Advanced enhanced rock weathering (A-ERW) technology actively combined with site characteristics

Entrustees:

- WASEDA University
- 京都府立大学 Kyoto Prefectural University
- 北海道大学 HOKKAIDO UNIVERSITY
- 三菱重工

Re-Entrusted Contractors:

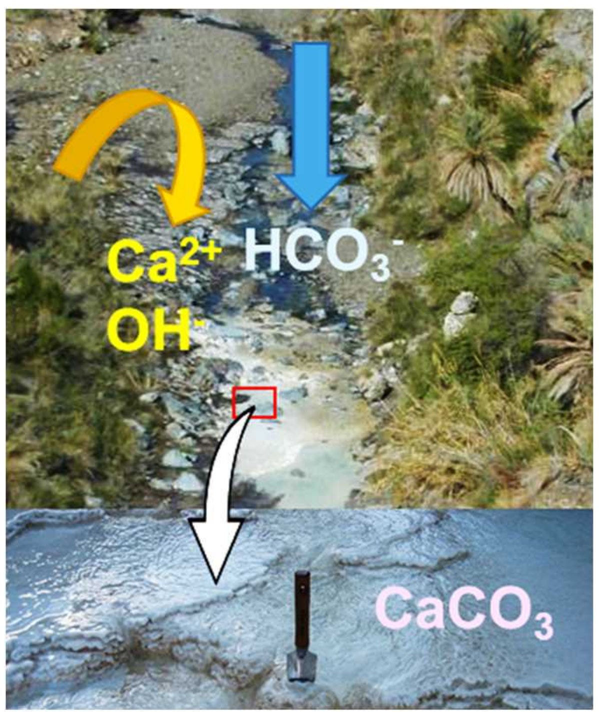
- ソブエクレー株式会社
- 国土防災技術株式会社
- QJ Science
- 地方独立行政法人 北海道立総合研究機構（道総研）
- 国立研究開発法人 森林研究・整備機構 森林総合研究所 Forestry and Forest Products Research Institute
- 農研機構 NARO
- 東京大学 THE UNIVERSITY OF TOKYO
- JIRCAS 国際農研
- 琉球大学 UNIVERSITY OF THE RYUKYUS
- 三菱重工パワー環境ソリューション

PM : Professor Takao NAKAGAKI
Waseda University

Overview: Enhanced rock weathering (ERW)

Weathering：Natural fracturing and leaching of rocks for 1,000~10,000 years and precipitating new compounds

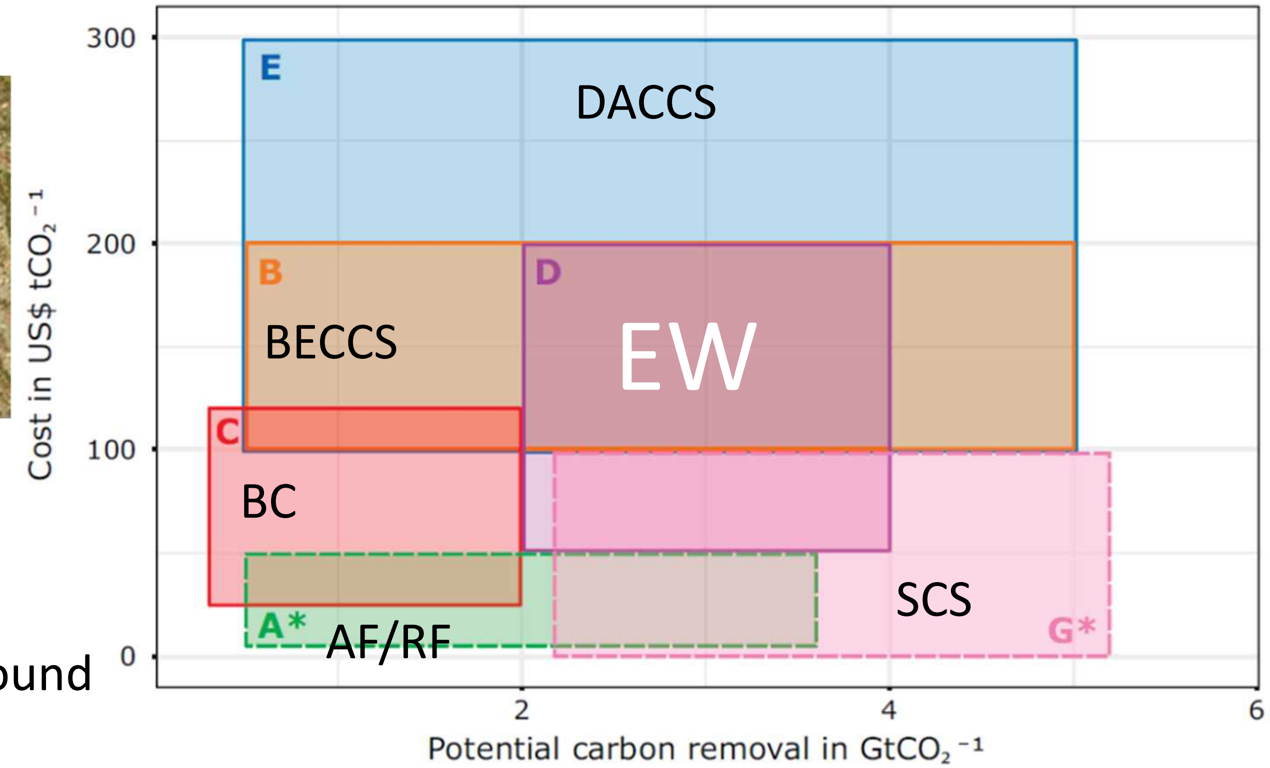
CO_2 mineralization：Sequestration of CO_2 as carbonates by silicate minerals containing Ca/Mg



Natural precipitation of calcium carbonate in a river

Carbfix project, Iceland CO_2 underground injection into basaltic formation

Cost and potential of CDR by NETs



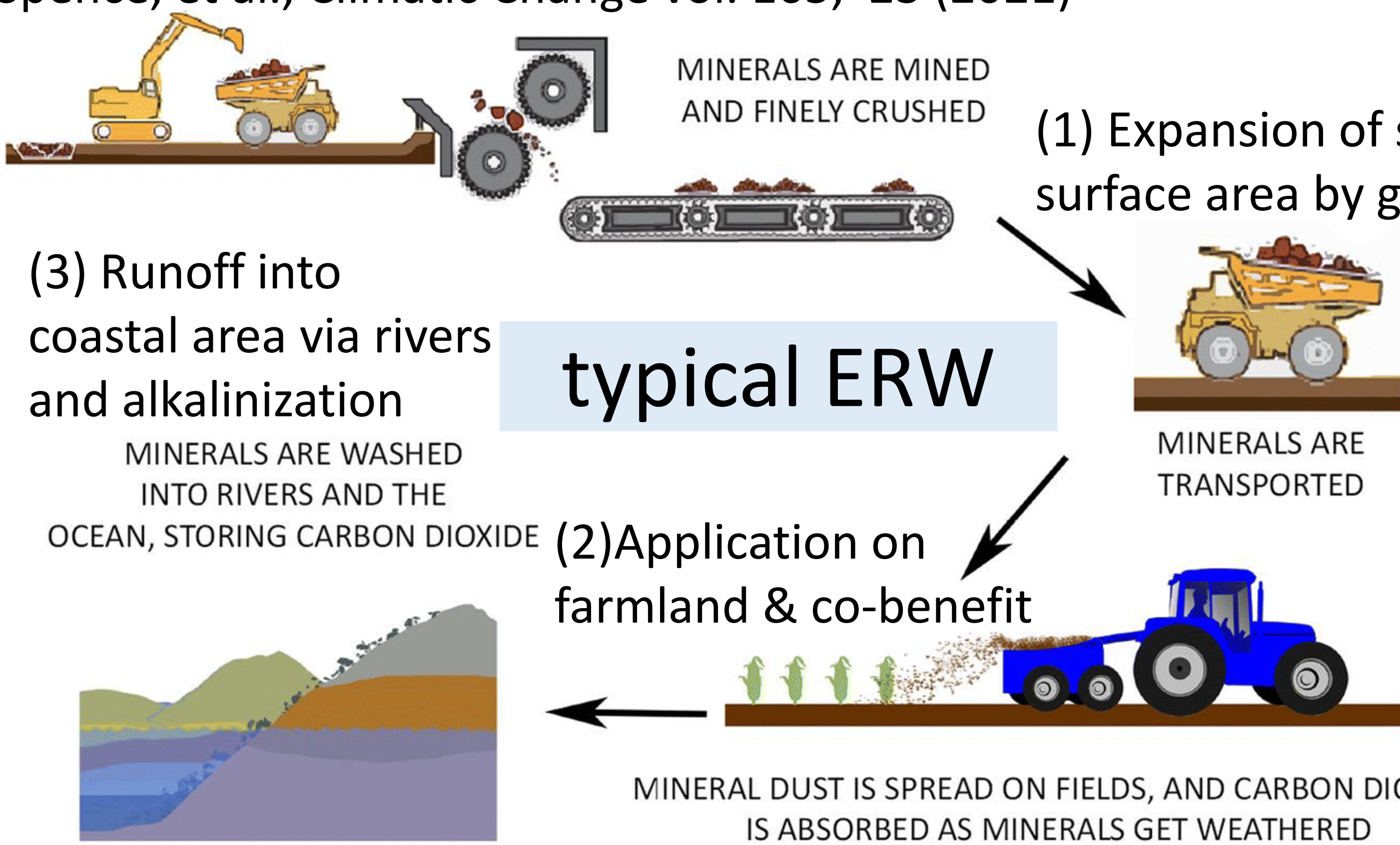
Pros & Cons of EW as a NETs
(Water usage of biological NETs is another Cons.)

NETs (TRL)	Landuse $m^2/t\text{-}CO_2/y$	Net reduction	Suitability for Japan
EW(4)	**29**	**Under validation**	◎
DACCS(6)	4	Confirmed	△
BECCS(7)	379	Confirmed	△
AF/RF(9)	978	Confirmed	○
SCS(7)	0	Under validation	○
BC(6)	580	Confirmed	○

This R&D PJ targets a novel ERW technology accelerating weathering x CO_2 mineralization of natural rock and clarifying net CDR effect (carbon accounting method).

ERW: current status & common problem in the world

Spence, et al., Climatic Change vol. 165, 23 (2021)



typical ERW

(1) Expansion of specific surface area by grinding

(2)Application on farmland & co-benefit

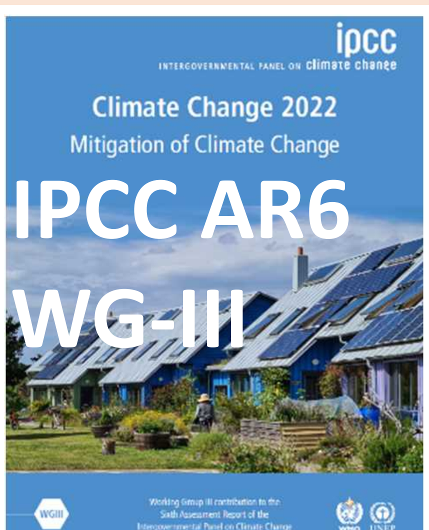
(3) Runoff into coastal area via rivers and alkalinization

(2) Limited application except farmland

Reference: Nature

Carbon accounting MUST be established

(1) Evaluation of pretreatment energy depending on rocks
(2) Quantification carbon storage depending on soils



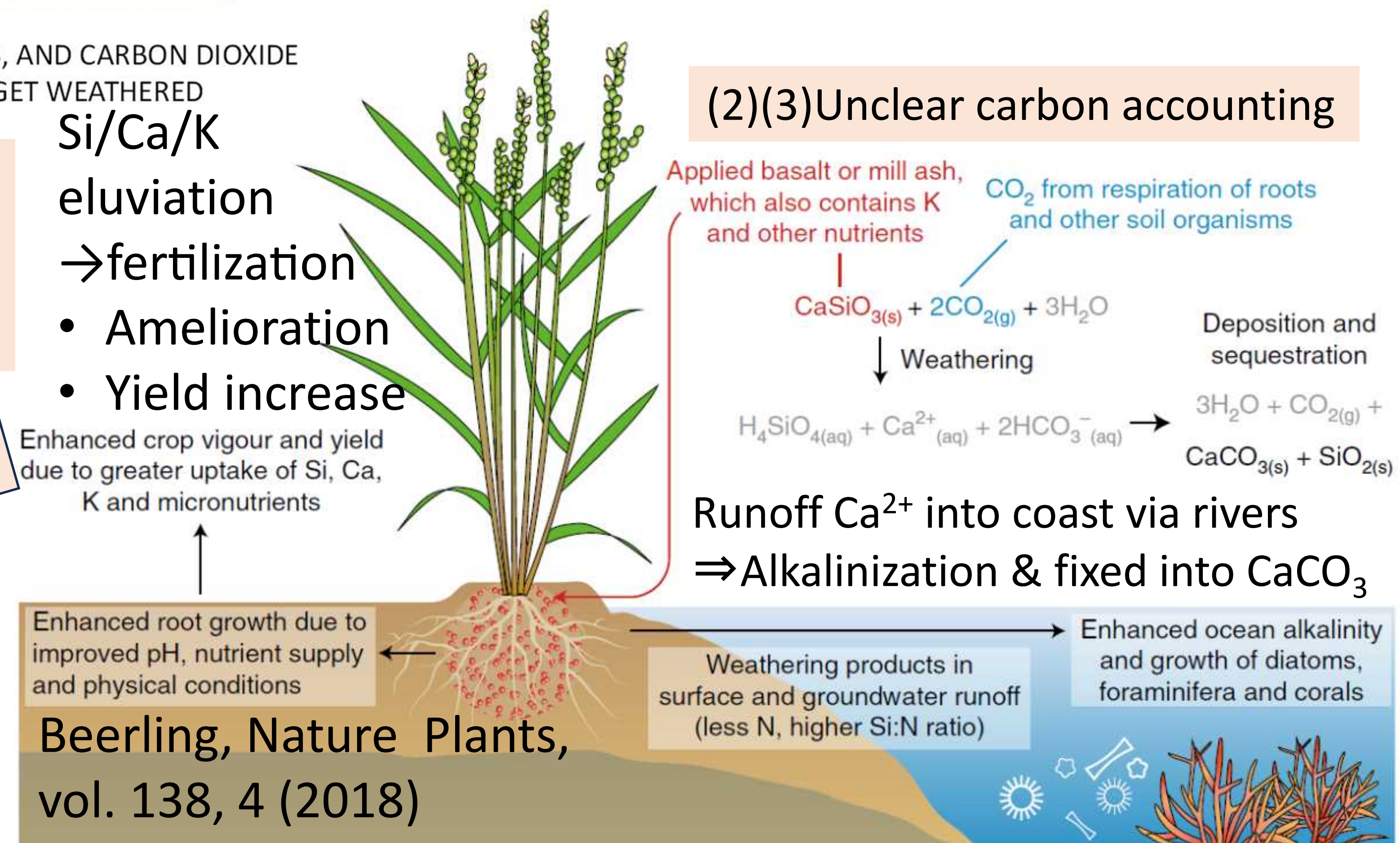
Collaborate with PM Morimoto

Great expectation found in these report, but…

Si/Ca/K eluviation
→fertilization

- Amelioration
- Yield increase

(2)(3)Unclear carbon accounting



Runoff Ca^{2+} into coast via rivers
⇒Alkalinization & fixed into $CaCO_3$

Beerling, Nature Plants, vol. 138, 4 (2018)

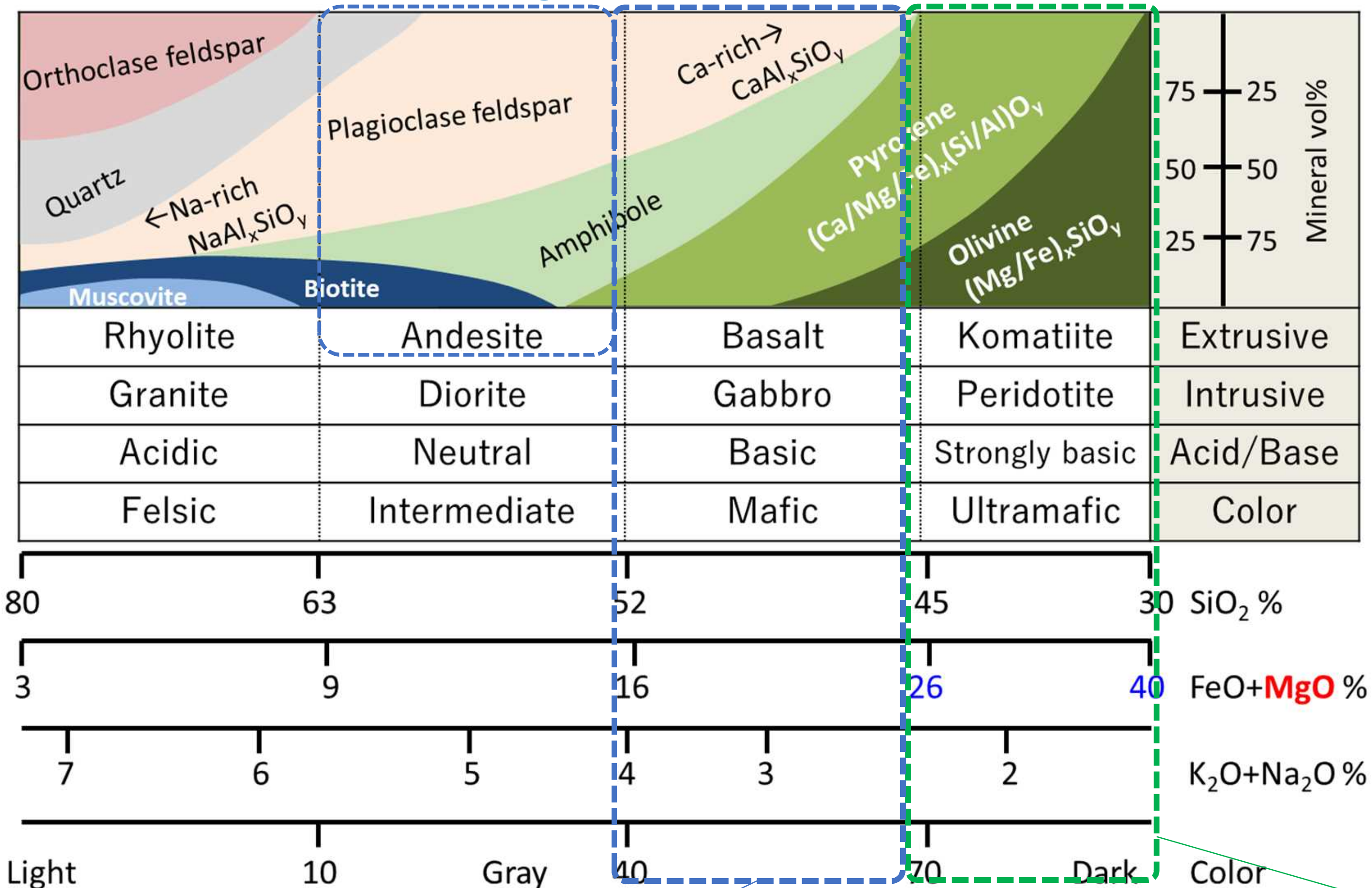
(2)Basalt only? (2) Side effect on soil?

A-ERW: Research activities

Accelerated
Accurate Accounting
Advanced
Active
Agro-industrial
Advantageous

-ERW

※Andesite will be investigated



Utilizing mafic rocks of high weathering potential scattered in Japan: 3 applications

- ✓ Development of cultivation and soil management aiming at enhancement of weathering and maximizing co-benefits
- ✓ Acceleration of weathering and new co-benefits creation by utilizing site characteristics
- ✓ Expanding availability of rocks utilizing geological characteristics of Japan

Ultramafic rocks	CO_2 mineralization house
Carbon accounting	Carbonation by rock Accurate measurement
Co-benefit	Backfilling as remediation material

Basalt	Application to farmland
Carbon accounting	Soil sequestration＋Ocean sequestration Climate × Soil × Crop × Rock condition All combinations should be investigated
Co-benefit	Increase in yield & organic carbon storage, nutrients supply, Improvement of physical conditions of soil, Reduction of CH_4/N_2O emission, OAE, etc.

Basic application of ERW

Enhanced weathering by acidic circumstance sites: Needless grinding energy

Basalt	Application to abandoned mines / forested slopes
Carbon accounting	Mainly ocean sequestration Accurate measurement for Ca/Mg leaching
Co-benefit	Neutralization of acidic mine drainage, OAE, CO_2 reduction by replacement of limestone, landslide prevention

CO_2 mineralization house
(Simple gas-solid contacting house)
@Honjo-Waseda campus

A-ERW's Team structure   Period: Sep. 2022 ~ Mar.2025

PD Dr. K. Yamaji
(President, RITE)

NEDO Dept. of Moonshot

PM T. Nakagaki

Waseda Univ.
Prof. T. Nakagaki

①Site suitability assessment(2)
②Mining and grinding test/assay evaluation(1)(2)(3)
③Acceleration of ERW(1)
⑤Information database of accurate carbon accounting(1)

(Subcontract)
Sobueclay, LTD.
②-(1)(2)(3)

MHI, LTD.
Decarbonization Business Dept.

④Field testing under real environment & development of effective monitoring(1)
⑤Consolidation of information database of accurate carbon accounting(1)
⑥Conceptual design of pilot-scale demonstration(1)

(Joint implementation)
MHI Power Environmental Solutions, Ltd.
①-(1), ①-(1), ②-(1)

Hokkaido Univ.
Prof. T. Sato

①Site suitability assessment(1)(2)
②Mining and grinding test/assay evaluation(1)(2)(3)
③Acceleration of ERW(2)
④Field testing under real environment & development of effective monitoring(2)(3)
⑤Information database of accurate carbon accounting(2)
⑥Conceptual design of pilot-scale demonstration(2)

(Subcontract)
QJ Science, LTD.
①-(1),② -(3),②-(2)
Japan Conservation Engineers & Co.,LTD.
①-(2),②-(1),④-(2),⑥-(2)
NARO ③-(2),④-(3)
HRO ②-(1),④-(2)
FFPRI ④-(2)

Kyoto Prefectural Univ.
Prof. A. Nakao

①Site suitability assessment(2)
③Acceleration of ERW(2)
④Field testing under real environment & development of effective monitoring(3)
⑤Information database of accurate carbon accounting(2)
⑥Conceptual design of pilot-scale demonstration(2)

(Subcontract)
The U. of Tokyo ③-(2), ②-(2)
JIRCAS ④-(3)
Ryukyu U. ④-(3)

Regarding carbon accounting, we collaborate with Dr. Morimoto PM team, and will invite oversea advisors.

NARO: National Agriculture and Food Research Organization
HRO: Hokkaido Research Organization
FFPRI: Forestry and Forest Products Research Institute
JIRCAS: Japan International Research Center for Agricultural Sciences

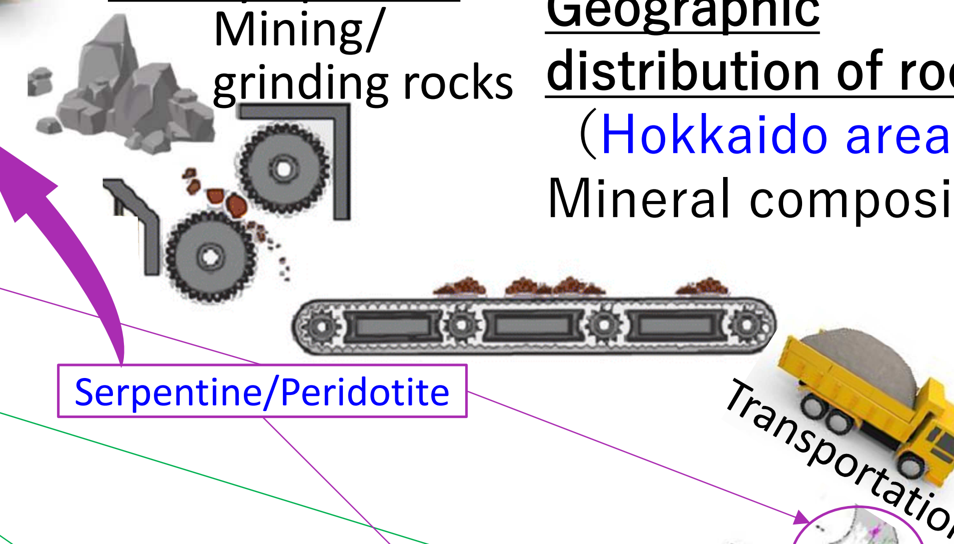
A-ERW project goal

Items	Subitems	2024FY Ultimate goal
①Site suitability assessment	(1)Geological assessment	Complete 8/8 sites × 4 rocks
	(2)Business environment assessment	Pick up 3 candidate sites for pilot-scale demonstration
②Mining & grinding test/ assay evaluation	(1)Candidate site of sampling	Trial mining at 3 sites & reflect to database
	(2)Grinding test & assay evaluation of mineral phase	Obtain test data of 32 rocks & Evaluate energy consumption from mining to grinding at 4 sites
	(3)Prediction of Pretreatment energy	Evaluate grinding energy in comparison with theoretical value & Consolidate LCA database
③Acceleration of ERW	(1)CO_2 mineralization by industrial methods	Complete mineralization data considering enhancement factors & Explore conditions for 0.2t-CO_2/t-Rock
	(2)ERW application on open sites	Complete modeling associated with conditions for each open site
④Field testing under real environment & development of effective monitoring	(1)Gas-solid contactor	Optimize industrial method for enhanced weathering
	(2)Application on forest slop / abandoned mine site	Complete field testing at two locations for each site
	(3)Application on farmland	Complete field testing at three locations different Climate/Soils/Crops
⑤Information database of accurate carbon accounting	(1)Carbon accounting for industrial CO_2 mineralization	Calculate net CDR data in t-CO_2/t-Rock
	(2)Carbon accounting including natural carbon cycle	Calculate net CDR and co-benefits by determining appropriate evaluation boundary toward TRL upgrading
⑥Conceptual design of pilot-scale demonstration	(1)Conceptual design of industrial ERW	Evaluate net CDR and economy assuming full-scale implementation, introduction of VRE, etc.
	(2)Conceptual design of ERW application on open sites	Complete conceptual design and rough budget

Carbon accounting database: An ultimate image

Project-based net CDR accounting
Σprojects = Potential in Japan
TEA
Dynamic LCA （～2050）

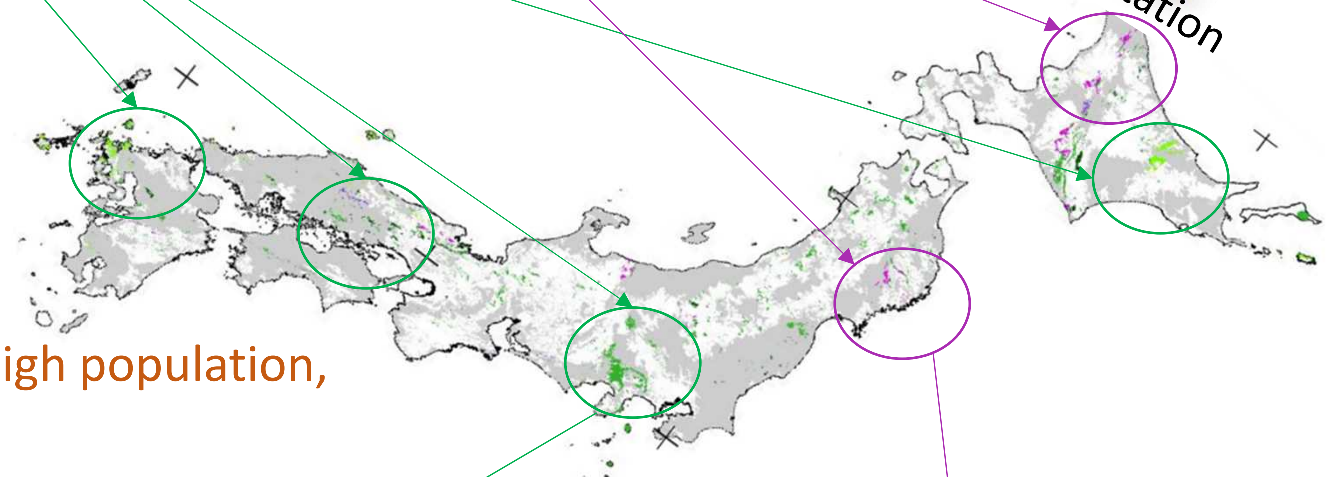
Evaluation of pretreatment energy customized for type of rocks



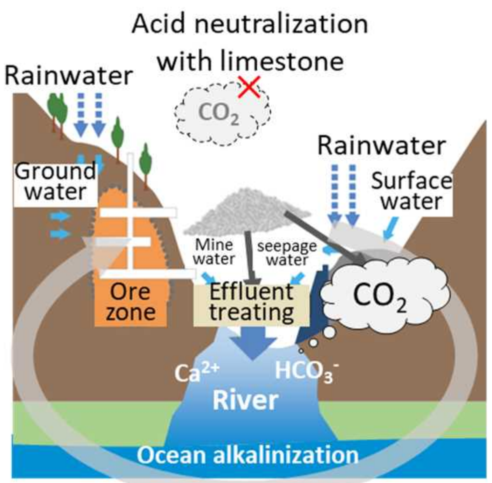
Geographic distribution of rock
（Hokkaido area）
Mineral composition

Alkali basalt

Serpentine/Peridotite

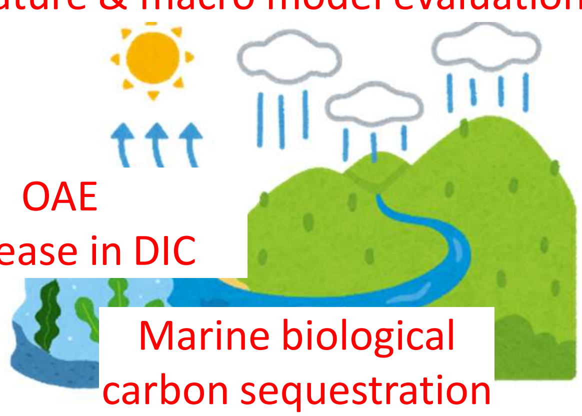


Forested slops
Abandoned mines

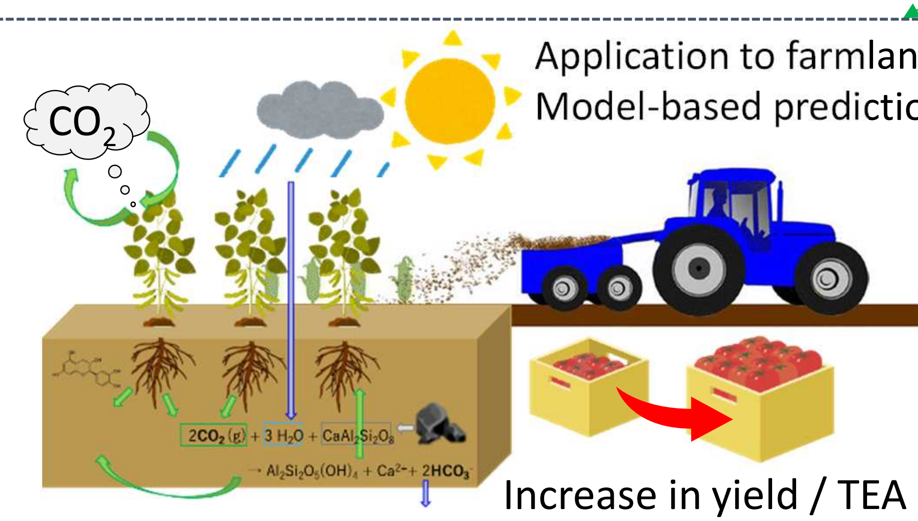


Keys to success for Japanese ERW:
3 condition-overlapping locations
= **Rocks applicable for ERW**
(HRO/AIST database)
× **Existing quarry operators**
(List from related associations)
× **Suitable application sites**
(Excluding areas: national parks, high population, no forest road)

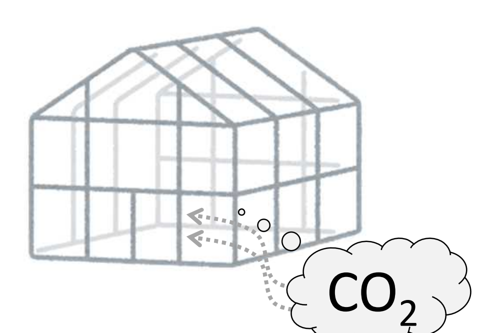
Sea←River←Groundwater
Literature & macro model evaluation

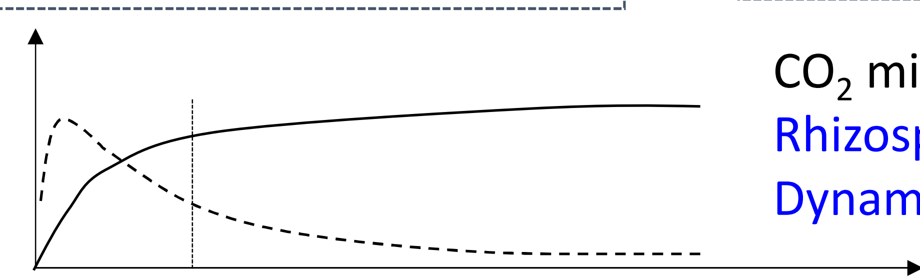


Application to farmland
Model-based prediction



Easiest carbon accounting:
Gas-solid contacting house





CO_2 mineralization & soil carbon balance (QPAC)
Rhizosphere refinement / Certainty improvement
Dynamic change in soil carbon balance

Color legend:
Common in two ERW PJ
A-ERW   AIST team
Literature-based estimation
(Out of scope)

Oct. 30, 2023 ERW WS@UDX Akihabara

第１回ムーンショット型研究開発事業

風化促進ワークショップ

稲葉敦（日本LCA推進機構理事長）

吉田朋央（NEDO新領域・MS部室長）

ビデオメッセージ
Dr.DouglasWicks（米国DOEARPA-EPROGRAMDIRECTOR）

中垣隆雄（早稲田大学/PM）

佐藤努（北海道大学）

中尾淳（京都府立大学）

森本慎一郎（産総研/PM）

徂徠正夫（産総研）

関原明（理研）

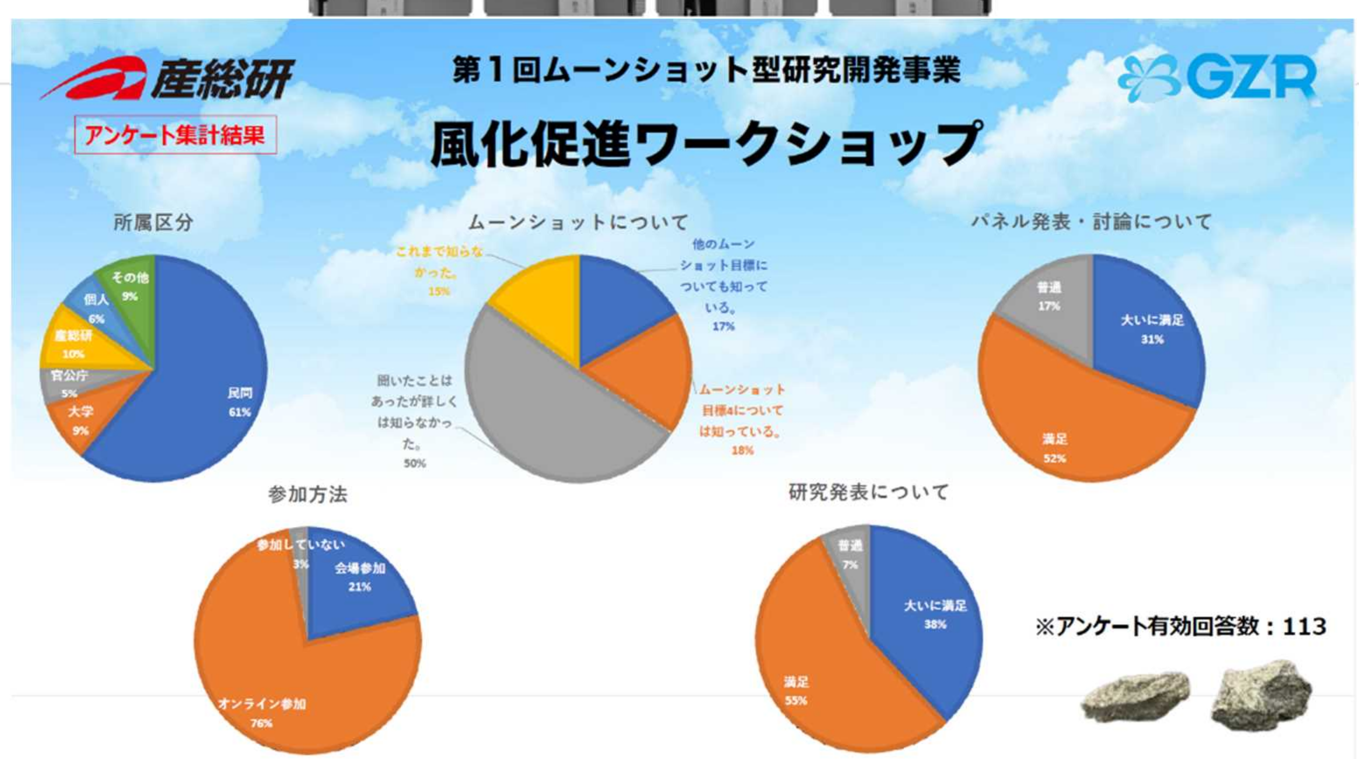
上野貴弘（電力中央研究所上席研究員）

辻悠介（三菱商事株式会社次世代エネルギー部門カーボンマネジメントオフィスCCUSライン長）

桑江朝比呂（ジャパンブルーエコノミー技術研究組合理事長）

吉野彰（産総研ゼロエミッション国際共同研究センター研究センター長）

Results of questionnaire
↓generally favorable



Workshop sponsored by GZR of AIST
Jointly held with Morimoto PM team

Profs. Nakagaki, Sato and Nakao joined to the workshop from A-ERW

Information database of accurate carbon accounting
Data & Management policy

Data management target: All A-ERW PJ data for carbon accounting

Geological distribution data
Geological/rock distribution (HRO)
Locations of Quarry operators (Related association)
Business area: available or not
(Forest roads, national parks, etc.. from GIS)

Pre-treatment data
Energy usage by primary quarry operation
Energy usage by milling, grinding, transportation (Sobueclay)
Energy usage by scattering of ground rock
(Related background data for power generation, equipment production, etc..)

Operation data under and after ERW
Energy usage by gas-solid contacting house operation, post-processing, etc.. (MHI, JCE)

Net CDR data
Potential and mineralization rate of rocks
Leaching and runoff to river/sea of Ca/Mg
Soil sequestration (U/NIs)

Co-benefit data
Abandoned mines/
Forested slopes
Farmlands (U/NIs)

U/NIs:
After publication

U/NIs:
Before publication

Companies:
Confidential data for competitiveness

Consultation

Consultation

U/NIs: Universities and National or Prefectural research institutes

QJ Science (data management, firewall)

Request for disclosure

Acceptance for disclosure

PM Morimoto team (Mission Innovation LCA/TEA WG → international standard)

Frequent meetings have been held since PJ start

③ Artificial enhancement: Methodology & Summary

Application	(1) Gas-solid contacting house	(2)-1 Abandoned mine	(2)-2 Forested slope	(3) Farmland
Target phenomena	CO_2 mineralization	Leaching/ Physical weathering	Leaching/ Physical weathering	Physical weathering/ CO_2 mineralization
Expandability	Quarry operator sites with spatial aggregation	Number of applicable sites	Total forest area	Total plant area

Reference case for benchmarking
(trace calculation based on Beerling et al.)

40 t-R/ha/y of 10㎛ basalt on farmland		Basaltic type	
	Unit	Alkali	Tholeiite
SS: Soil Sequestration	t-CO_2/ha/y	1.42	1.55
	t-CO_2/t-R/y	0.035	0.039
OS※: Ocean Sequestration	t-CO_2/ha/y	6.66	2.70
	t-CO_2/t-R/y	0.166	0.068
SS+OS	t-CO_2/ha/y	8.08	4.25
	t-CO_2/t-R/y	0.202	0.106
Potential	t-CO_2/t-R	0.345	0.320
	1 year extent	62.6%	50.9%

※ Assuming that 83.1% of DIC will remain even after several decades.

(1) Gas-solid contacting house
Increase in potential up to 0.2 t-CO_2/t-R/y (> x4) by:
Plutonic/ultra-mafic rocks, PSD control,
Humidification, Forced convection
Quarry operator sites with spatial aggregation
*Stacked shelves: No limitation of 40 t-CO_2/ha/y

(2)-1 Abandoned mine site
Cut off grinding-related CO_2 emission 0.0425 t-CO_2/t-R (28~47% decrease against OS) by optimizing:
Low pH effect of acidic mine effluent,
Mechanical effect of river, PSD
Credit OS value
*Site-specific amount: No area limitation (spot site)

(2)-2 Forested slope
Cut off grinding-related CO_2 emission 1.70 t-CO_2/ha/y (28~47% decrease against SS+OS) by optimizing:
Low pH effect of rainwater (≃5.6) ,
Mechanical effect of river, PSD, Credit OS value
Target total forested area: 25 × 10^6 ha
*Area-specific amount: 20 t/ha

(3) Farmland
Development of cultivation and soil management method (climates, soils, crops, rocks) with quantifying:
local dependency (around root zone) ,
soil carbon sequestration, other GHGs except CO_2
Target toral plant area 4.3 × 10^6 ha

A-ERW in Japan: Potential estimation example

	A) Gas-solid contacting house	B)-1 Abandoned mine site	B)-2 Forested slope	C) Farmland
$t\text{-}CO_2/ha/y$	6,600~13,200	50 (per site)	0.3	3.0
Area/annual fixation potential	33,000~66,000 $t\text{-}CO_2$	50 $t\text{-}CO_2/y$	37,500 $t\text{-}CO_2$	20,000 $t\text{-}CO_2$
Assumptions/ Conditions	CO_2 Mineralization potential =0.5 $t\text{-}CO_2/t\text{-}R$ Reaction extent=44% Required area =0.1ha/site Amount of rock=3,000~6,000 t/y/site Mining depth 2m/y	CO_2 Mineralization potential =0.0845 $t\text{-}CO_2/t\text{-}R$ Applying 1000 t/y at Shojin river mine site in Hokkaido	CO_2 Mineralization potential =0.0492 $t\text{-}CO_2/t\text{-}rock$ Applying 20 t-R/ha at Shojin river slope in Hokkaido	150 t-R/ha basalt application on soba farmland in Fukushima (equivalent to 0.59 $t\text{-}CO_2/ha/2.5months$)

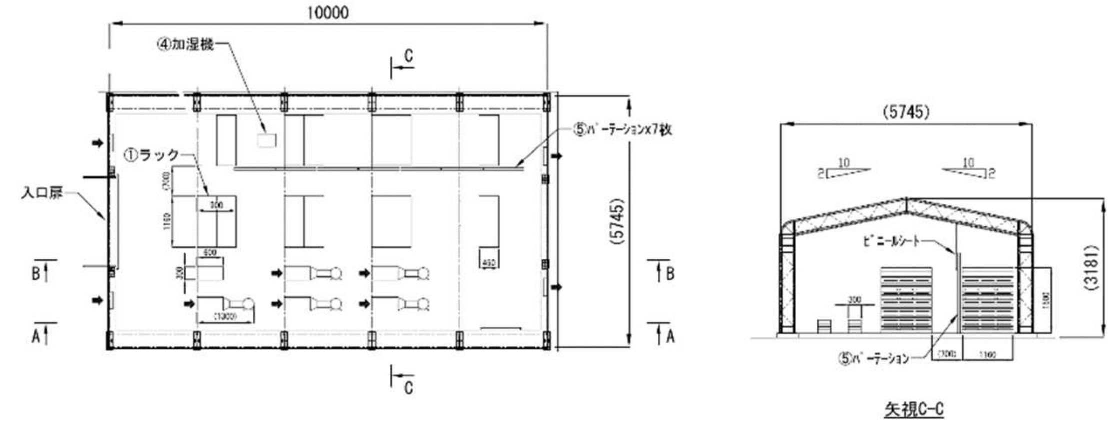
Cheap/Fast/Massive weathering
→Spatial aggregation
Gas-solid contacting house

Premium/
High value-added products
by natural growth
→Farmland application

Best of two applications
→ Abundant mine / Forest slope

A-ERW　Field testing pictures

Open-pit peridotite quarry



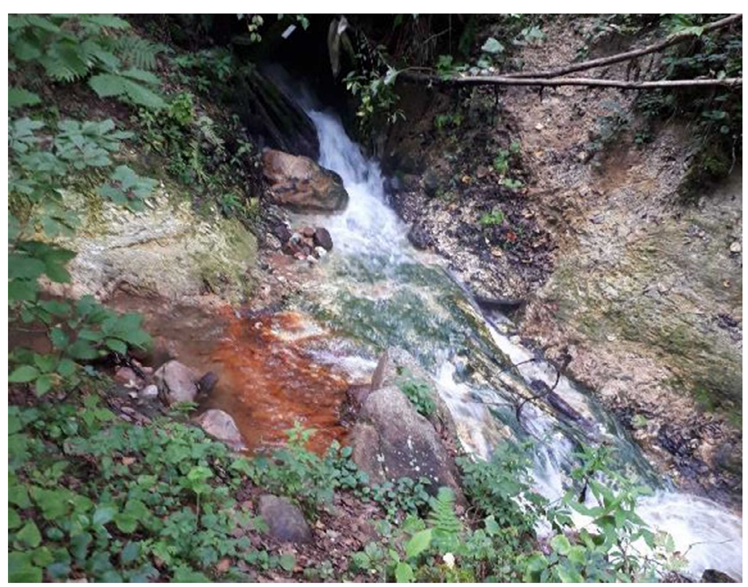
Gas-solid contacting house at Honjo-Waseda campus

Rice farming @ Kyoto

Soybeans @ Hokkaido Univ.

Soybeans @ Tsukuba NARO

Forested slope
@ Hokkaido



Shojin river mine entrance
@Hokkaido

Sugarcane
@ Ishigaki island JIRCAS

②Mining & grinding test / assay evaluation
(2) Grinding test & assay evaluation of mineral phase

Database of CO_2 mineralization potential

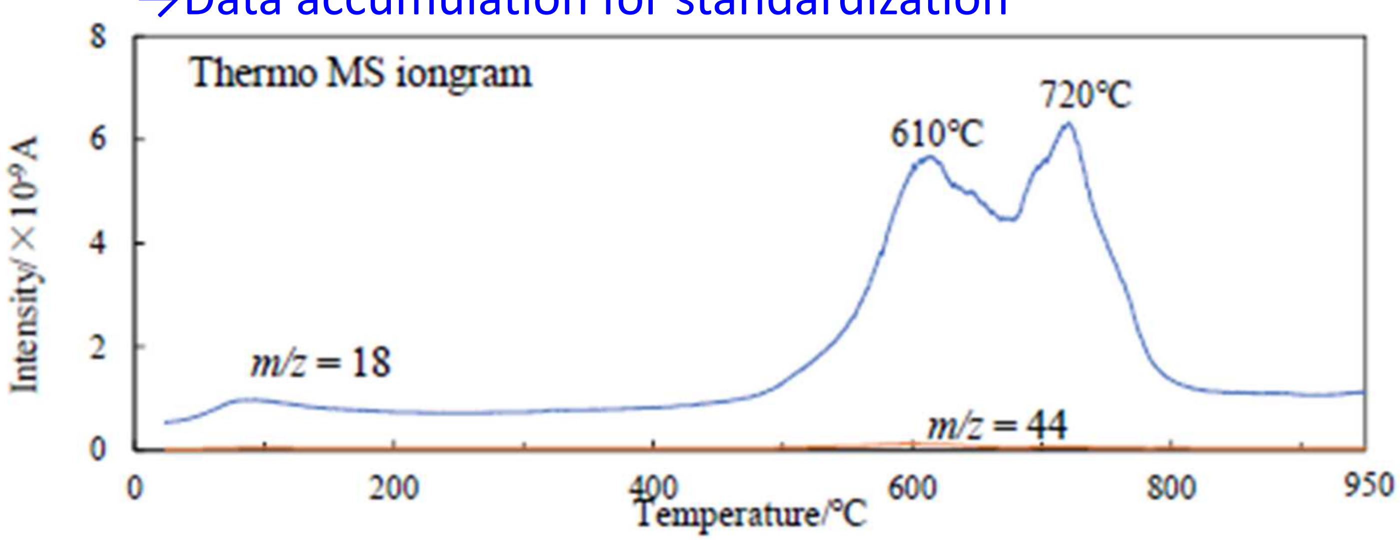
A. Determine CO_2 mineralization potential =Quantify effective minerals

- ✓ Polarizing microscopy (petrographic analysis, shape)
- ✓ XRD (composition, Rietveld analysis)
- ✓ XRF (major/minor elemental analysis)
- ✓ Electroscope (petrographic analysis, chemical composition)
- ✓ Development of simple chemical extraction method

B. Asbestos analysis

- ✓ XRD qualitative assay according to JIS A 1481-1
- ✓ TGA
- ✓ TG-DTA-MS

※Asbestos in natural rock can be quantified
→Data accumulation for standardization



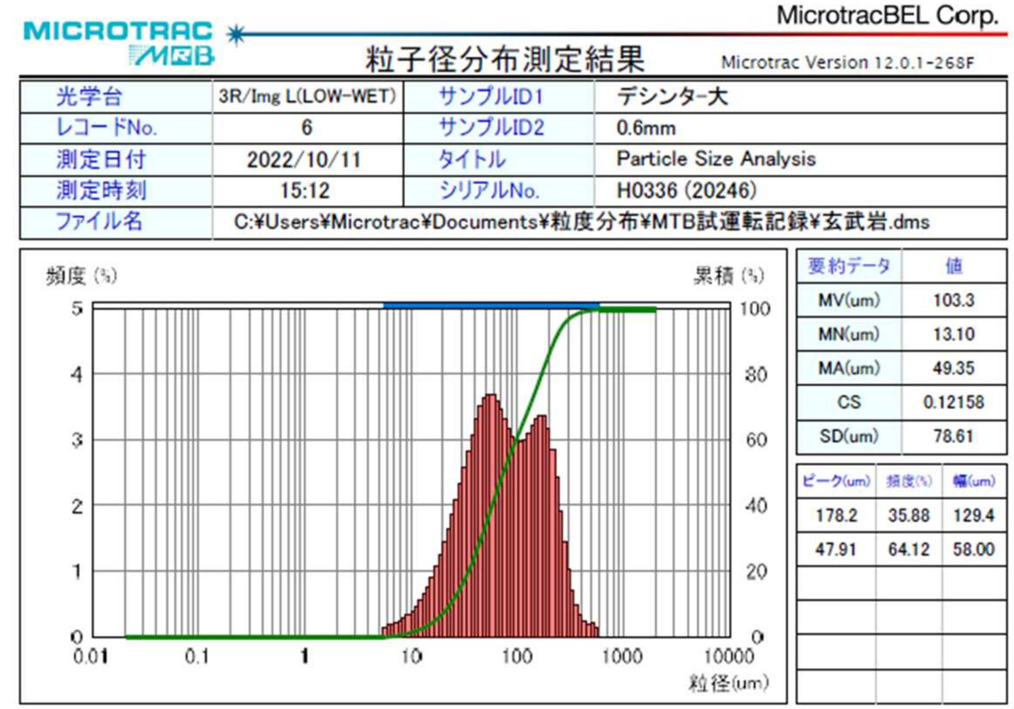
H_2O < 600 °C → Lizardite
H_2O ≃ 650 °C → Chrysotile
H_2O > 700 °C → Antigorite

C. Grinding test & post-process analysis

<u>Data analysis</u>

→<u>Evaluation for grinding</u>

- ✓ PSD before grinding
- ✓ PSD after grinding
- ✓ Electricity usage
- ✓ Grinding rate (kg/h)
- ✓ Absolute specific gravity

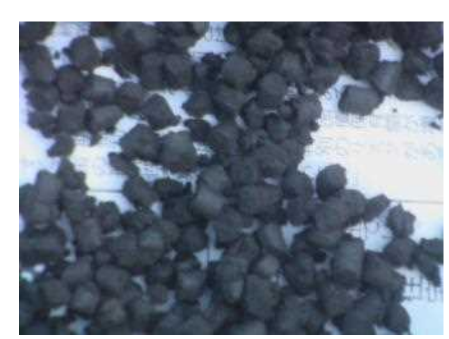


光学台	3R/Img L(LOW-WET)	サンプルID1	デシンタ-大
レコードNo.	6	サンプルID2	0.6mm
測定日付	2022/10/11	タイトル	Particle Size Analysis
測定時刻	15:12	シリアルNo.	H0336 (20246)
ファイル名	C:¥Users¥Microtrac¥Documents¥粒度分布¥MTB試運転記録¥玄武岩.dms		

要約データ	値
MV(um)	103.3
MN(um)	13.10
MA(um)	49.35
CS	0.12158
SD(um)	78.61

ピーク(um)	頻度(%)	幅(um)
178.2	35.88	129.4
47.91	64.12	58.00

D. Pelletization: Trial & testing



②(3) Prediction of Pretreatment energy

Example

Actual measurement value (Basalt dust)

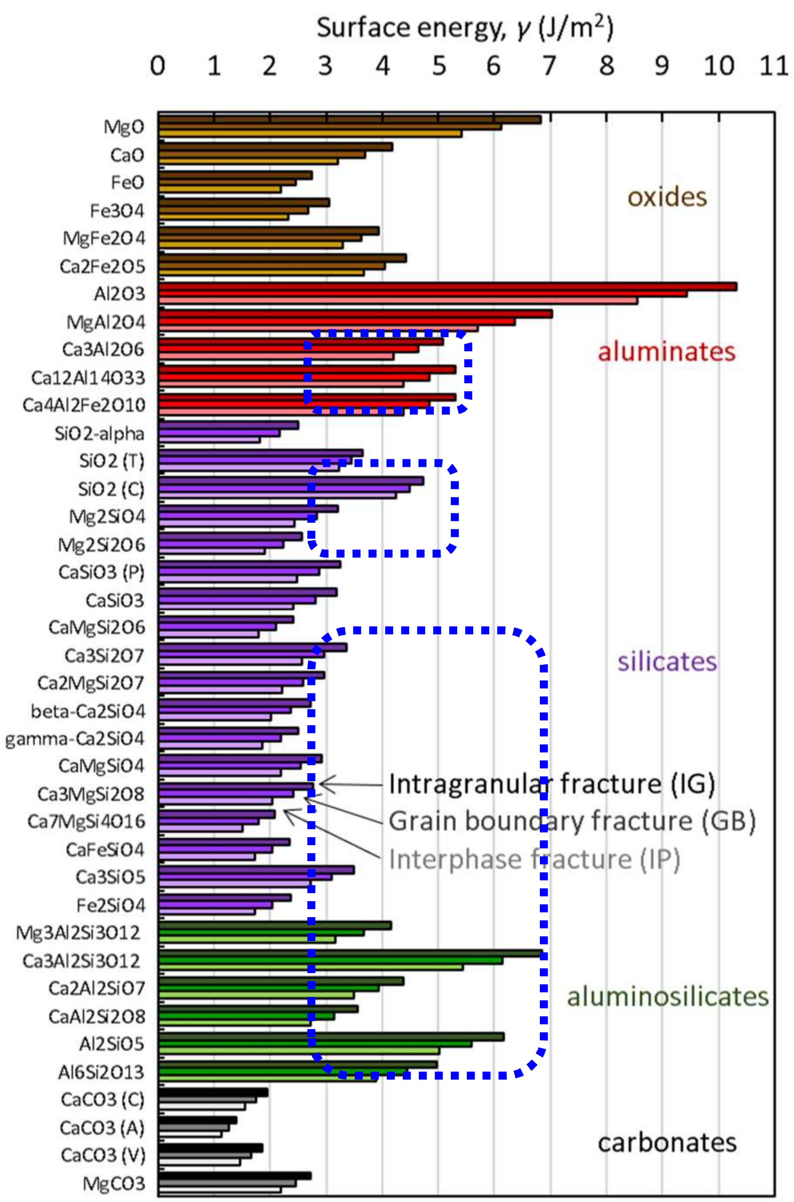
900～1000 kg/h Roller mill
Average rate: 950 kg/h
Average voltage: 205.6 V
Average amperage: 56.65 A
Average power: 20.17 kW

950kg/h, 20.17 kWh = 72612 kJ
→76.4 kJ/kg
0.010 t-CO_2/t-R (0.48 kg-CO_2/kWh)
40 t-R/ha/y → 1.70 t-CO_2/ha/y
※Consistent with 0.013 t-CO_2/t-Rock reported in J-LCA CR2 project

$$\eta = \frac{\gamma \Delta SA}{E_{grind}}$$

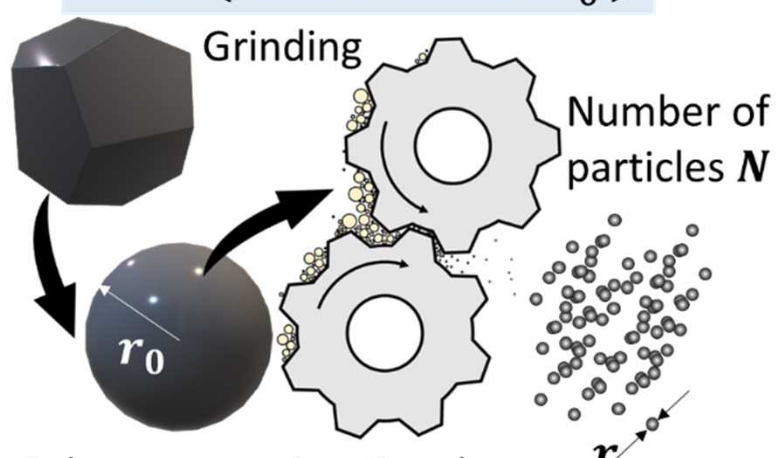
ΔSA ：Change in surface area [m^2/kg]
E_{grind} ：Electricity usage [J/kg]
γ ：Surface energy [J/m^2]
η ：Energy efficiency [%]

CH	粒径(um)	頻度(%)	累積(%)	CH	粒径(um)	頻度(%)	累積(%)	CH	粒径(um)	頻度(%)	累積(%)	CH	粒径(um)	頻度(%)	累積(%)
1	2000	0.00	100.00	34	114.1	1.77	55.65	67	6.541	0.33	1.47	100	0.375	0.00	0.00
2	1826	0.00	100.00	35	104.7	1.81	53.88	68	5.998	0.29	1.14	101	0.344	0.00	0.00
3	1674	0.00	100.00	36	95.96	1.87	52.07	69	5.500	0.25	0.85	102	0.315	0.00	0.00
4	1535	0.00	100.00	37	88.00	1.95	50.20	70	5.044	0.23	0.60	103	0.289	0.00	0.00
5	1408	0.00	100.00	38	80.70	2.03	48.25	71	4.625	0.22	0.37	104	0.265	0.00	0.00
6	1291	0.00	100.00	39	74.00	2.11	46.22	72	4.241	0.15	0.15	105	0.243	0.00	0.00
7	1184	0.00	100.00	40	67.86	2.20	44.11	73	3.889	0.00	0.00	106	0.223	0.00	0.00
8	1086	0.00	100.00	41	62.23	2.27	41.91	74	3.566	0.00	0.00	107	0.204	0.00	0.00
9	995.6	0.27	100.00	42	57.06	2.33	39.64	75	3.270	0.00	0.00	108	0.187	0.00	0.00
10	913.0	0.42	99.73	43	52.33	2.36	37.31	76	2.999	0.00	0.00	109	0.172	0.00	0.00
11	837.2	0.47	99.31	44	47.98	2.37	34.95	77	2.750	0.00	0.00	110	0.158	0.00	0.00
12	767.7	0.53	98.84	45	44.00	2.36	32.58	78	2.522	0.00	0.00	111	0.145	0.00	0.00
13	704.0	0.59	98.31	46	40.35	2.33	30.22	79	2.312	0.00	0.00	112	0.133	0.00	0.00
14	645.6	0.69	97.72	47	37.00	2.29	27.89	80	2.121	0.00	0.00	113	0.122	0.00	0.00
15	592.0	0.82	97.03	48	33.93	2.23	25.60	81	1.945	0.00	0.00	114	0.111	0.00	0.00
16	542.9	1.02	96.21	49	31.11	2.16	23.37	82	1.783	0.00	0.00	115	0.102	0.00	0.00
17	497.8	1.29	95.19	50	28.53	2.08	21.21	83	1.635	0.00	0.00	116	0.094	0.00	0.00
18	456.5	1.74	93.90	51	26.16	1.99	19.13	84	1.499	0.00	0.00	117	0.086	0.00	0.00
19	418.6	2.43	92.16	52	23.99	1.89	17.14	85	1.375	0.00	0.00	118	0.079	0.00	0.00
20	383.9	2.96	89.73	53	22.00	1.77	15.25	86	1.261	0.00	0.00	119	0.072	0.00	0.00
21	352.0	3.33	86.77	54	20.17	1.65	13.48	87	1.156	0.00	0.00	120	0.066	0.00	0.00
22	322.8	3.45	83.44	55	18.50	1.51	11.83	88	1.060	0.00	0.00	121	0.061	0.00	0.00
23	296.0	3.30	79.99	56	16.96	1.38	10.32	89	0.972	0.00	0.00	122	0.056	0.00	0.00
24	271.4	3.05	76.69	57	15.56	1.24	8.94	90	0.892	0.00	0.00	123	0.051	0.00	0.00
25	248.9	2.70	73.64	58	14.27	1.10	7.70	91	0.818	0.00	0.00	124	0.047	0.00	0.00
26	228.2	2.40	70.94	59	13.08	0.97	6.60	92	0.750	0.00	0.00	125	0.043	0.00	0.00
27	209.3	2.14	68.54	60	12.00	0.86	5.63	93	0.688	0.00	0.00	126	0.039	0.00	0.00
28	191.9	1.96	66.40	61	11.00	0.75	4.77	94	0.630	0.00	0.00	127	0.036	0.00	0.00
29	176.0	1.84	64.44	62	10.09	0.66	4.02	95	0.578	0.00	0.00	128	0.033	0.00	0.00
30	161.4	1.76	62.60	63	9.250	0.57	3.36	96	0.530	0.00	0.00	129	0.030	0.00	0.00
31	148.0	1.73	60.84	64	8.482	0.50	2.79	97	0.486	0.00	0.00	130	0.028	0.00	0.00
32	135.7	1.72	59.11	65	7.778	0.44	2.29	98	0.446	0.00	0.00	131	0.026	0.00	0.00
33	124.5	1.74	57.39	66	7.133	0.38	1.85	99	0.409	0.00	0.00	132	0.023	0.00	0.00



ΔSA Surface area expansion

$$= RF\left(N \cdot 4\pi r^2 - 4\pi r_0^2\right)$$



Sphere approximation
× RF (1.5~2)

$$\Delta SA = RF \sum_i \left(\frac{V_i}{\frac{4}{3}\pi r_i^3} \cdot 4\pi r_i^2 - \frac{V_{i0}}{\frac{4}{3}\pi r_{i0}^3} \cdot 4\pi r_{i0}^2 \right)$$

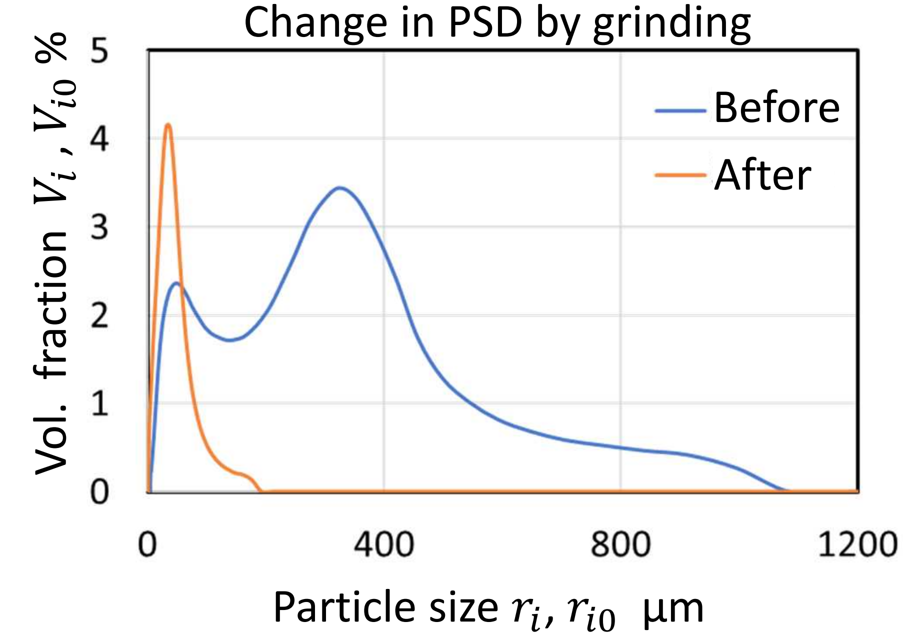
$$= (1.5\sim2) \times (275.4 - 52.6)$$

$$= 334.2\sim445.6\ \mathrm{m^2/kg}$$

(Calculate from change in PSD)

$\gamma = 3\sim7\ \mathrm{J/m^2}$, $\boldsymbol{\eta} = \mathbf{1.3\sim4.1}\%$

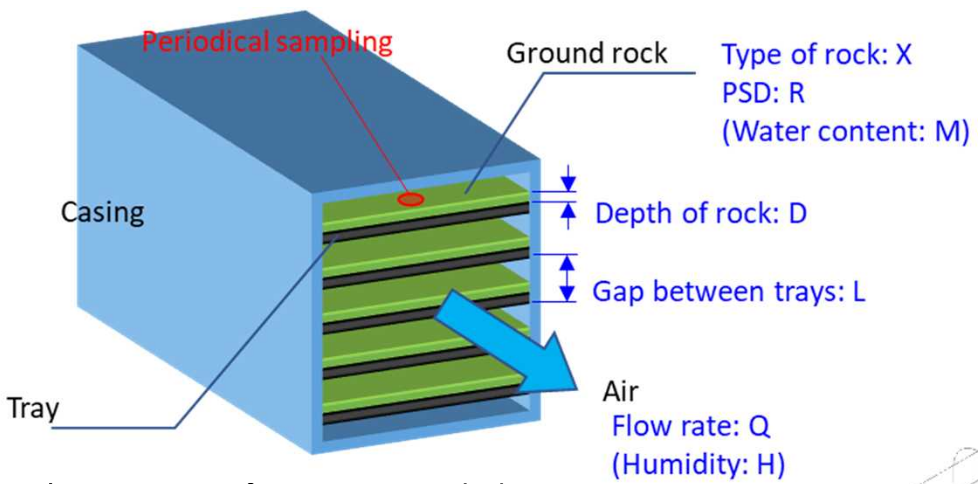
Change in PSD by grinding



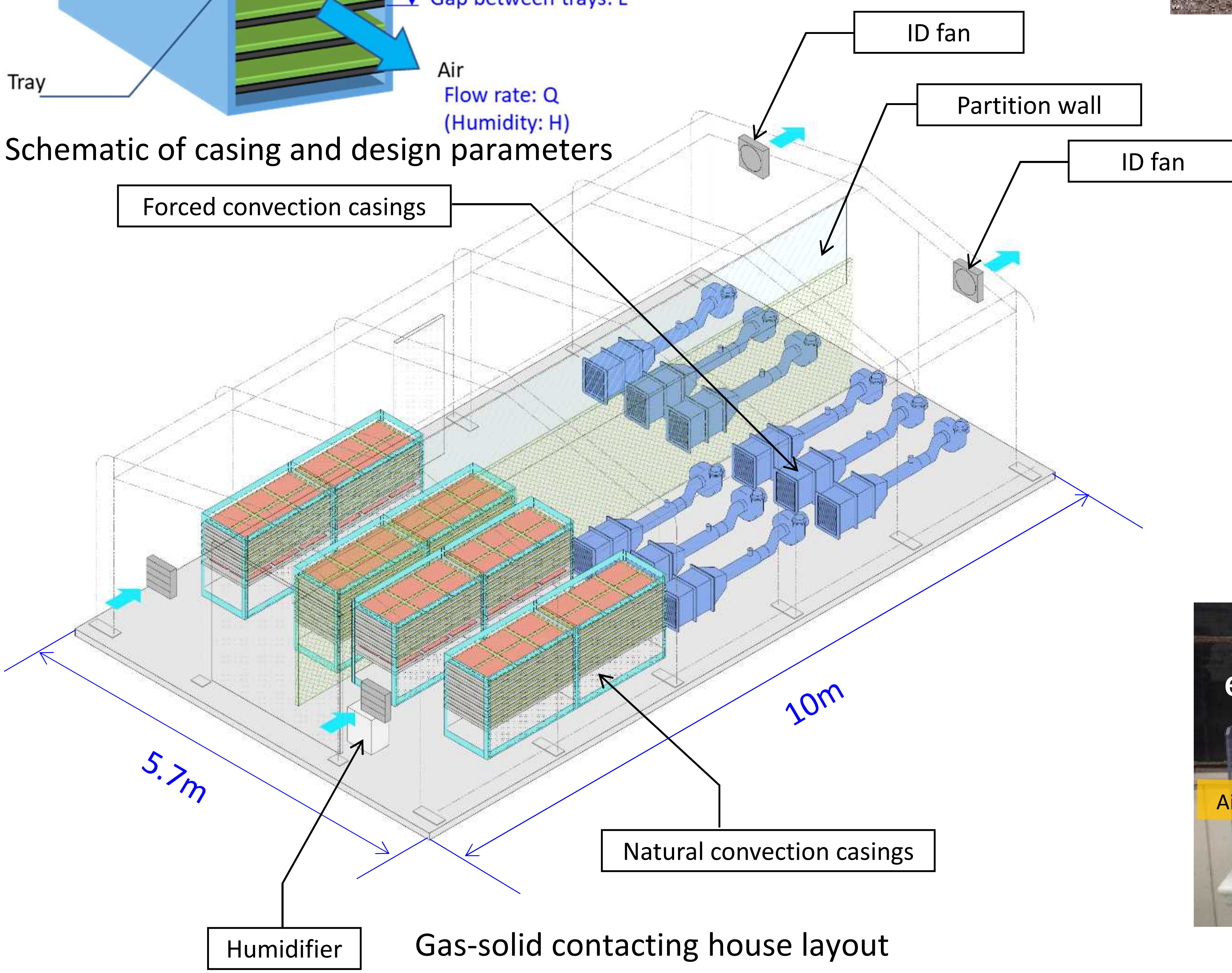
④Field testing under real environment & development of effective monitoring (1)Gas-solid contactor

Gas-solid contacting house

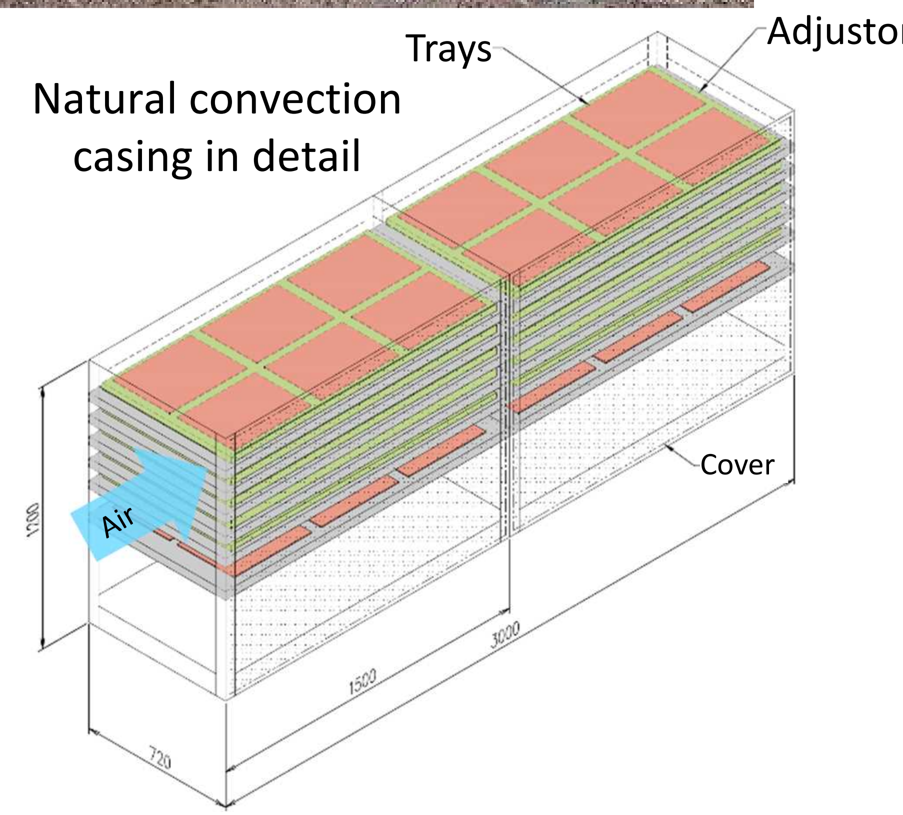
- Design and building permission of gas-solid contacting house
- The house will be commissioned by Feb. 2024
- ERW testing from April 2024 to March 2025



Schematic of casing and design parameters



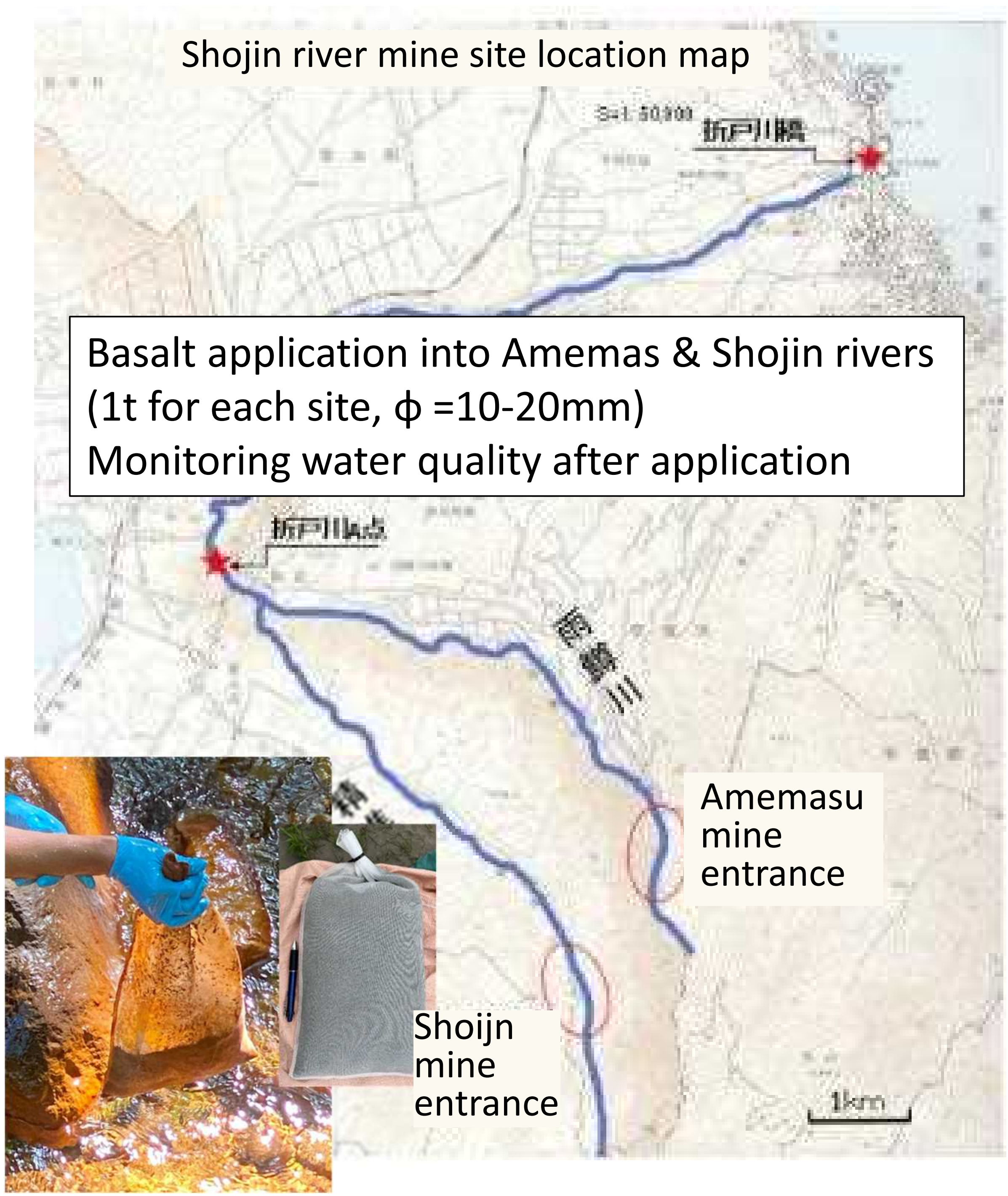
Gas-solid contacting house layout



④(2)Forest slope / Abandaned mine site

1. Verification for rate-base mineral leaching model & 1-D reaction-transport model
2. Carbon accounting quantified by ERW and related CDR as ocean sequestration

Abundant mine site



Basalt application into Amemas & Shojin rivers (1t for each site, ϕ =10-20mm)
Monitoring water quality after application

Forest slope (Amamasu river side)

Installation and monitoring the following experimental fields

- ✓ Main plots (2m × 5m × 2 plots, 6 plots in total)
- ✓ On-site testing using Wagner pots
- ✓ Sub plots (1m × 1m × 2 plots, 10 plots in total)

*Monitoring for main plots: Sectional investigation, precipitation, temperature, humidity, WD/WS, CO_2 concentration on the ground, soil water content, pH, nutrients, heavy metals in soil

① Site suitability assessment (2)Business environment assessment: Methodology
③ Acceleration of ERW (2)ERW application on open sites

Abandoned mine site

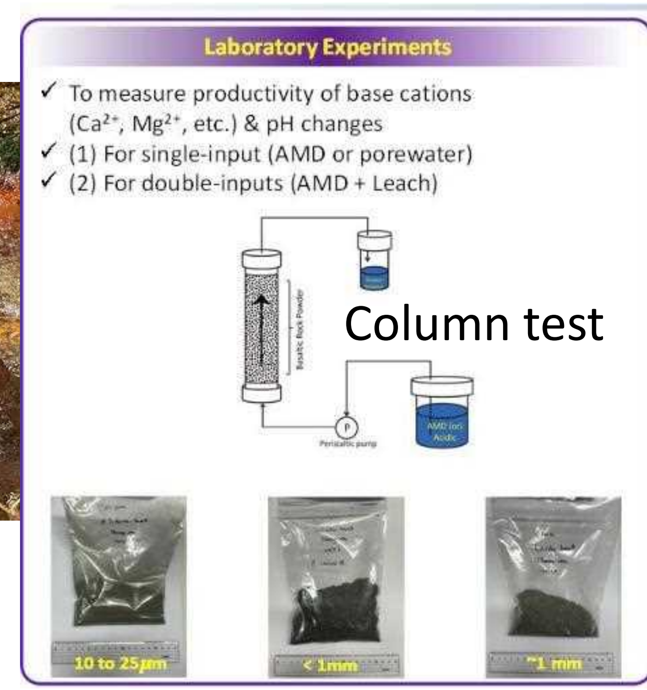
<u>Platform combined with 1-D reaction-transport model and carbon accounting</u>

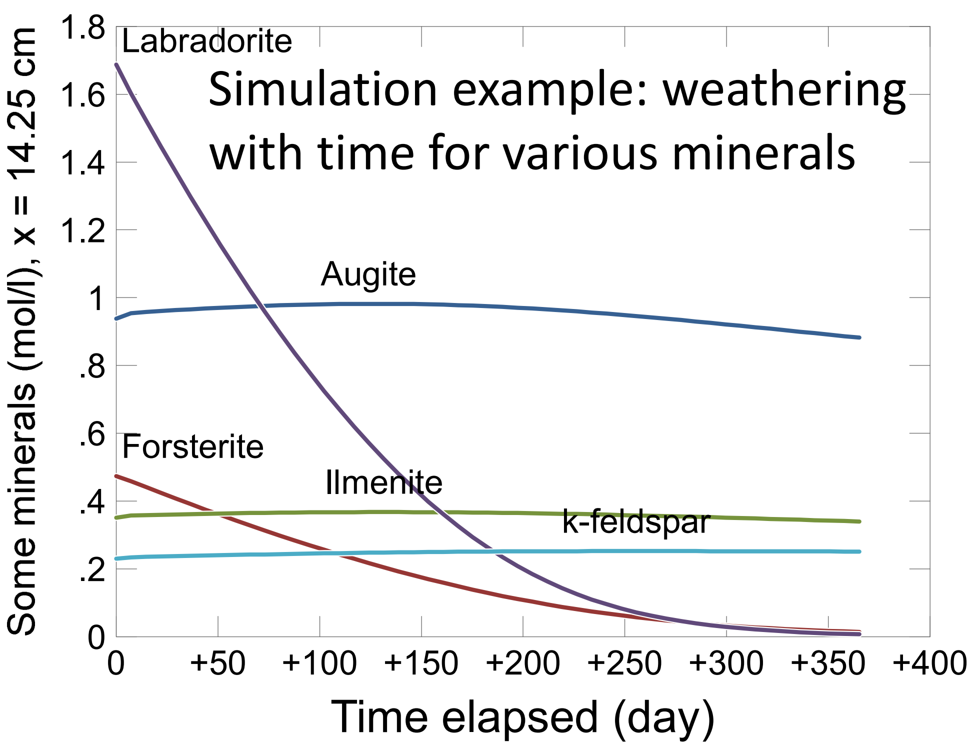
1. CO_2 mineralization potential map in Hokkaido →Business potential map
2. ELSI activities at abandoned mine site →Pilot-scale demonstration
3. Possible candidate sites (Abandoned mine site + Forested slope, farmland, Gas-solid contacting house)

- Estimate annual consumption of effective minerals by acidic mine drainage flow rate from abandoned mine sites around Japan (Approx. pH≒2.8) and PSD (100μm & 1 mm) and net CDR by ERW using the geochemical model
- Calculate transport distance between abandoned mine site and quarry operation site
- Evaluate business potential as net CDR (Collaboration with Morimoto PM team)

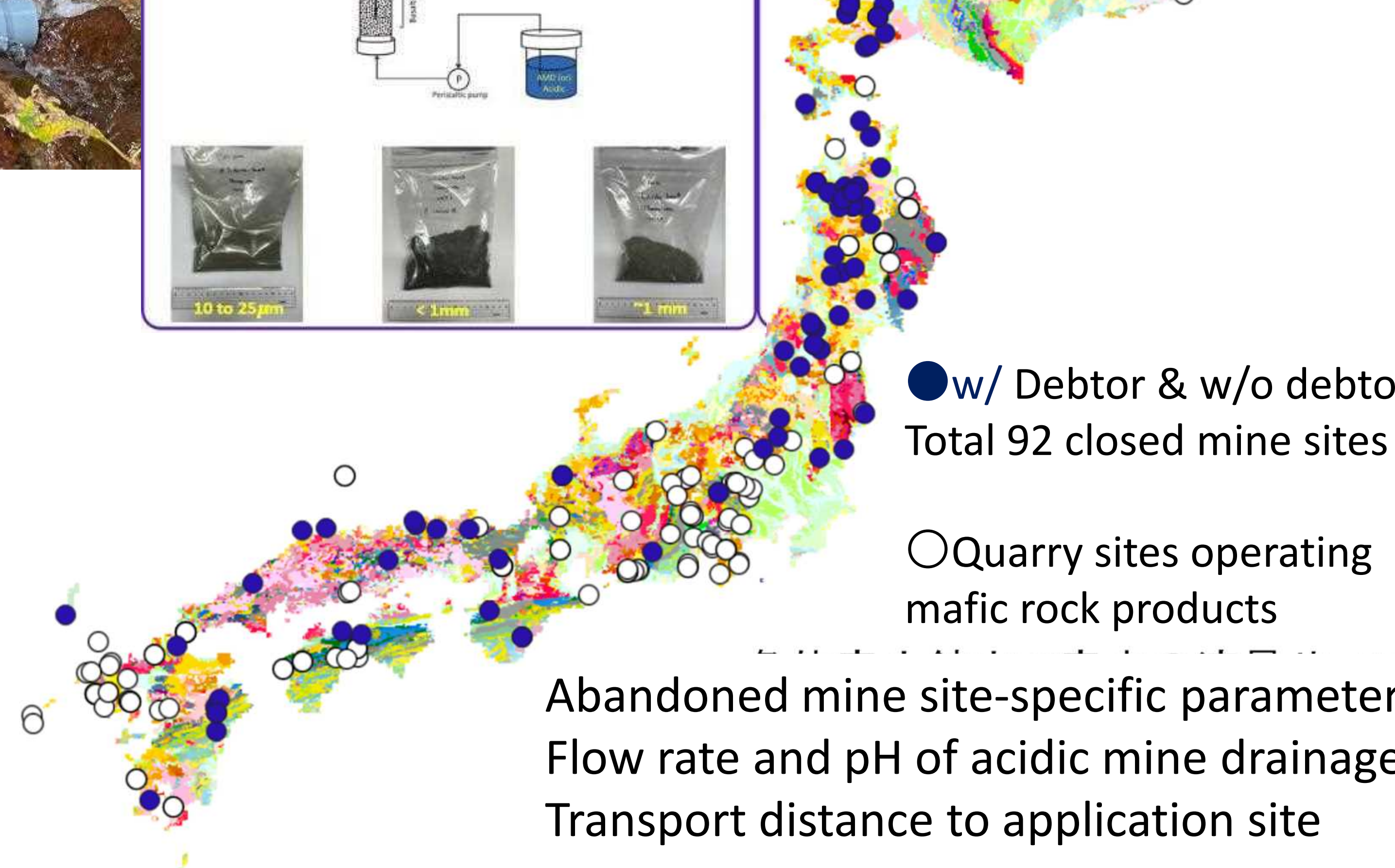
Verification by column test

•Reaction/transport model
•Reaction rate for each mineral
•Reaction surface area of mineral (related to PSD)
•Water velocity



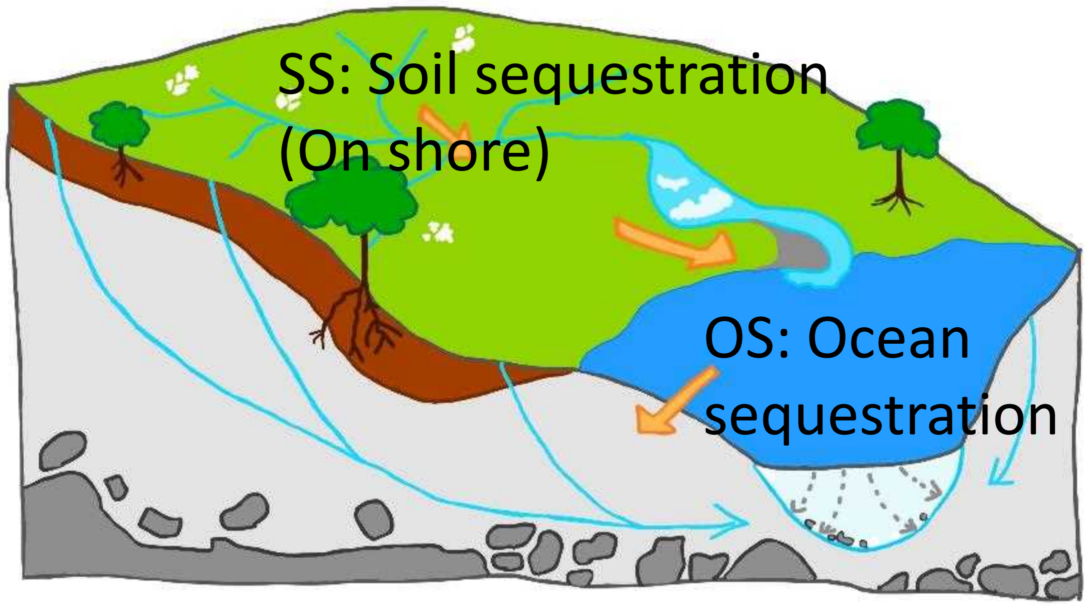


Evaluate business potential by LPLC deployment utilizing site characteristic



Abandoned mine site-specific parameters
Flow rate and pH of acidic mine drainage,
Transport distance to application site

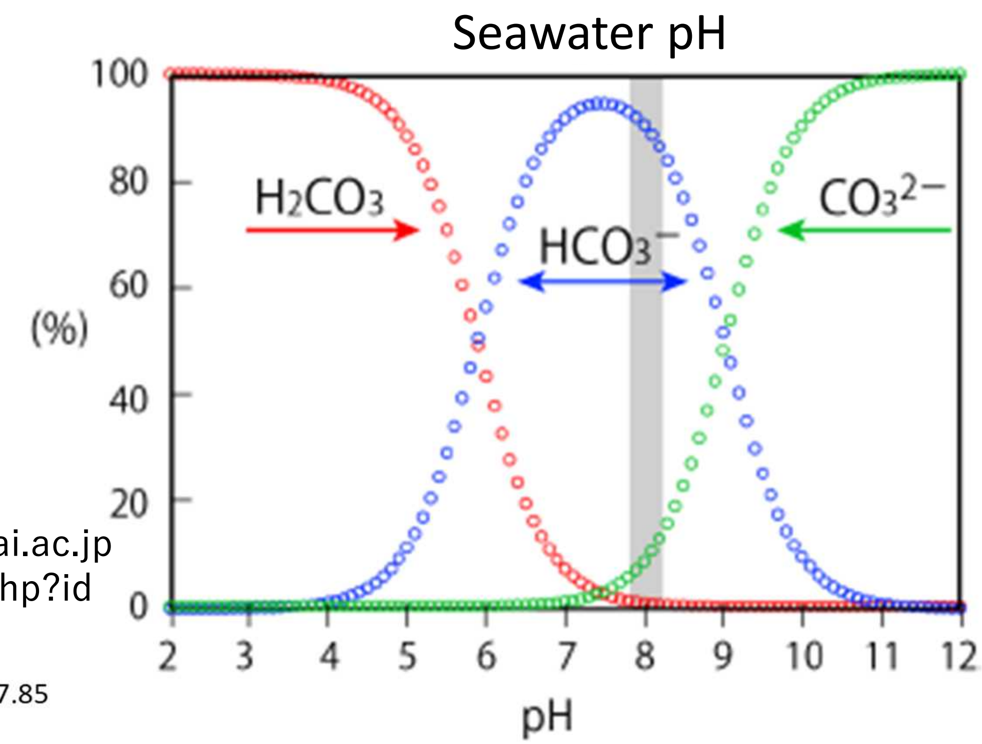
⑤(2)Natural land application: CDR by Ca/Mg in seawater



SS: leaching mechanism
Acidic mine drainage pH<3
Rainwater pH≈5.6
※Humidity=Gas-solid contacting house

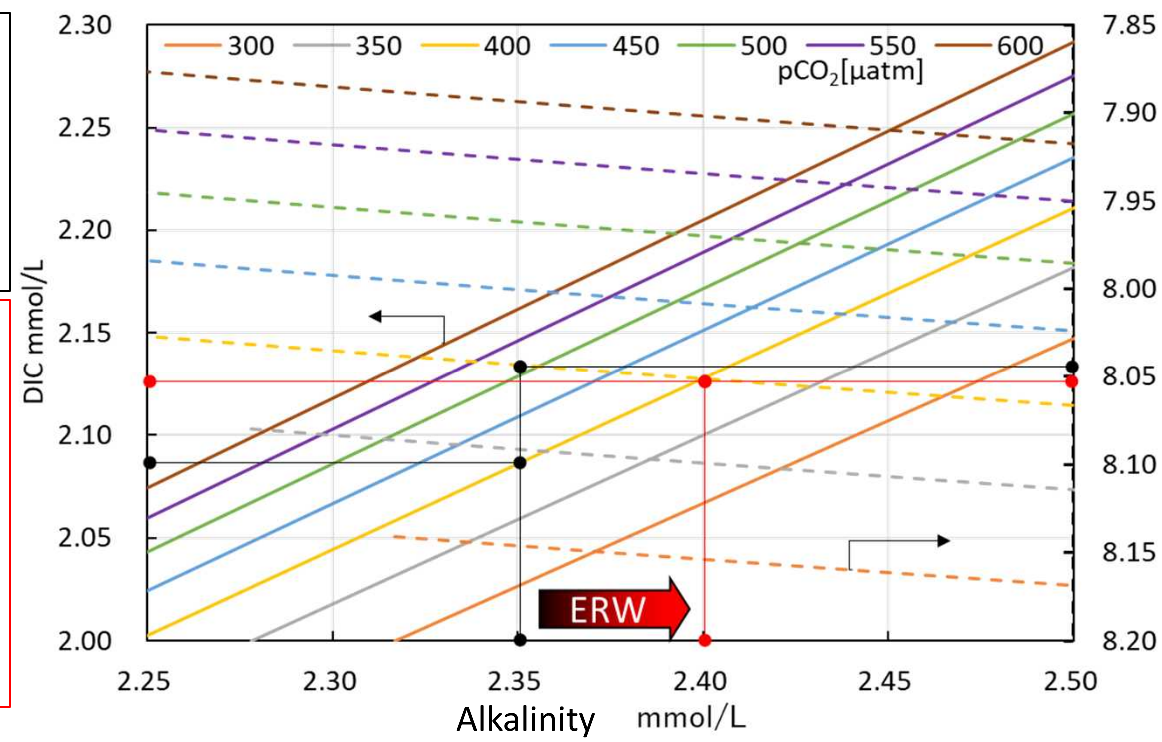
OS: For all natural land applications

https://repun-app.fish.hokudai.ac.jp/course/view.php?id=415



Before application:
Alkalinity 2.35mmol/L
pH = 8.04
DIC = 2.08mmol/L

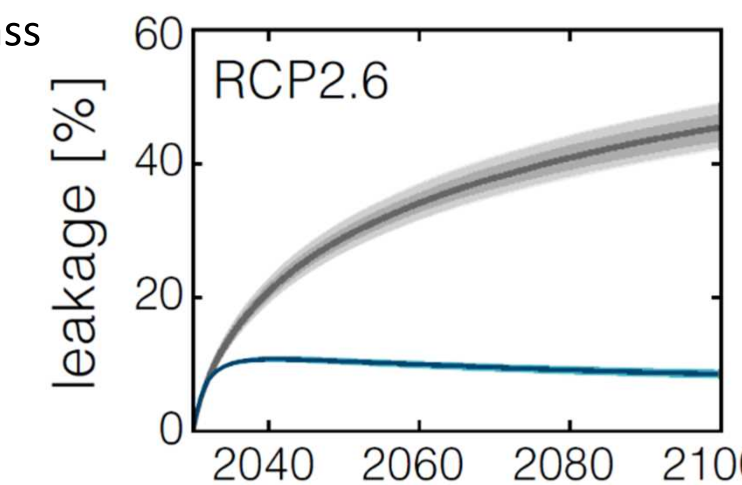
After application:
Alkalinity 2.40mmol/L
pH=8.05
DIC = 2.12mmol/L
ΔDIC=+0.04mmol/L
→**Surface seawater CDR**



$2HCO_3^- + Ca^{2+} \leftrightarrows CaCO_3\downarrow + H_2CO_3$
$H_2CO_3 \leftrightarrows HCO_3^- + H^+ \leftrightarrows 2H^+ + CO_3^{2-}$
High alkalinity should be kept

Blue carbon-related accounting:
Emission of NO_3^- derived from organics decomposition
→Decrease in Alkalinity
Fe supplement by ERW
→Effect on algae biomass growth, persistent biomass

Fixation for several years:
Surface seawater alkalinity is stable even by inflow of natural Ca^{2+}/Mg^{2+}
→Foraminifer & shellfish uptake as calcite or aragonite
No dissolution of $CaCO_3$ in supersaturated surface seawater
⇒CO_2 fixation equivalent to inflow Ca^{2+}
Long-range fixation until 2100: Refer to the latest research report
40% leakage from DIC in seawater due to global warming
→ERW-derived Ca^{2+} suppresses the leakage down to 10% by keeping alkalinity



Kanzaki, et al., PNAS Nexus, 2023, 2, 1–9
https://doi.org/10.1093/pnasnexus/pgad059

①Site suitability assessment (2)Business environment assessment

Farmland

1. Sample soils from 178 farms around Japan
2. Quantify composition of minerals with high weathering susceptibility inherently existing in the soils
3. Less minerals with high weathering susceptibility = More effective soils for basalt application

- Volcanic soils categorized to Andosols are rich in Ca-plagioclase indicating high weathering susceptibility and poor in weathering-resistant quartz.
- Non-volcanic soils are rich in weathering-resistant crystalline minerals such as Na-plagioclase, potash feldspar, quartz, isinglass, etc.: →More effective soils for basalt application due to its weathering nature

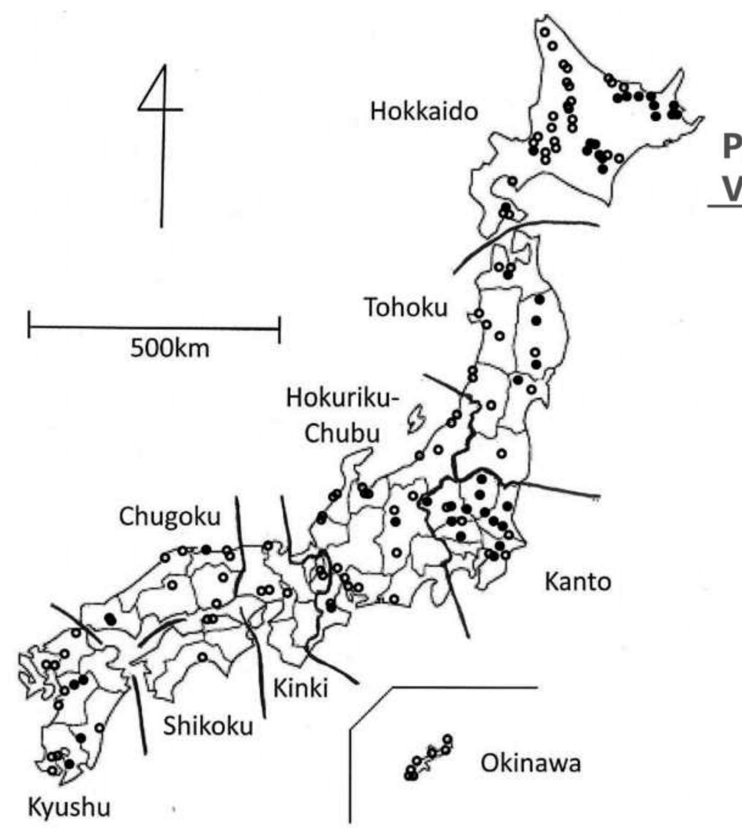
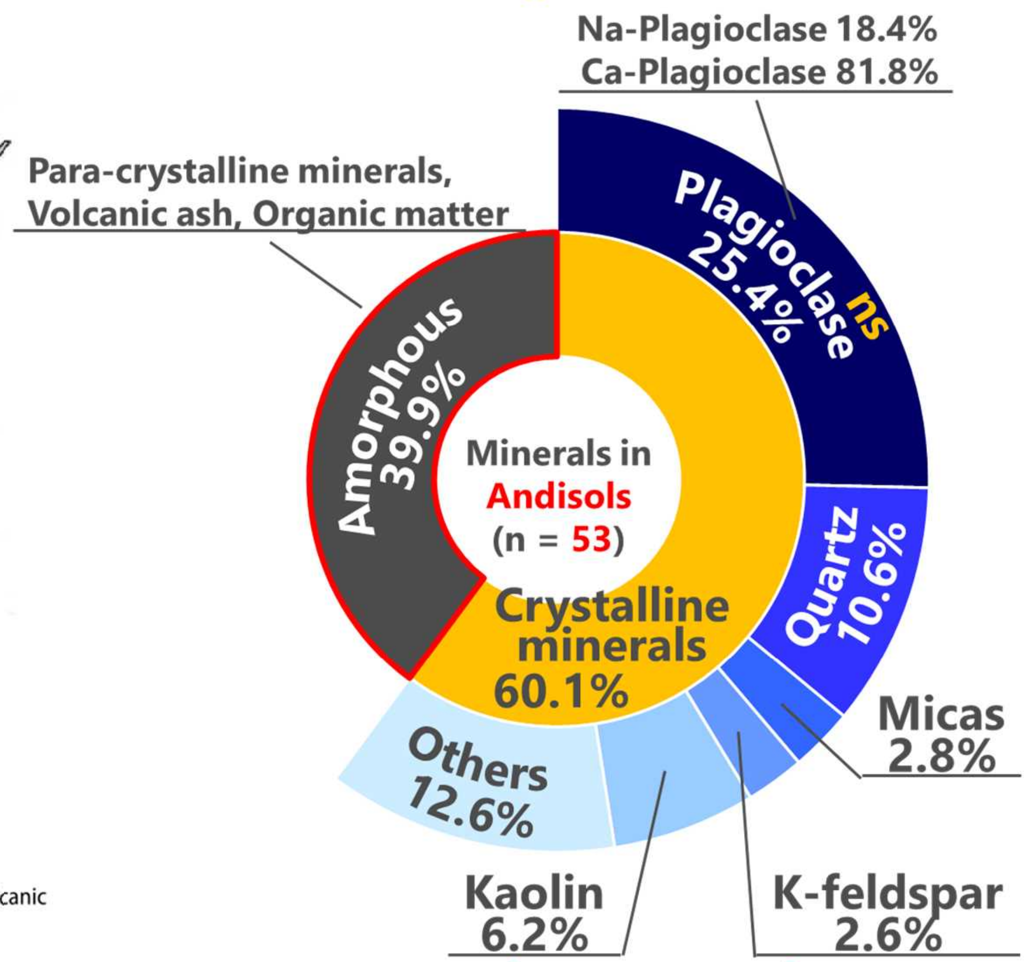
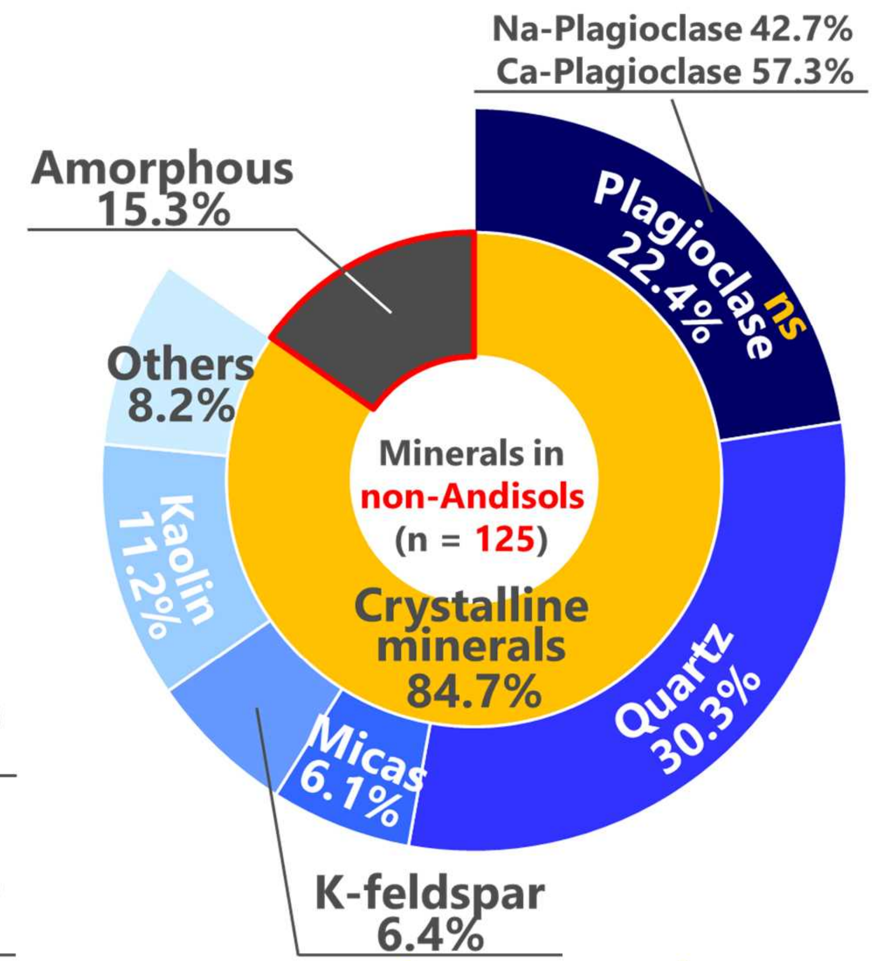


Figure 1. Locations of the sampling sites. ●: Volcanic soils. ○: Non-volcanic soils.

178 soil samples distribution



Volcanic soil

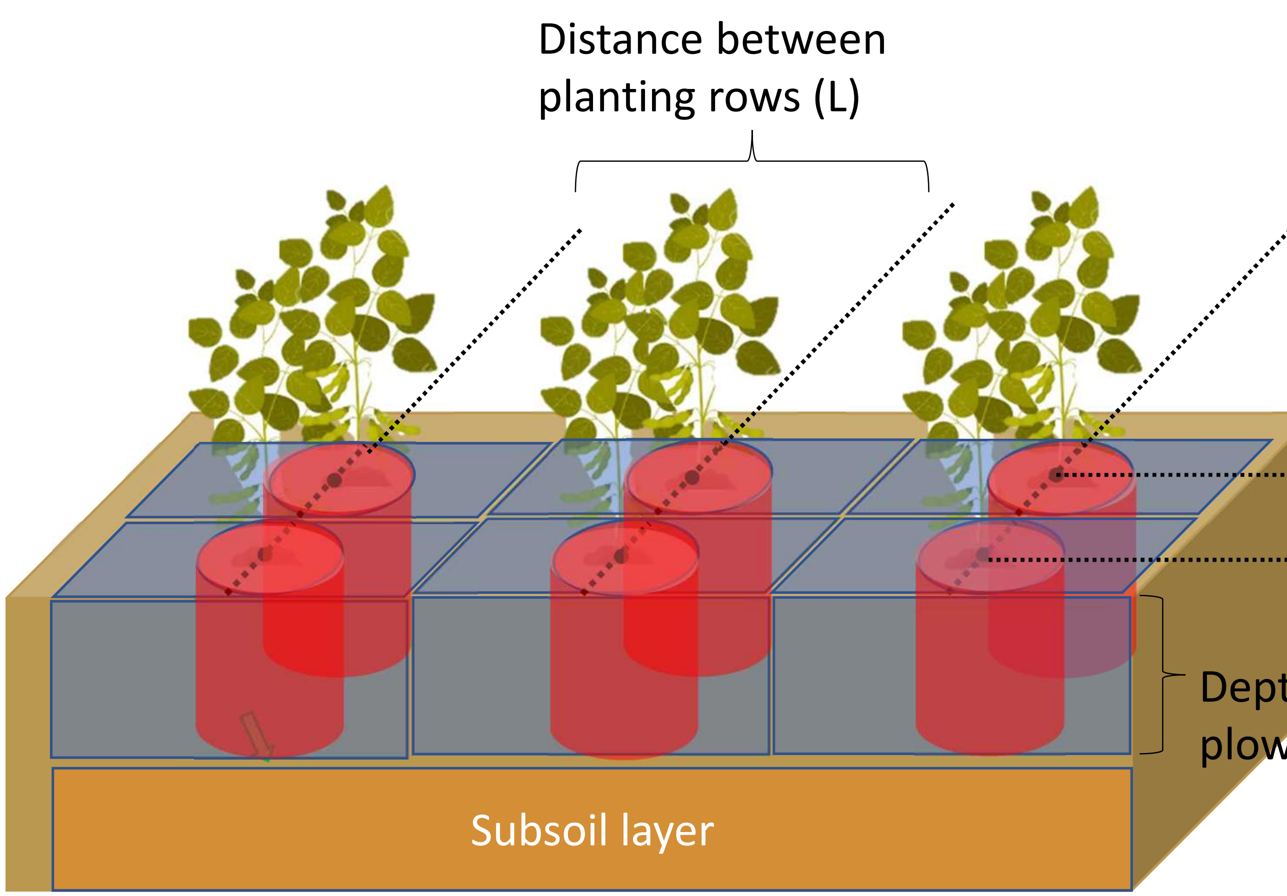


Non-volcanic soil

⑤Information database of accurate carbon accounting
(2) Carbon accounting including natural carbon cycle

Farmland

ERW + dynamic change in organic carbon by rock application = Novel carbon accounting

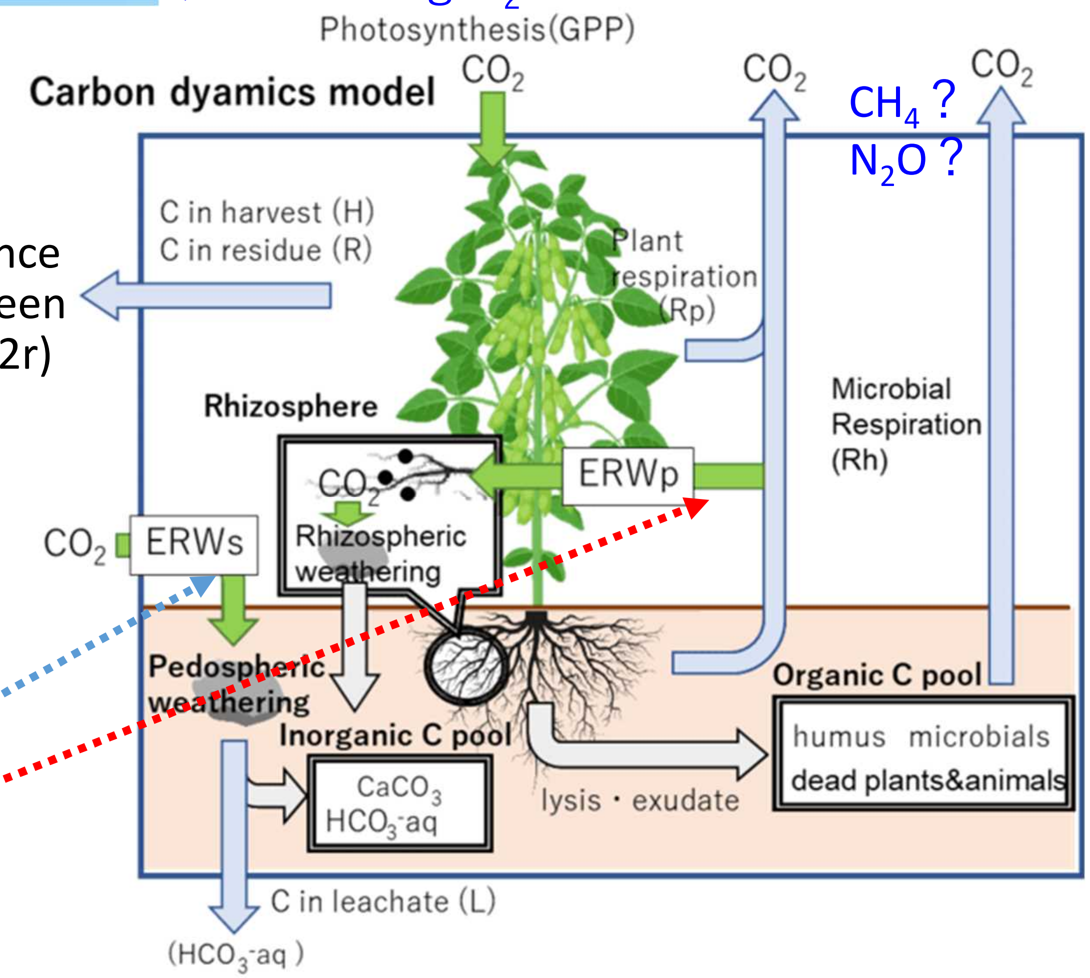


Collaboration with Minamizawa PM PJ

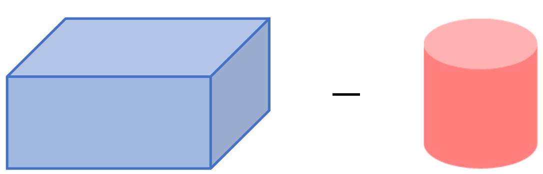
"Mitigation of Greenhouse Gas Emissions From Agricultural Lands by Optimizing Nitrogen and Carbon Cycles"

Participation for soil sampling as civil science

→Accounting N_2O reduction as a co-benefit



Measurement/Evaluation method



Plowed soil − Rhizosphere = plane soil

Rhizosphere weathering ERWp

Soil zone weathering ERWs

CO_2 absorption measured by XRD & Calcimeter linearly Converted by area

Measurement
- CO_2 emission (Chamber method)
- Carbon leaching (Lysimeter & Porous cup)
  - Precipitation (Climate monitoring)
  - Soil water content (Climate monitoring)

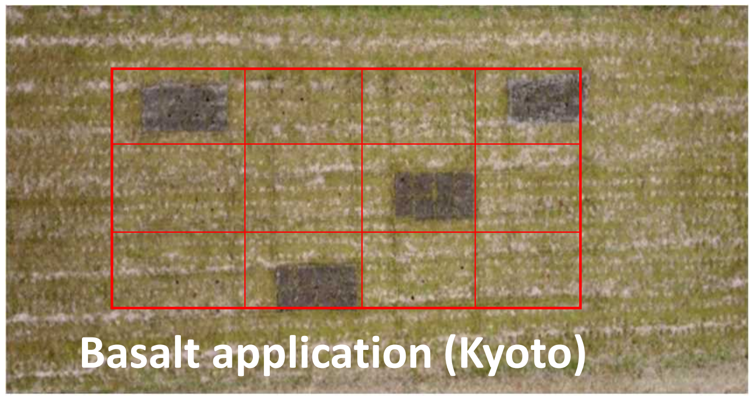
Multi-regression model predicting annual net carbon flux using continuous data

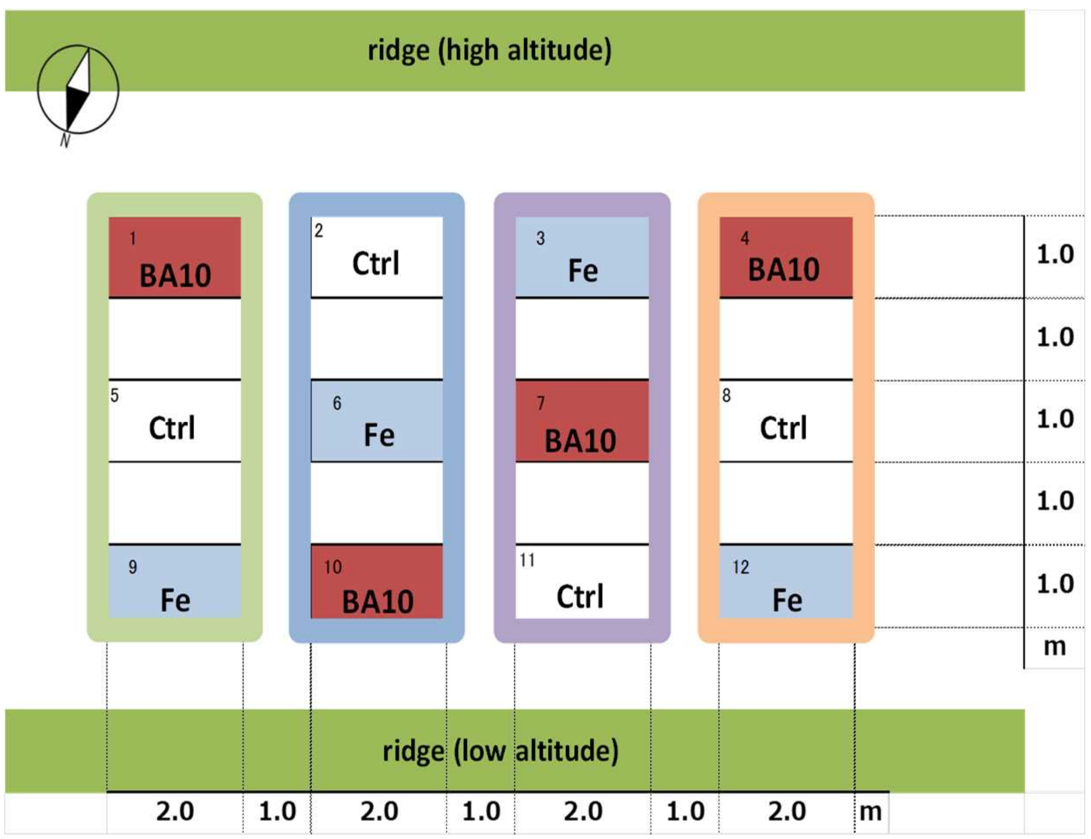
④ Field testing under real environment & development of effective monitoring

(3) Application on farmland

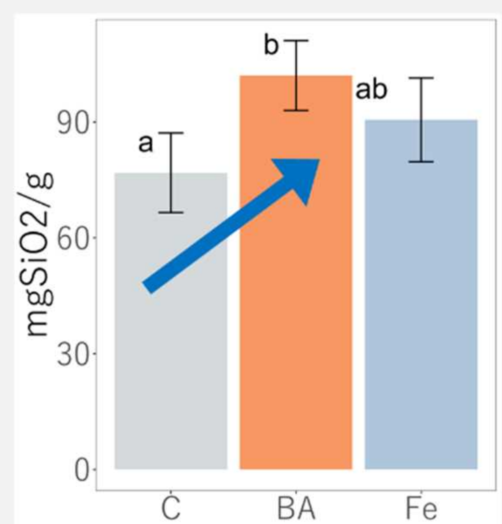
Farmland

1. Cultivation & harvesting on experimental farms with basalt application (Hokkaido, Tsukuba, Ishigaki island)
2. Cultivation & harvesting on farming rice paddy field with basalt application (Kyoto)
3. Cultivation on oversea experimental farm with basalt application (Taiwan)





Well-growth of rice with increase in SiO_2



SiO_2 concentration in straw

Significant increase
in basalt application area

Monitoring data:

- ✓ Soils

pH, Cation exchange capacity , Available content of nutrient element

- ✓ Crops

Biomass weight, Absorption of nutrient element

- ✓ Leaching water

Bicarbonate ion and other concentration of nutrient element

- ✓ Other environmental data

Precipitation, Temperature, Humidity, CO_2 concentration in soil, etc..

- Harvesting and soil sampling have been completed (except experimental farm in Taiwan)
- Under analysis for elemental composition of crop & weathering minerals in soil
- <u>Increase in Si concentration</u> of rice crop, co-benefit of decrease in <u>Ni concentration</u>
- Decrease in yield depending on soil-crop combination (To be listed in don'ts after cause investigation)

④ Field testing under real environment & development of effective monitoring

(3) Application on farmland

Farmland

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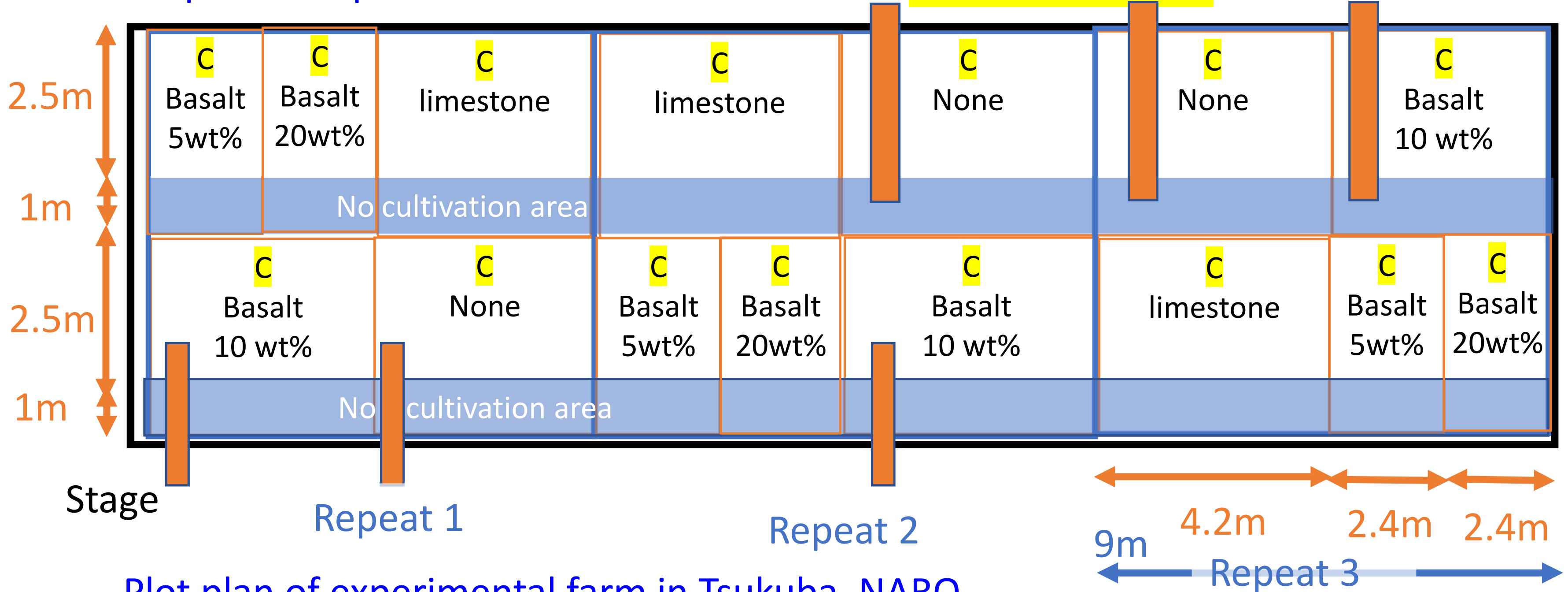
3. Cultivation on oversea experimental farm with basalt application (Taiwan)

Plot plan of experimental farm in Hokkaido U. C:Cultivation area



Both of **Basalt application areas** :

- Increase in dry density of topsoil（Only Hokkaido U.）
- Increase in pH & CO_2 concentration in top and bottom soils （Consistent with column experiment & published paper）
- Increase in electroconductivity（Effect of Ca/Mg eluviation）

Plot plan of experimental farm in Tsukuba, NARO