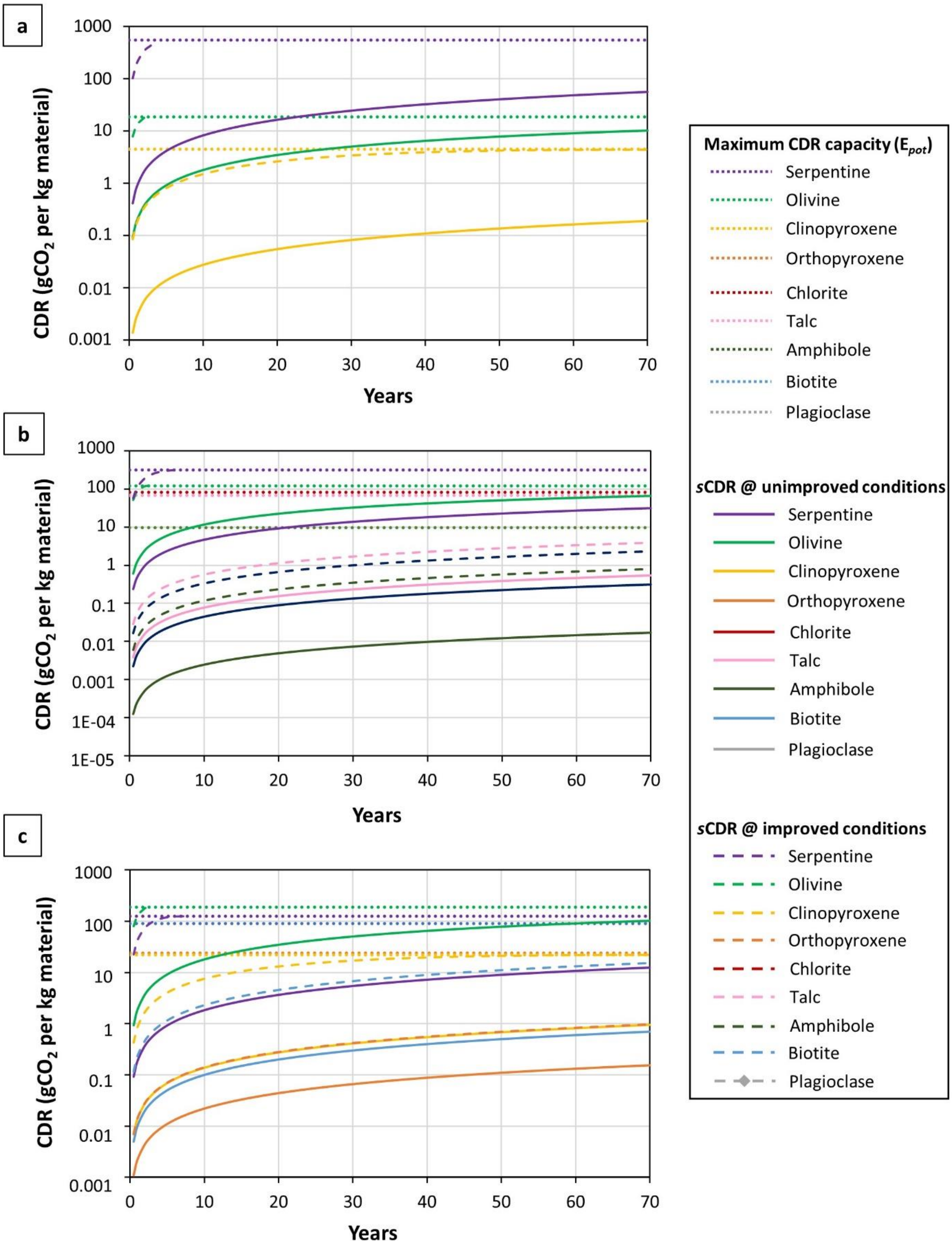
Minimum and maximum production tonnages reflect different ratios of known commodity production to tailings production for the different suitable tailings.

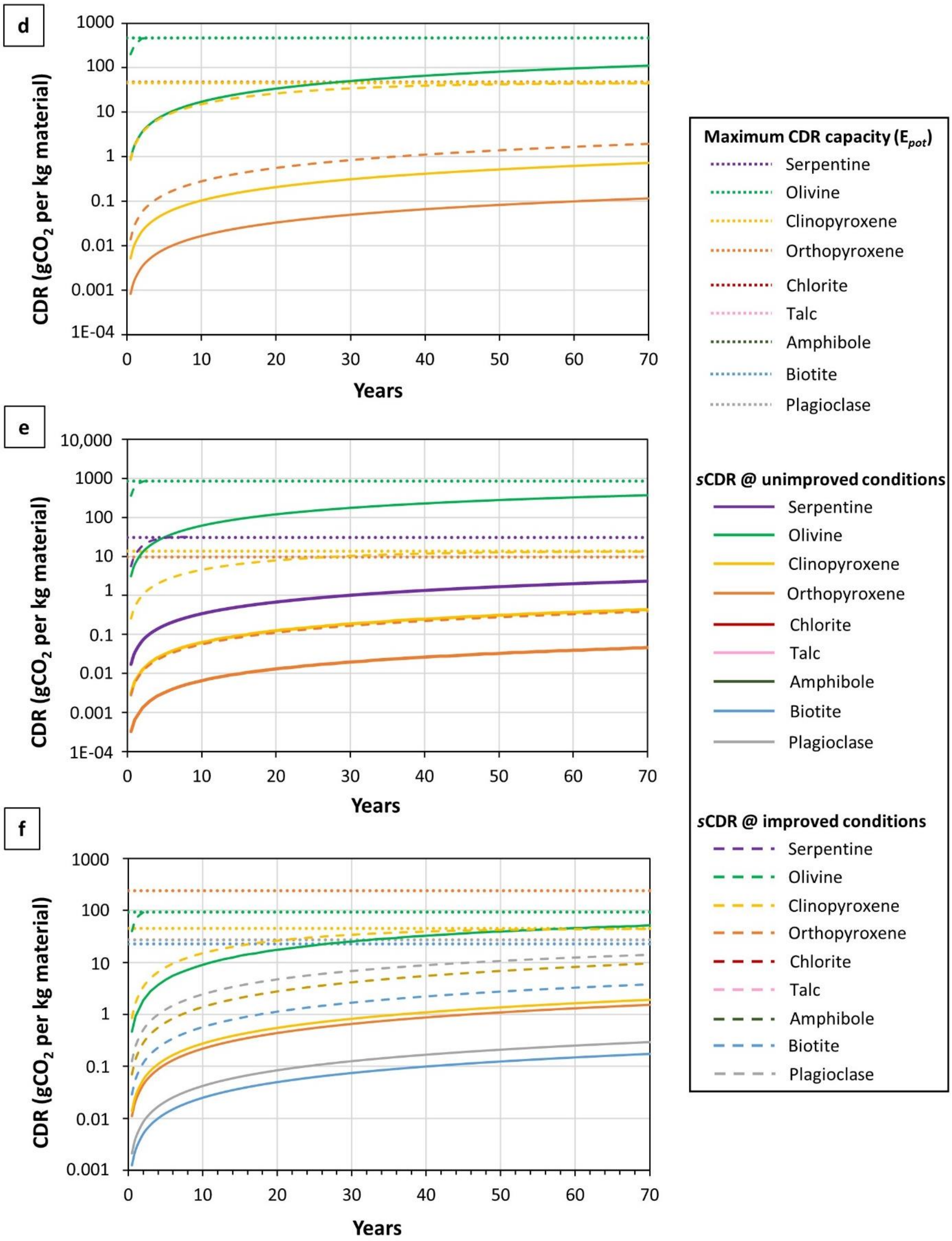
Supplementary Table F. Estimated CDR capacity (cumulative for the estimated annual tailings production at 2030 (*s*CDR) and total cumulative CDR (*t*CDR) as alkalinity for 2050 and 2100) for select countries that produce and host suitable tailings. CDR presented as estimated capacity when materials are subjected to unimproved reaction conditions ("@Unimproved") and under improved conditions ("@Improved"). Also shown are the national CO_2 emissions and estimated contributions to offsetting emissions and possible annual contribution (from 2030) towards a globally relevant goal of 2 Gt CDR per year under different reaction conditions.

Country	*t*CDR $MtCO_2$ 2030-2031 @Unimproved	*t*CDR $MtCO_2$ 2030- 2050 @Unimproved	*t*CDR $MtCO_2$ 2030-2100 2100 @Unimproved	*t*CDR $MtCO_2$ 2030-2031 @Improved	*t*CDR $MtCO_2$ 2030- 2050 @Improved	*t*CDR $MtCO_2$ 2030- 2100 @Improved	PA contribution (based on *s*CDR averaged over 70 years) @Unimproved	PA contribution (based on *s*CDR averaged over 70 years) @Improved	National reported emissions (2019; Mt CO_2e/yr)	Contribution to emissions (based on *s*CDR averaged over 70 years) @Unimproved	Contribution to emissions (based on *s*CDR averaged over 70 years) @Improved
Angola	0.03	9.8	115	2.6	154	603	0.08	0.42	38	4.25	22.34
Australia	0.02	5.8	72	3.3	152	580	0.05	0.41	1645	0.06	0.50
Austria	<0.001	0.2	1.8	0.05	2.5	9.4	<0.01	0.01	137	0.02	0.10
Botswana	0.04	16	186	4.3	250	980	0.13	0.69	6.3	41.59	218.53
Brazil	0.01	4.5	55	2.0	96	362	0.04	0.26	1863	0.04	0.27
Canada	0.1	53	625	14.6	782	3273	0.44	2.3	2307	0.38	2.00
China	0.02	6.8	83	3.2	150	568	0.06	0.40	40,699	<0.01	0.02
Congo	0.01	3.7	43	1.0	58	226	0.03	0.16	3.5	17.53	92.13
Finland	0.002	0.8	10	0.5	21	80	0.01	0.06	125	0.11	0.97
France	<0.001	0.1	1.2	0.04	2.7	10.2	<0.01	0.01	324	0.01	0.04
Greece	0.01	4.4	52	1.4	62	231	0.04	0.16	67	1.09	4.84
Guinea	<0.001	0.2	2.2	0.05	2.9	11	<0.01	0.01	3.2	0.96	5.05
India	0.001	0.2	2.6	0.08	5.6	21	<0.01	0.02	5233	<0.01	0.01
Italy	0.004	1.6	19	0.5	24	88	0.01	0.06	674	0.04	0.18
Japan	0.03	12	141	3.7	170	628	0.10	0.44	2213	0.09	0.40
Kazakhstan	<0.001	0.03	0.4	0.02	1.7	6.7	<0.01	<0.01	639	<0.01	0.01
Lesotho	0.003	1.2	14	0.3	19	75	0.01	0.05	2.2	9.09	47.76
Mexico	0.002	0.9	11	0.3	13	47	0.01	0.03	439	0.03	0.15
Norway	0.06	21	247	6.4	295	1094	0.17	0.77	42	8.19	36.27
Other nations	0.03	9.6	120	5.7	265	1011	0.08	0.71	-	-	-
Pakistan	<0.001	0.04	0.5	0.01	1.0	4.0	<0.01	<0.01	249	<0.01	0.02
Russia	0.4	52	612	38	864	3474	1.24	6.2	6713	0.37	1.85
Sierra Leone	0.002	0.7	7.9	0.2	11	41	0.01	0.03	1.0	10.82	56.86
South Africa	0.5	194	2276	44	2332	10,646	1.6	7.5	1436	2.23	10.44
South Korea	<0.001	0.08	0.9	0.03	2.0	7.6	<0.01	0.01	611	<0.01	0.02
Spain	0.01	4.4	53	1.4	63	234	0.04	0.16	253	0.29	1.31
Taiwan	0.006	2.4	28	0.7	34	125	0.02	0.09	263	0.15	0.67
Tanzania	0.001	0.4	4.3	0.1	5.8	23	<0.01	0.02	12	0.52	2.74
Turkey	0.002	0.9	11	0.3	13	47	0.01	0.03	810	0.02	0.08
United States	0.05	19	225	4.6	238	1074	0.16	0.76	21,139	0.01	0.07
Zimbabwe	0.08	28	325	6.8	354	1588	0.23	1.12	42	11.03	53.91

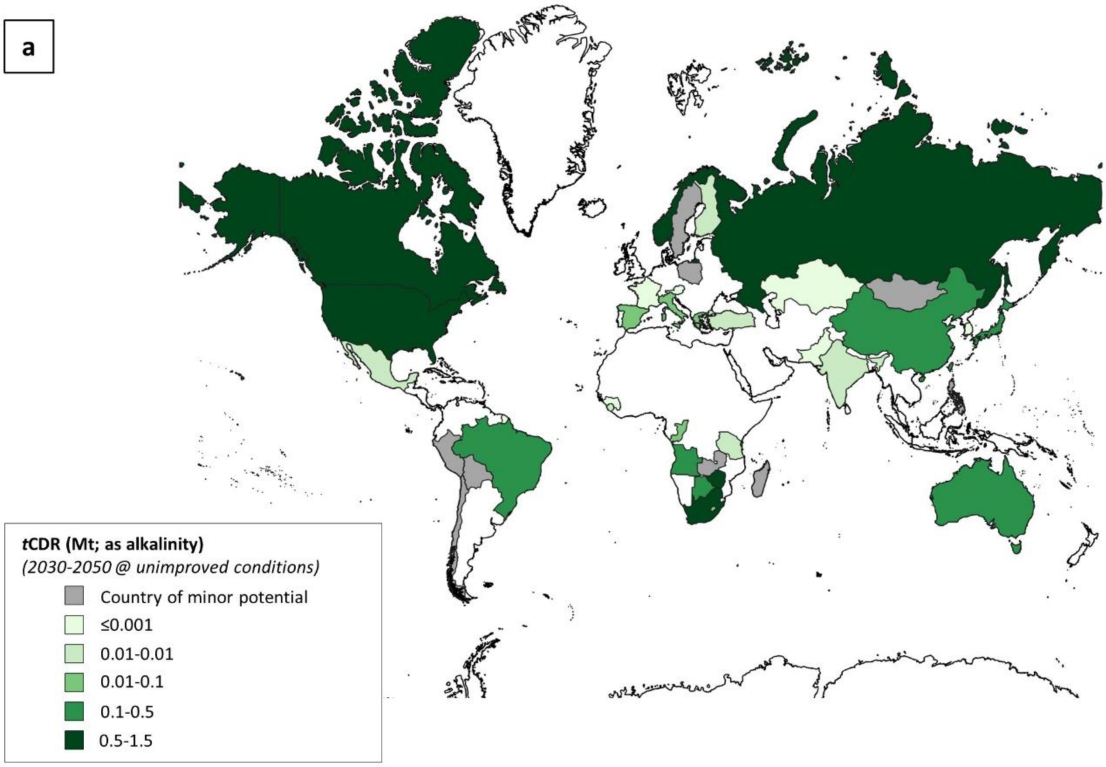
"Other nations" represents the total suitable tailings that originate from commodity production as catalogued by the USGS (2021), but not attributed to a particular country.

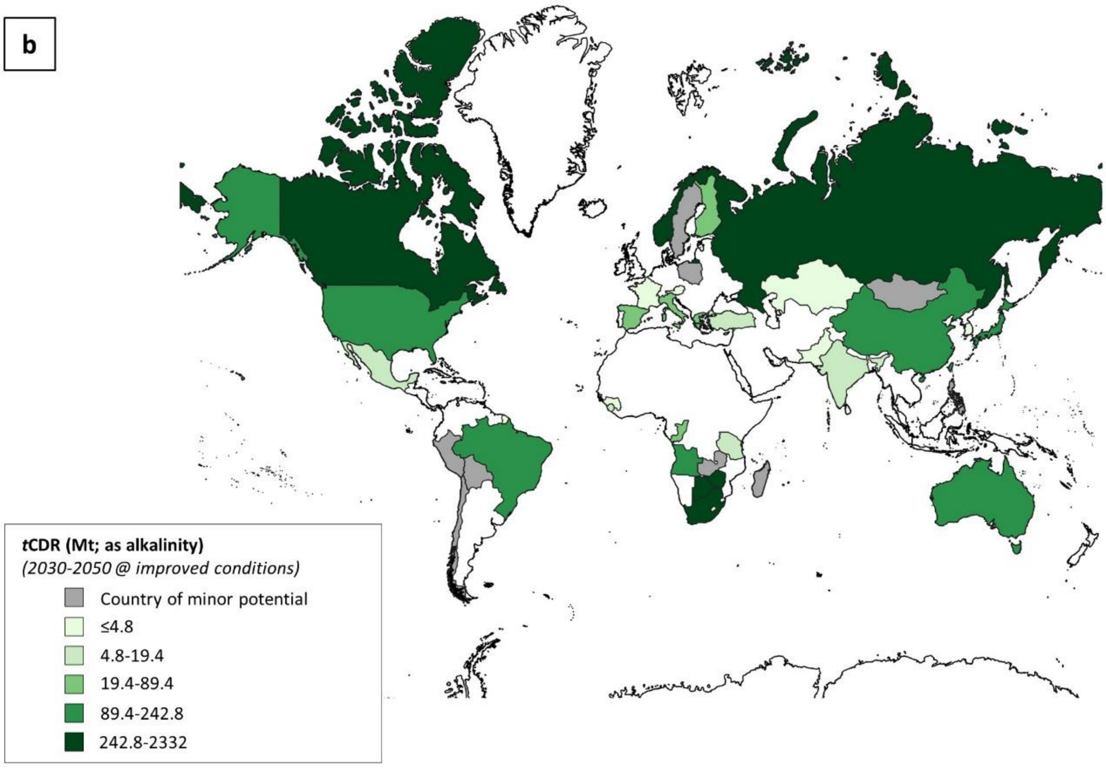
Supplementary Figures

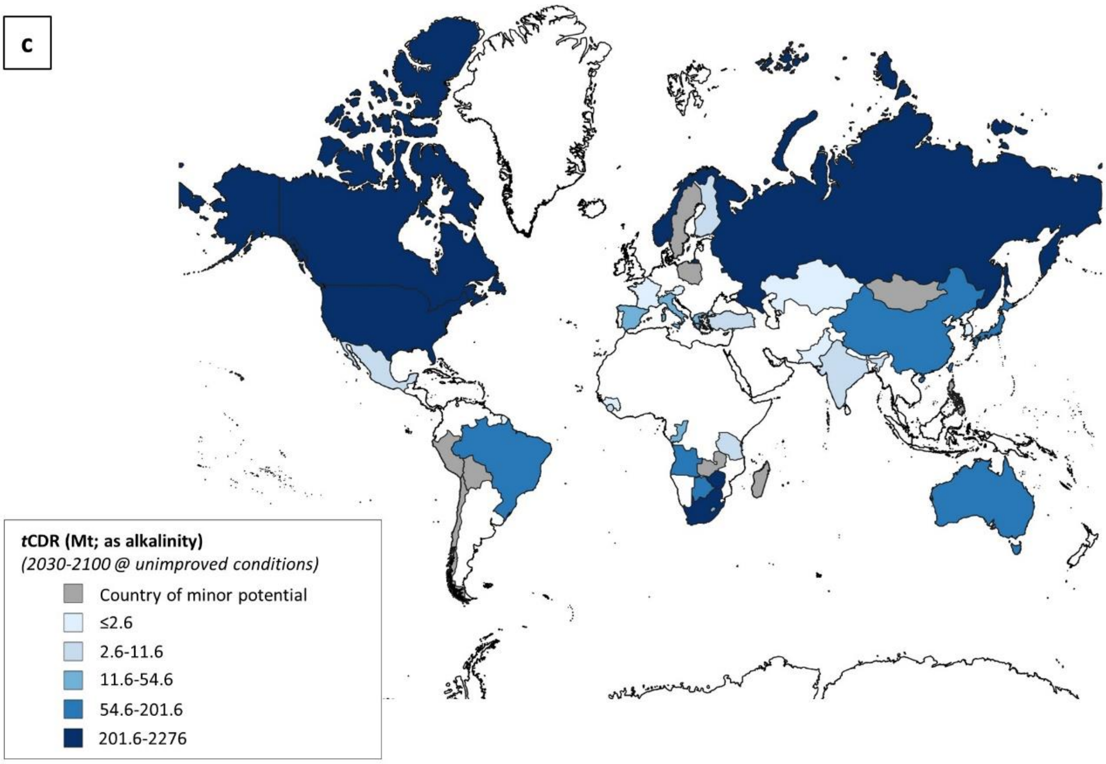


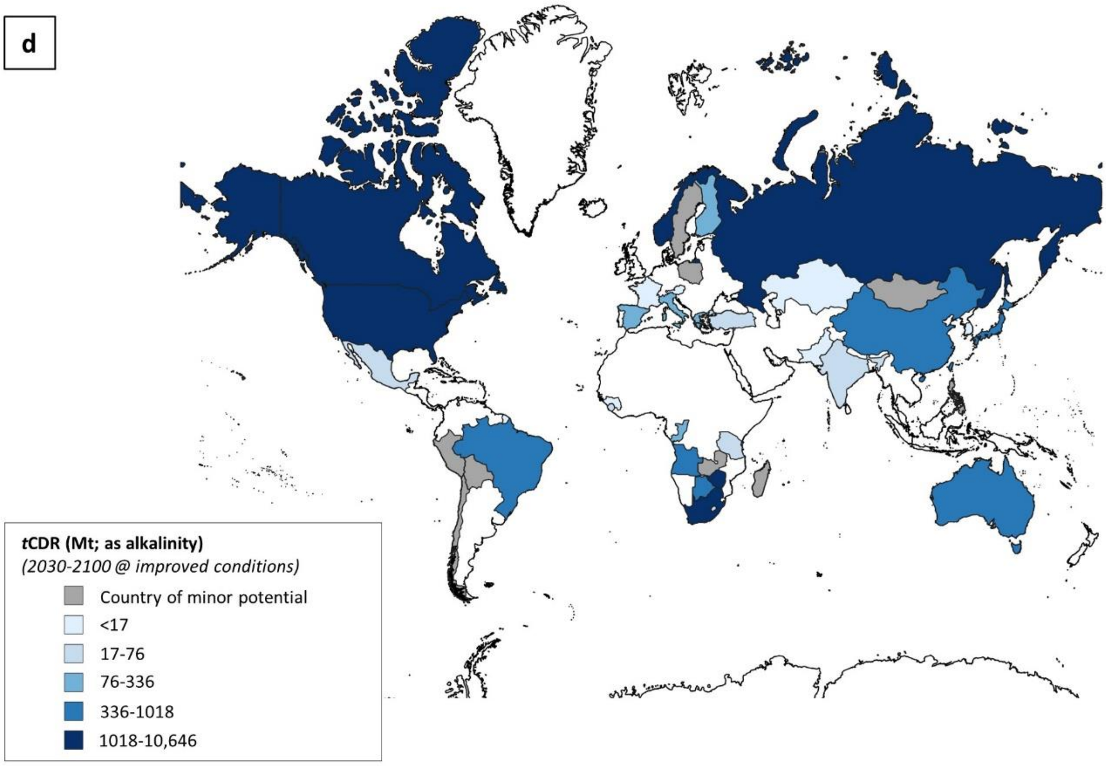


Supplementary Fig. A. Shrinking core modelling of theoretical 1 kg of the most suitable mine tailings materials for CDR purposes over decadal timescales: (a) Asbestos serpentinites; (b) talc serpentinites; (c) diamond kimberlites; (d) Ni sulphides; (e) olivine dunites; (f) PGM layered mafic intrusions. Model shows *s*CDR extent of minerals typically contained within each tailings material (abundance based on modal mineralogy, with non-reactive or untargeted minerals not included) under unimproved and targeted EW reaction conditions (conditions reflect differences in grain size and pH reaction solution; see text). Maximum CDR capacity for each mineral (based on E_{pot} and abundance in tailings) also shown.

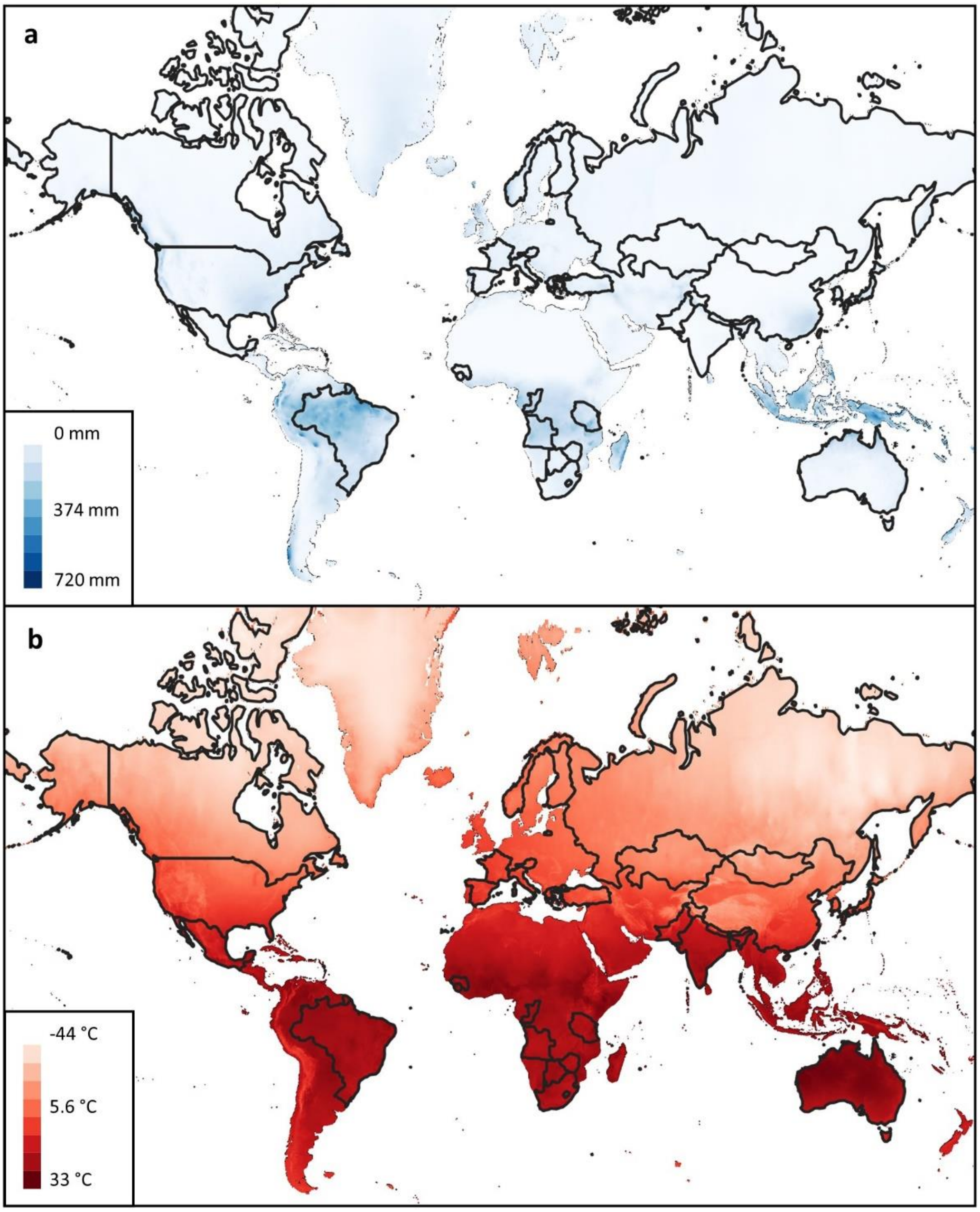

a
tCDR (Mt; as alkalinity)
(2030-2050 @ unimproved conditions)
Country of minor potential
≤0.001
0.01-0.01
0.01-0.1
0.1-0.5
0.5-1.5


b
tCDR (Mt; as alkalinity)
(2030-2050 @ improved conditions)
Country of minor potential
≤4.8
4.8-19.4
19.4-89.4
89.4-242.8
242.8-2332





Supplementary Fig. B. Total cumulative CDR potential (*t*CDR; $MtCO_2$ removed through alkalinity generation) for countries hosting suitable mine tailings for (a) the period 2030-2050 under unimproved reaction conditions, (b) 2030-2050 under targeted EW conditions, (c) the period 2030-2100 under unimproved conditions, and (d) 2030-2100 under targeted EW conditions.



Supplementary Fig. C. Average climate data for (a) monthly precipitation (mm), and (b) temperature (°C), with countries hosting large tonnages of suitable tailings for potential CDR purposes outlined. Note areas of darker blue and red colours, where CDR by EW is anticipated to be more effective (e.g., Southern Africa, Central and South America, Southeast Asia). Data represents average monthly climate data for 1970-2000 (after WorldClim 2.1 (2020); http://worldclim.org).

Other Supplementary Materials

Supplementary Material A. Typical grain size classification

Grain sizes utilised in the shrinking core model typically represent some reported average sizes achieved following the initial stages of grinding and/or flotation. Some utilised sizes represent a mean particle diameter standard size achieved across several commodity types, such as 75 µm used in some asbestos, PGM, and diamond operations (e.g., Swami et al., 2007; Amponsah-Dacosta, 2017; Rackley, 2017), or 200 µm, used for olivine operations (e.g.,Pasek Minerales, 2021). Some utilised sizes also represent a maximum or near-maximum (e.g., ≥80% up to 100%) material passing a particular size classification, such as for some chrome operations, e.g., Las Cruces project Cu tailings, Spain (European Commission, 2009), Cr beneficiation plant tailings, Sukinda region, India (Das, 2015), and Pb-Zn tailings from Balıkesir Balya region, Turkey (Kursun et al., 2017). Another approach is to report average size based on the corresponding particle size when the cumulative percentage reaches 50 (i.e., D50), such as the classification of some Cu tailings from Bahuerachi, Mexico (Hu et al., 2017) and Moa River nickel tailings dams, Cuba (Rodríguez et al., 1998). Average crushed grain sizes may not be universally reported (beyond internal reports), meaning the typical in-situ grain size of the targeted commodity-hosting mineral may provide an indication of the likely mean or modal liberated grain size that will be present in the tailings, for instance, platy talc deposits of eastern Finland (0.5 up to 2 mm; European Commission, 2009) or the predominant gangue minerals of the Tellnes titanium mine tailings (10 to 200 µm; Olsgard and Hasle, 1993; Schulz et al., 2017).

While these reported values give a first-hand indication of a "typical" grain size for a given commodity extraction operation, they also show the inherent variability in achieved grain sizes for a given tailings deposit. This variation exists across different mining regions, but also within a given operation. For example, while a mineral feedstock may be typically reduced to a mean particle diameter of less than 75 µm, a further stage reduction to less than 53 µm or 38 µm ultra-fine grinding could also be implemented, with the ultimate decision depending on the considerations for additional energy costs (~80 kWh/t) and increased mineral conversion (Humphries et al., 2006; Amponsah-Dacosta, 2017; Rackley, 2017). Tailings associated with commodities such as copper, olivine, and diamond may also produce two or more classifications of waste size fractions (e.g., coarse and fine tailings). This regional and site variation, coupled with the different approaches to reporting a "typical" grain size for a given commodity or operation, means that the grain sizes utilised in this study act as an indication of the associated overall CDR potential, and tailings that are ground to finer sizes than the utilised size will inherently show a higher CDR potential than that presented here.

Supplementary Material B. Production volumes (2020) source, 2030 production estimates and anticipated market growth (2020-2030).

Production volumes (2020) source

Tailings production tonnages were made for materials deemed potentially suitable, based on modal mineralogy, E_{pot} and C_{pot} values (free of mineral reaction kinetics). Commodity production (e.g., annual production in tonnes of asbestos, nickel, PGM, diamond etc) taken from United States Mineral Commodity Summaries (USGS, 2021), with the exception of olivine production (taken from Kremer et al., 2019; world production of peridotite). Production values presented as total global volumes and national volumes, where available. For these tonnages, the proportional contribution of annual production of each commodity from different host rocks (e.g., diamond production from kimberlites, Ni production from Ni sulphides) has been estimated based on the information presented in Kesler and Simon (2015), Ndlovu et al. (2017) and USGS (2021). This is to account for the proportion of the total commodity production that may come from other host rock types that are not targeted for CDR purposes, e.g., diamonds from alluvial deposits, nickel from laterite deposits, Pb-Zn from sedimentary exhalative deposits.

2030 production estimates

Estimated production of commodities that are hosted within targetable host rocks (and therefore produce potentially suitable tailings tonnages) for 2030 were made by adding reported compound annual growth rates to the 2020 production volumes. In some instances, reported market growth is only projected to 2022 (in the cases of asbestos and lead-zinc), 2026 (nickel and PGM). For these commodities, growth is assumed to stay constant up to 2030, and all commodities are assumed to remain constant up to 2100 (due to limited or uncertain market forecasts beyond 2030).

Anticipated market growth (2020-2030)

Asbestos - compound annual growth rate of 3.3% up to 2022 (The Business Research Company, 2020).

Chromium - compound annual growth rate of 3% up to 2030 (Merchant Research & Consulting Ltd, 2021).

Copper - compound annual growth rate of 20% up to 2030 (Fastmarkets, 2021).

Diamond - compound annual growth rate of 3% up to 2030 (Grand View Research, 2019).

Nickel - compound annual growth rate of 5% up to 2026 (Mordor Intelligence, 2020a).

Olivine - assumed to mimic pyroxenite market (commodity that is of similar physical and chemical properties and is mined for the same usage - e.g., refractory material for steel production). compound annual growth rate of 2% up to 2030 (Transparency Market Research, 2020).

Lead-zinc - using zinc market growth as the indicator, compound annual growth rate of 3.8% up to 2022 (Mining Technology, 2019).

Platinum Group Metals - compound annual growth rate of 4.5% up to 2026 (Mordor Intelligence, 2020b).

Talc - compound annual growth rate of 3.6% up to 2026 (Business Wire, 2021).

Titanium - compound annual growth rate of 3.6% up to 2030 (MarketResearch.com, 2021).

References

Acker and Bricker (1992) Geochimica et Cosmochimica Acta 56, 3073-3092.

Amponsah-Dacosta (2017) Masters' thesis, University of Cape Town.

Amrhein and Suarez (1992) Geochimica et Cosmochimica Acta 56, 1815-1826.

Apollaro et al. (2018) Journal of Mediterranean Earth Sciences 10, 5-15.

Bailey (1974) International Symposium on Water-Rock Interaction (1st) 1976, Praha. 375-380.

Bandstra et al. (2008). In: Kinetics of Water-Rock Interaction (Brantley et al. (eds)) White, New York, Springer, 737-823.

Barnes and Naldrett (1985) Economic Geology 80, 627-645.

Barnes et al. (1992) Australian Journal of Earth Science 39, 335-347.

Becker and Le Roex (2006) Journal of Petrology 47, 673-703.

Bhilisse et al. (2014) Journal of Tethys 2, (4), 287-313.

Blum and Lasaga (1988) Nature 331, 431-433.

Bolaños-Benítez et al. (2018) Minerals 8, 261.

Boschi et al. (2006) Ofioliti 31, (2), 129-140.

Bullock et al. (2017) Minerals 7, (11), 229.

Business Wire (2021) https://www.businesswire.com/news/home/20210618005287/en/Global-Talc-Market-Outlook-and-Forecast-2021-2026---ResearchAndMarkets.com.

Buyukkahraman and Coban (2013) European Scientific Journal 9, (33), 123-135.

Carroll and Knauss (2001) DOE/NETL First National Conference on Carbon Sequestration 2001, Washington, DC.

Carten et al. (1988) Economic Geology 83, 266-296.

Casey et al. (1991) American Minerologist 76, 211-217.

Chen and Brantley (1998) Chemical Geology 147, 233-248.

Chou and Wollast (1984) Geochimica et Cosmochimica Acta 48, 2205-2217.

Chou and Wollast (1985) American Journal of Science 285, 963-993.

Dongre and Tappe (2019) Lithos 338-339, 155-173.

Duchesne (1999) Mineralium Deposita 34(2), 182-198.

Emsbo et al. (2010) U.S. Geological Survey Scientific Investigations Report, 2010-5070-N.

Eriksson (1982) Vatten 38, 409-415.

European Commission (2009) https://prtr-es.es/Data/images//Residuos-de-miner%C3%ADa.pdf.

Fastmarkets (2021) https://www.metalbulletin.com/Article/3979154/COPPER-SEMINAR-Copper-demand-to-reach-35-mln-tonnes-by-2030-on-EV-growth.html.

Ferenc et al. (2016) Journal of Geosciences 61, 239-254.

Friend et al. (2002) Contributions to Mineralogy and Petrology 143, 71-92.

Frogner and Schweda (1998) Chemical Geology 151, 169-179.

Gemmell and Large (1992) Economic Geology 102 (5), 893-922.

Golubev et al. (2005a) Chemical Geology 217, 227-238.

Grand View Research (2019) https://www.grandviewresearch.com/industry-analysis/diamond-market.

Grandstaff (1977) Geochimica et Cosmochimica Acta, 41, 1097-1103.

Grandstaff (1980) Third International Symposium onWater-Rock Interaction, WRI-3, 72-74.

Grandstaff (1986) In: Rates of Chemical Weathering of Rocks and Minerals (Colman and Dethier (eds)) Academic Press, Inc, 41-59.

Harris and Einaudi (1982) Economic Geology 77, 877-898.

Henderson (2013) 43-101 Technical Report prepared for Amerigo Resources Ltd.

Holdren and Speyer (1987) Geochimica et Cosmochimica Acta 51, 2311-2318.

Holwell and McDonald (2006) Mineralium Deposita 41, 575-598.

Hu et al. (2017) Journal of Materials in Civil Engineering 29 (2), 04016220.

Hume and Rimstidt (1992) American Mineralogist 77, 1125-1128.

Humphries et al. (2006) International Platinum Conference 'Platinum Surges Ahead'. The Southern African Institute of Mining and Metallurgy.

Industrial Minerals (2015) Industrial Minerals Research Features, ISSN 0019-8544, 574.

Johnson et al. (2001) First National Conference on Carbon Sequestration 2001, Washington, DC.

Kalinowski and Schweda (1996) Geochimica et Cosmochimica Acta 60, 367-385.

Kesler and Simon (2015). Mineral Resources, Economics and the Environment, 2nd Edition. Cambridge: Cambridge University Press.

Khedr and Arai (2010) Contributions to Mineralogy and Petrology 159, 137-157.

Knauss et al. (1993) Geochimica et Cosmochimica Acta 57, 285-294.

Korneliussen et al. (2000) NGU Bulletin 346, 27-38.

Kremer et al. (2019) Minerals 9, (8), 485.

Kursun et al. (2017) Balkan Mineral Processing Congress XVII.BMPC-2017.

Larson (1984) Economic Geology 79, 1880-1896.

Lechat et al. (2016) International Journal of Greenhouse Gas Control 47, 110-121.

Liu et al. (2012) Gondwana Research 22 (2), 597-614.

Machin (2000) Masters' thesis, Rhodes University.

Maier et al. (2008) Mineralium Deposita 43, 37-60.

Manley and Evans (1986) Soil Science 141, 106-112.

Manyeruke et al. (2005) South African Journal of Geology 108, 381-396.

MarketResearch.com (2021) https://www.marketresearch.com/Heavy-Industry-c1595/Materials-Chemicals-c91/.

Marston et al. (1981) Economic Geology 76, 1330-1363.

Martin et al. (2018) Mineralogical Magazine 82, 97-724.

May et al. (1995) Clay Minerals Society Programme Abstracts 32, 8819.

McCutcheon et al. (2017) Minerals 7, 191.

McCutcheon et al. (2017) Minerals 7, 191.

McFall et al. (2018) Ore Geology Reviews 99, 344-364.

McIntosh (2017) Masters' thesis, University of Witwatersrand.

Merchant Research & Consulting Ltd (2021) https://mcgroup.co.uk/researches/chromium.

Mindat.org (2016) https://www.mindat.org/loc-18742.html.

Mining Technology (2019) https://www.mining-technology.com/comment/zinc-outlook-2019.

Mordor Intelligence (2020a) https://www.mordorintelligence.com/industry-reports/base-metals-market.

Mordor Intelligence (2020b) https://www.mordorintelligence.com/industry-reports/platinum-group-metals-market.

Mosier et al. (2012) U.S. Geological Survey Scientific Investigations Report 2012-5157. 45 p.

Munro (1992) IMERYS Report 425354.

Nayak et al. (2020) International Journal of Phytoremediation 22, (8), 804-818.

Ndlovu et al. (2017) CRC Press, Taylor & Francis Group, Boca Raton, U.S.A., 532 p.

Ndlovu et al. (2017). Waste Production and Utilization in theMetal Extraction Industry. Boca Raton: CRC Press, Taylor and Francis Group.

Nickel (1973) Contributions in Sedimentology 1, 1-68.

Niranjana Minerals (2006) http://www.environmentclearance.nic.in/writereaddata/FormB/EC/FORM_1/24012017U2F8E64PForm1.pdf.

Niranjana Minerals (2013) http://environmentclearance.nic.in/writereaddata/FormB/EC/FORM_1/15022017JWI1P2O6FORM.pdf.

Ochoa-Landín et al. (2017) Ore Geology Reviews 81, (3), 1158-1171.

Oelkers and Schott (2001) Geochimica et Cosmochimica Acta 65, 1219-1231.

Olsgard and Hasle (1993) Journal of Experimental Marine Biology and Ecology. 172, 1-2, 185-213.

Oskierski et al. (2013) Chemical Geology 358, 156-169.

Oxburgh (1994) Geochimica et Cosmochimica Acta 58, 661-669.

Page (1979) U.S. Geological Survey Professional Paper, 1038, 69 p.

Palandri and Kharaka (2004) U.S. Geological Survey Open File Report 2004-1068.

Pasek Minerales (2021) Internal Report for the Landoy dunite mine.

Patten et al. (2017) Ore Geology Reviews 86, 487-508.

Pietek and Kurylak (2017) MET Grow Report, Metal Recovery from Low Grade Ores and Wastes Plus. Deliverable 2. 6., 12 p.

Pokrovsky and Schott (2000a) Geochimica et Cosmochimica Acta 64, 3313-3325.

Power et al. (2014) Minerals 4, 399-436.

Pronost et al. (2011) Environmental Science and Technology 45, 9413-9420.

Punturo et al. (2015) International Journal of Environmental Research and Public Health 9, (2), 405-418.

Quan et al. (1987) Economic Geology 82, 1912-1930.

Rackley (2017) Carbon Capture and Storage (Second Edition), pp. 253-282.

Rio Tinto (2019) https://riotintokennecott.com/wp-content/uploads/2019/05/Tailings.pdf.

Rodríguez et al. (1998) In: Environmental Geotechnics: Proceedings of the third international congress on Environmental Geotechnics, Balkema, Lisbon, Portugal, 7-11.

Rosso and Rimstidt (2000) Geochimica et Cosmochimica Acta 64, 797-811.

Schott et al. (1981) Geochimica et Cosmochimica Acta 45, 2123-2135.

Schulz et al. (2017) U.S. Geological Survey Professional Paper 1802-T.

Schweda (1989) Proceedings of the Sixth International Symposium on Water/Rock Interaction (Miles (ed)) A. A. Balkema, Rotterdam, 609-612.

Scoates and Mitchell (2000) Economic Geology 95, (4), 677-701.

Shen et al. (2009) Gondwana Research 16, 227-242.

Siegel and Pfannkuch (1984) Geochimica et Cosmochimica Acta 48, 197-201.

Somarin (2004) Journal of Geochemical Exploration 81, (1), 47-57.

Søndergaard (2019) Scientific Report, Aarhus University, Danish Centre for Environment and Energy, 319, 36 p.

Statista (2019) Energy & Environment. Statistics and market data on energy & environment.

Stillings and Brantley (1995) Geochimica et Cosmochimica Acta 59, 1483-1496.

Stillings et al. (1996) Chemical Geology 132, 79-89.

Sverdrup (1990a) The kinetics of base cation release due to chemical weathering. Lund University Press, Sweden. 246 pp.

Swami et al. (2007) Journal of the Transportation Research Board 1989-2, (1), 131-134.

Swoboda-Colberg and Drever (1993) Chemical Geology 105, 51-69.

Taylor et al. (2000a) Geochimica et Cosmochimica Acta 64, 2389-2400.

Teixeira et al. (2010) Comunicacoes Geologicas 97, 99-112.

The Business Research Company (2020) https://www.thebusinessresearchcompany.com/report/asbestos-mining-global-market-report.

Thom et al. (2013) Applied Geochemistry 35, 244-254.

Transparency Market Research (2020) https://www.transparencymarketresearch.com/pyroxenite-market.html.

U.S. Geological Survey (2021) National Minerals Information Center - Commodity Statistics and Information.

Ulrich and Heinrich (2002) Economic Geology 106, (4), 667-686.

van Hess et al. (2002a) Chemical Geology 189, 199-211.

Welch and Ullman (1993) Geochimica et Cosmochimica Acta 57, 2725-2736.

Welch and Ullman (2000) Chemical Geology 167, 337-354.

Wilson et al. (2006) Economic Geology 104, (1), 95-112.

Wilson et al. (2009) American Mineralogist 91, 1331-1341.

WMC Resources Ltd (2005) Annual Sustainability Report 2004. WMC Resources Ltd, Melbourne, Australia.

Wogelius and Walther (1991a) Geochimica et Cosmochimica Acta 55, 943-954.

Yalçin and Bozkaya (2006) Clays and Clay Minerals 54, (3), 333-350.

Zhang (1990) PhD thesis, University of Minnesota.

Zhang et al. (1993) Geochimica et Cosmochimica Acta 57, 1681-1689.

Zhang et al. (1996) Geochimica et Cosmochimica Acta 60, 941-950.

Zhang et al. (2019) Computers and Geosciences 133, 104316.

Zhou et al. (1996) Journal of Petrology 37, 3-21.