NAWG-18@Manchester, 2026.6.8th Wed.

International Bentonite Longevity (IBL) project: The Potential for Bentonite Erosion under River Flow Conditions

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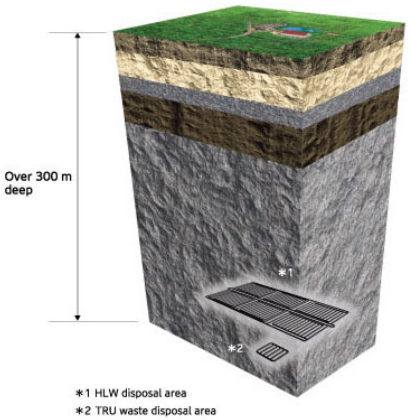
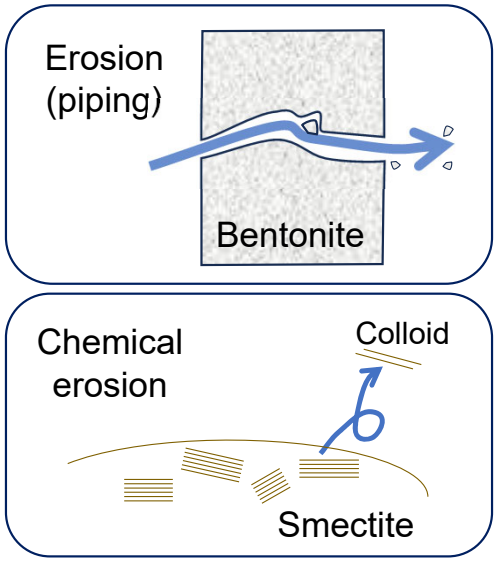
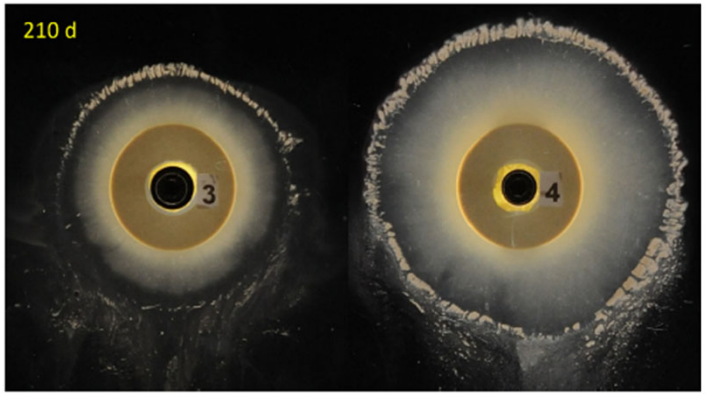
Erosion: mass loss of bentonite



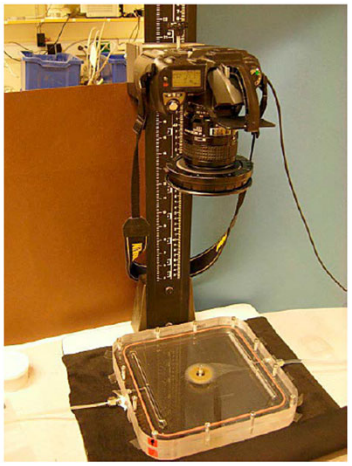
Two "erosion" types



Erosion experiments



(Hedström et al. 2023)

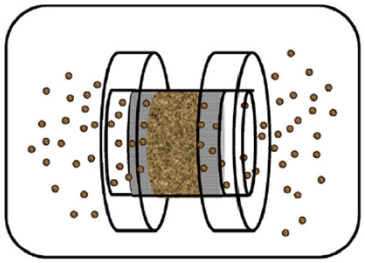


(Hedström et al. 2016)

Simulating bentonite flow in a fissure

Simulating colloidal outflow

(c)



(Alonso,2018)

Challenges & Objective

Challenges in erosion research

- Highly device-dependent
- **Lack of case studies verifying long-term behavior**

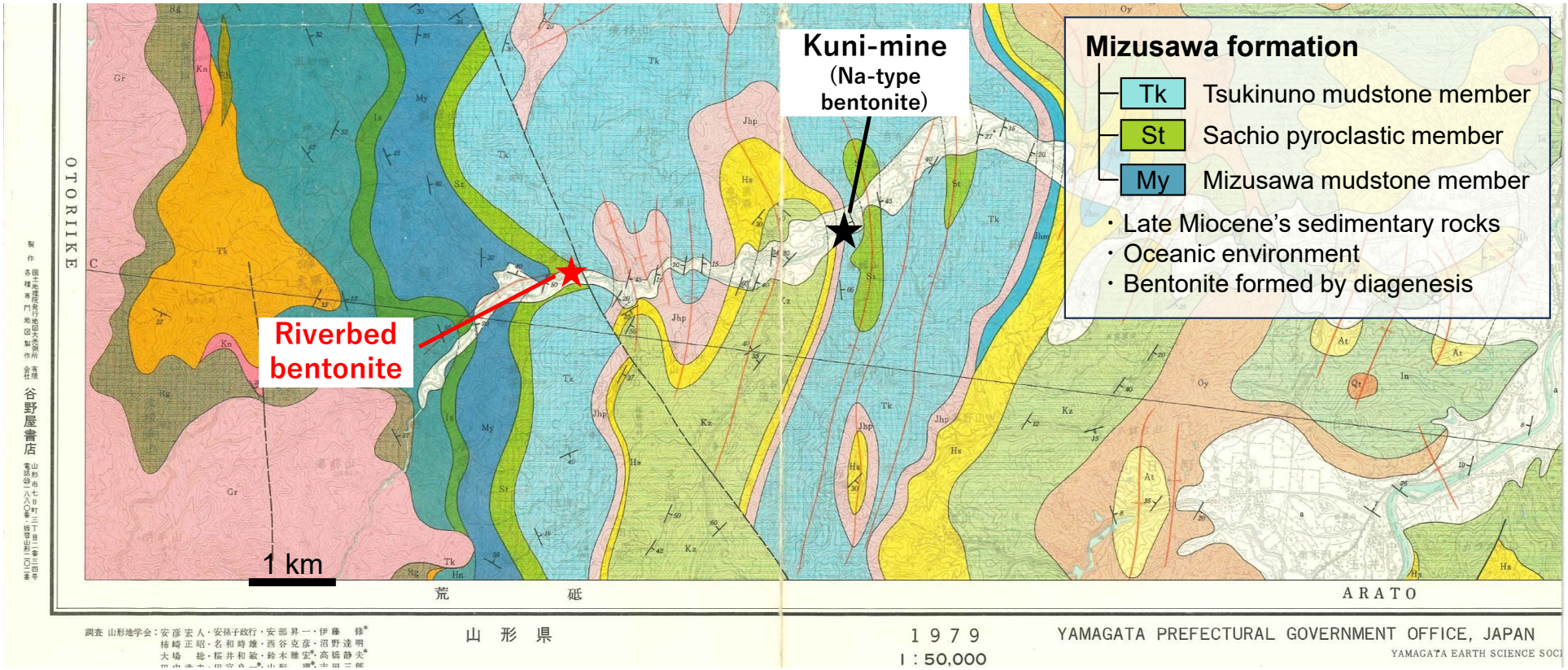
IBL

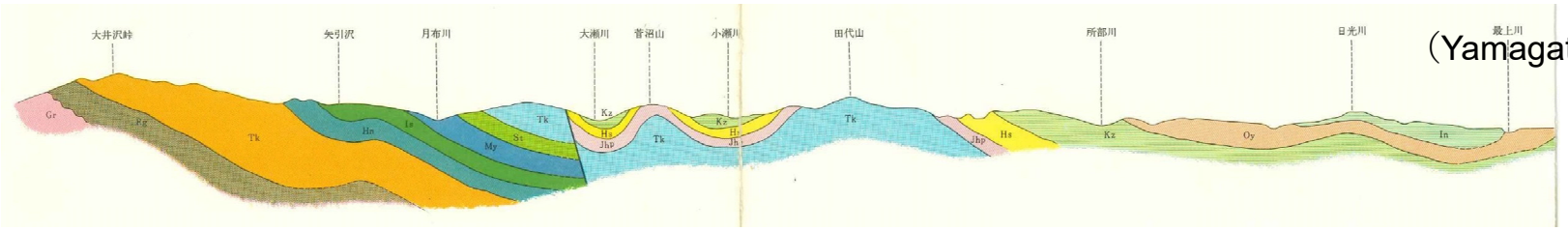
Expectation for riverbed bentonite

- **Long-term erosion behavior in natural river flow condition including both types of erosion**
- Natural saturation states
- Bentonite – surface water interaction

1. **Clarify the properties of the riverbed bentonite (mineralogy, chemistry, density, etc.)**
2. **Estimate erosion rate in natural river environment**

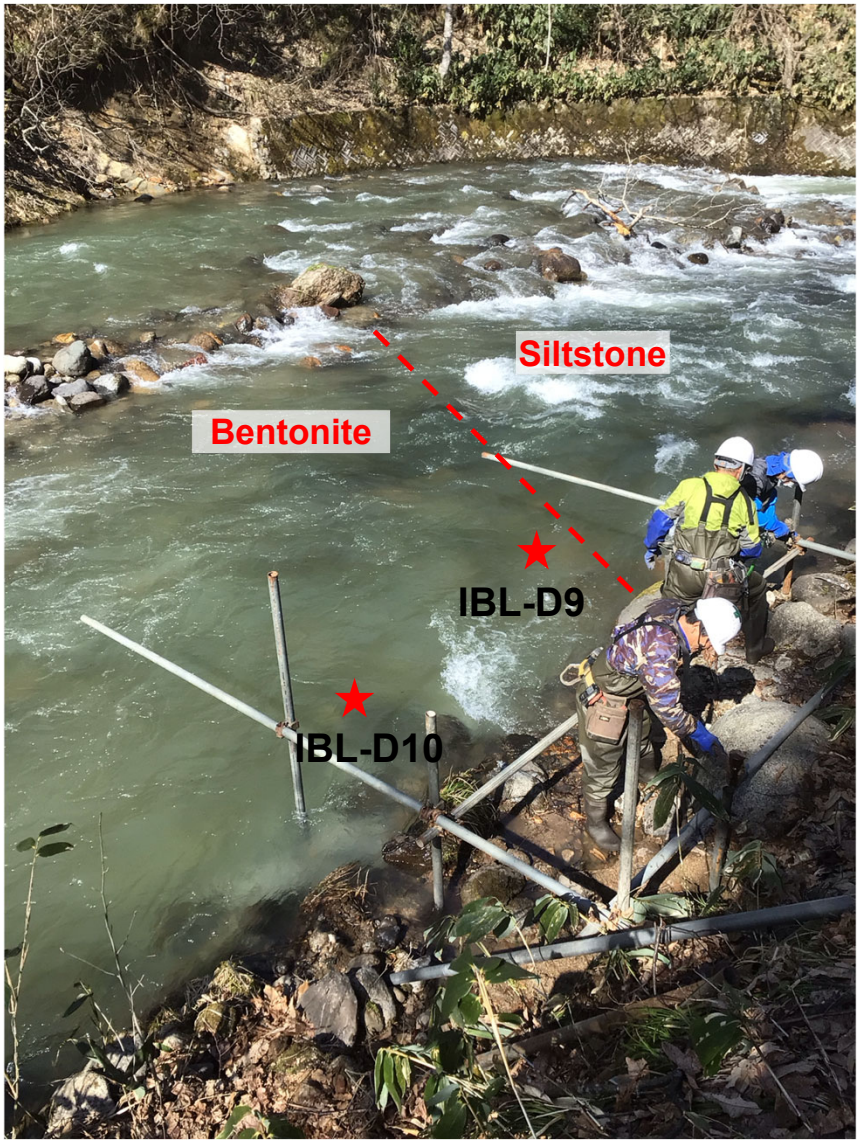
Geological setting

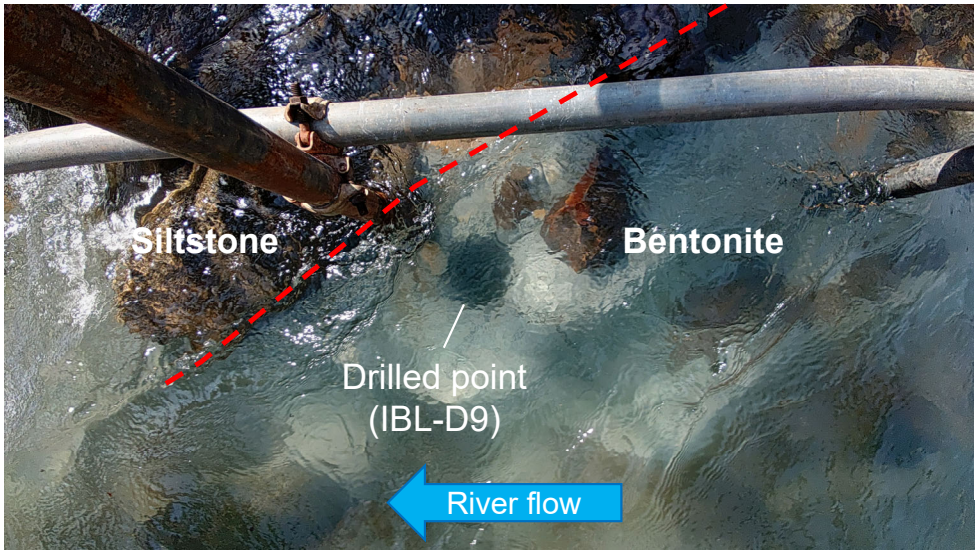


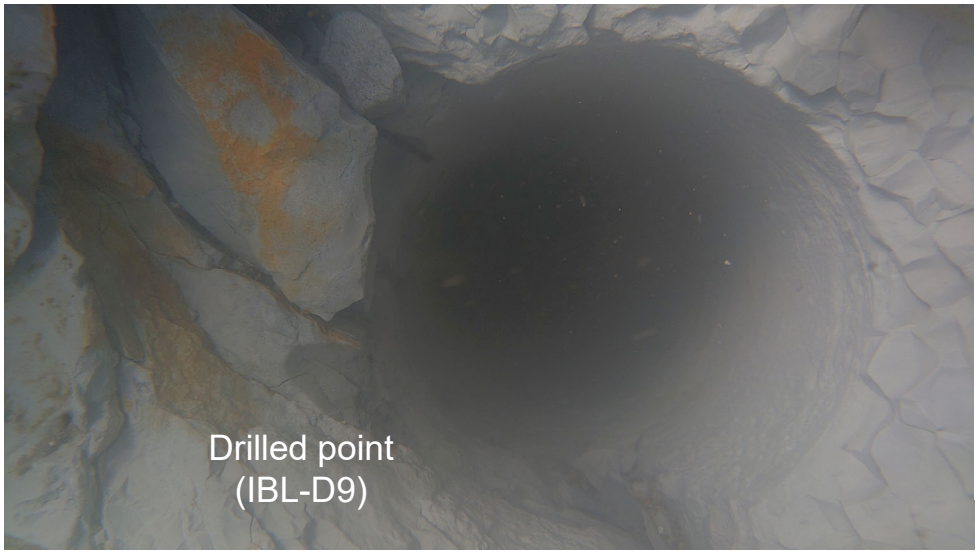


(Yamagata Pref., 1979)

Drilled points

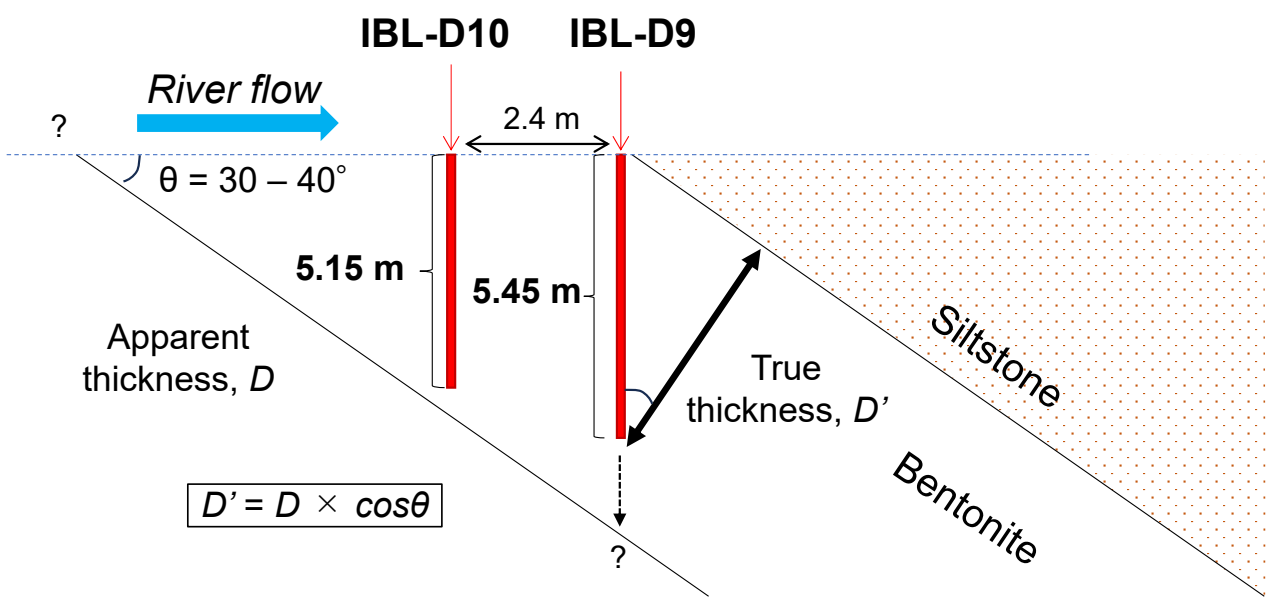


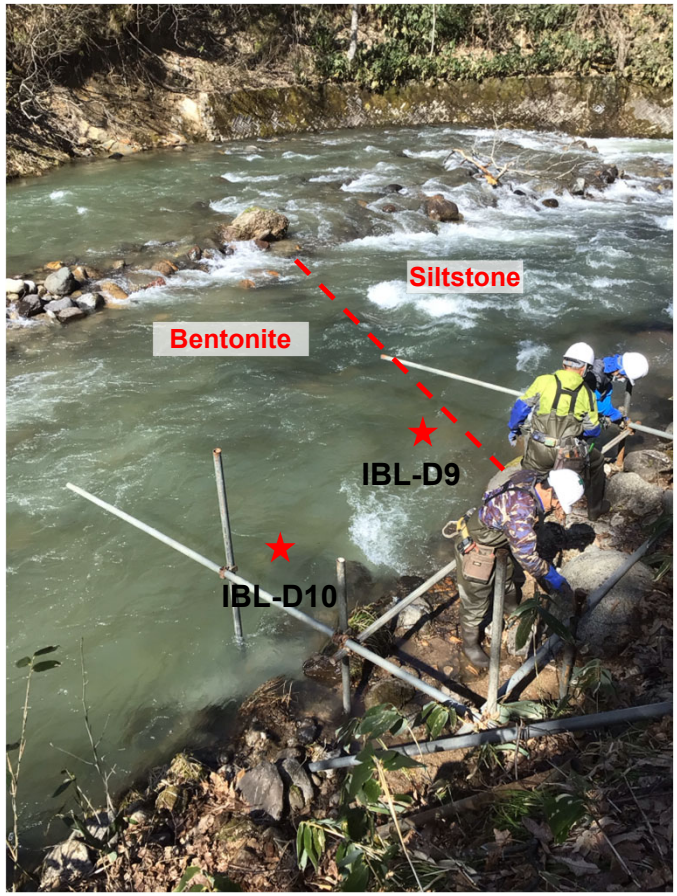




IBL-D9 & D10 positions

Schematic veiw





☑ **Whole part of boring cores are bentonite**
☑ **Bentonite thickness is more than 4.7 m**

River water chemistry

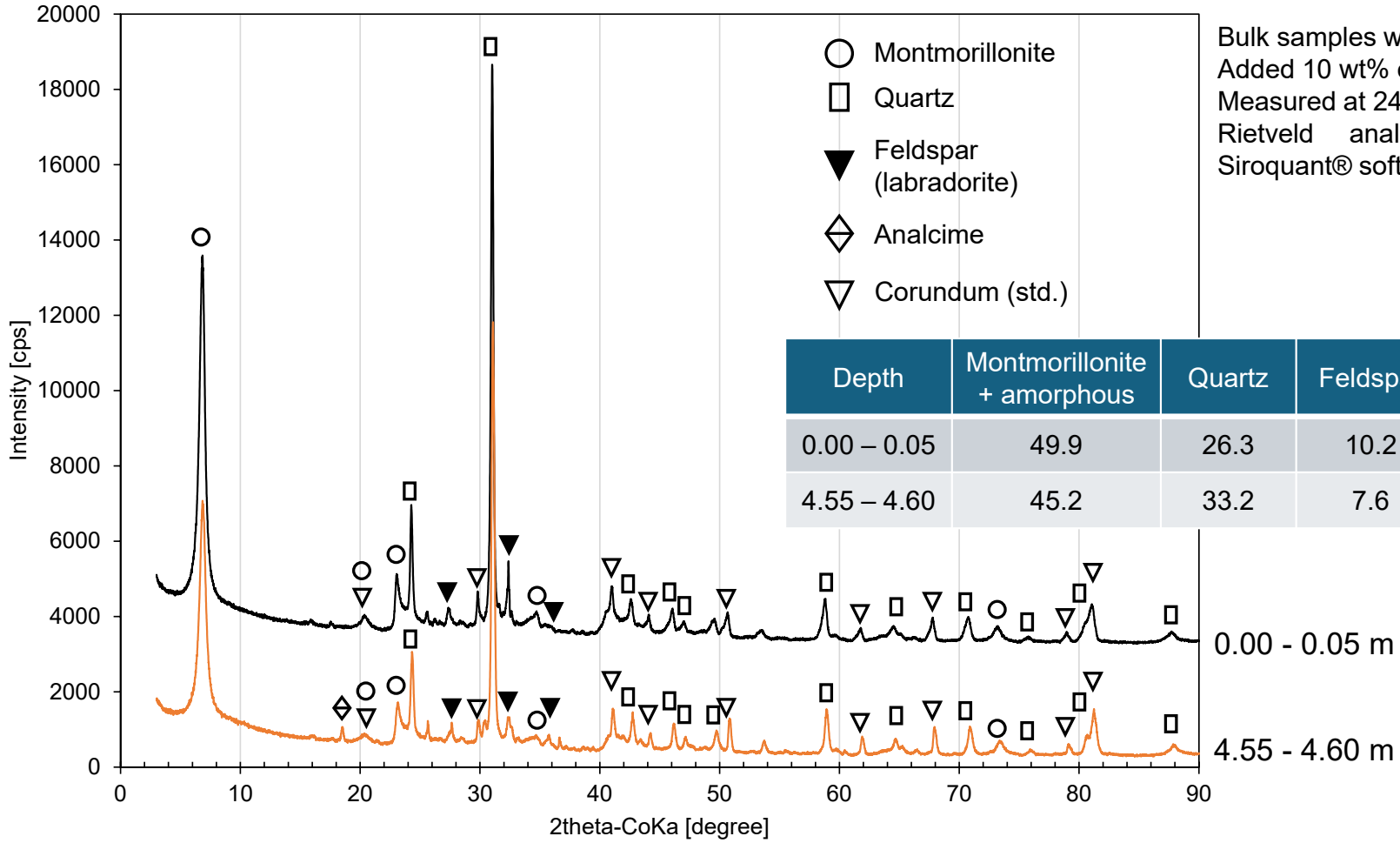
In-situ measurement

	1st Apr. 2024	6th Jul. 2025
Temperature [˚C]	10.9	26.3
pH	7.36	7.92
ORP [mV]	272.3	43.3
Turbidity [ntu]	8.63	0.00
Alkalinity [$CaCO_3$ mg/L]	15.83	24.00
Fe^{2+} [mg/L]	< 0.1	< 0.1

☑ **Dilute condition that chemical erosion is likely to occur (< 4 mM).**

[mg/L]	This study 2024. Apr.	This study 2025. Jul.	(Saji et al., 2005) 2001. Oct.
Na	**4.18**	**5.76**	8
Ca	**5.28**	**7.71**	6
K	0.62	0.60	<1
Mg	1.27	1.50	1
Fe^{2+}	< 0.1	< 0.1	<1
Fe^{3+}	N.A.	N.A.	<1
Fe_{total}	0.025	0.071	N.A.
Al	0.110	< 0.025	<1
Si	4.34	4.70	6
Cl^-	5.77	5.57	5
SO_4^{2-}	**7.97**	**10.38**	11
NO_3^-	1.06	3.75	N.A.
Total charge equivalent of cations (mM)	**1.2**	**<1.5**	**<1.8**

Mineralogical compositions

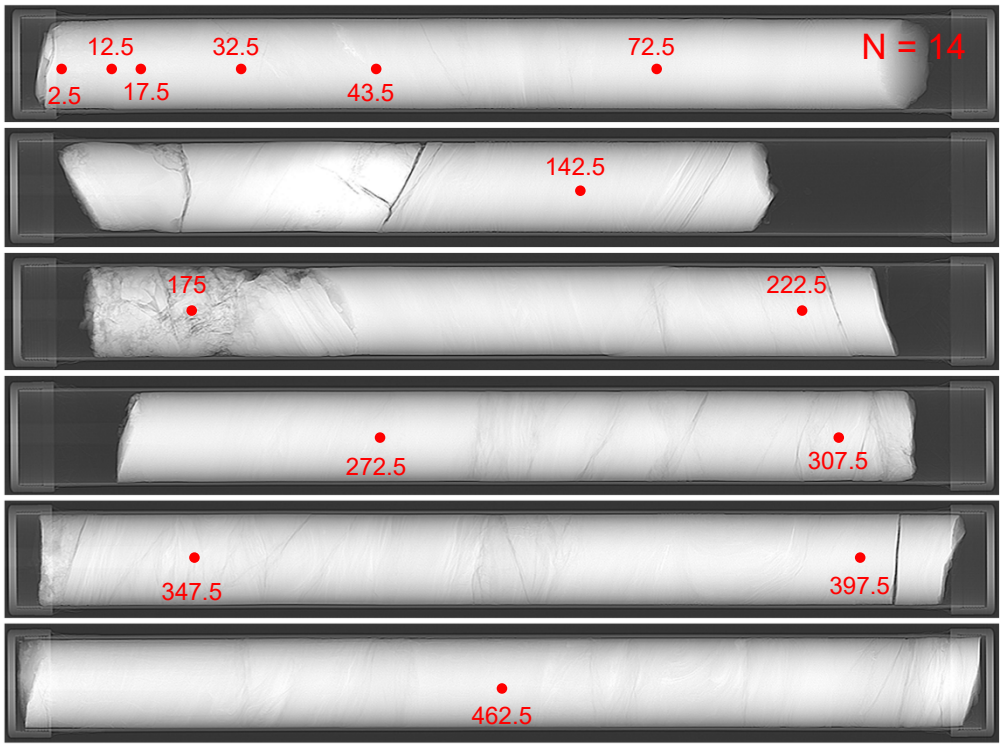


Bulk samples were Ca-saturated.
Added 10 wt% of Al_2O_3 as an internal std.
Measured at 24-25˚C, RH45-47%.
Rietveld analysis was done using Siroquant® software.

Depth	Montmorillonite + amorphous	Quartz	Feldspar	Calcite	Analcime
0.00 – 0.05	49.9	26.3	10.2	3.7	-
4.55 – 4.60	45.2	33.2	7.6	1.8	2.2

(wt%)

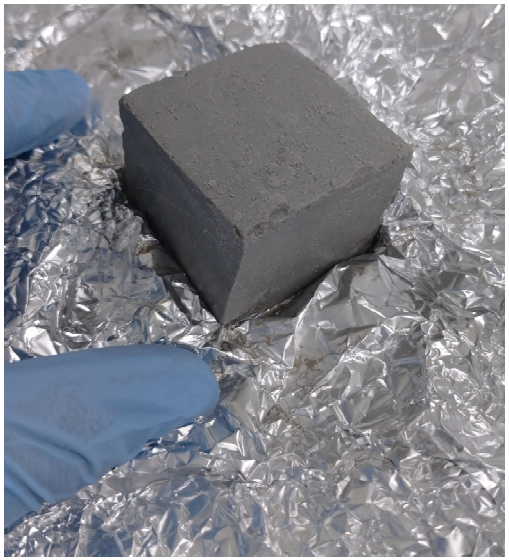
Density measurement (IBL-D10)



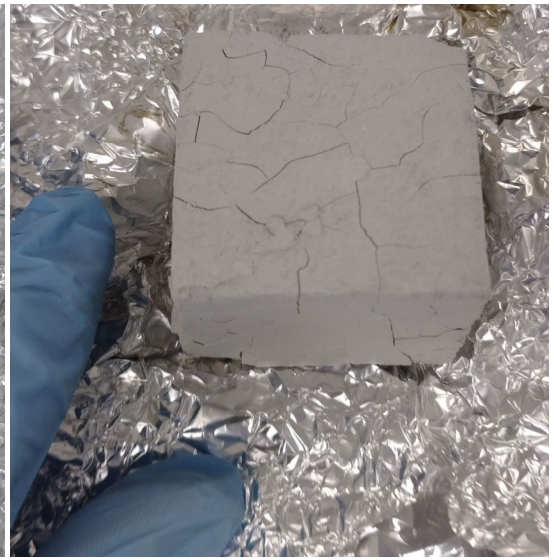
X-CT images and sampling points for density measurement
Numbers represent depth (cm).

Density measurement procedures

1. Extract blocks of 5 cm thick slices from each depth.
2. Shape a cube about 2 - 3 cm by cutting knife.
3. Measure the lengths of the three sides with calipers (*3 points per side).
4. Weighing the wet mass.
5. Weighing the dry mass after heating at 110℃ for 24 h.



Before heating

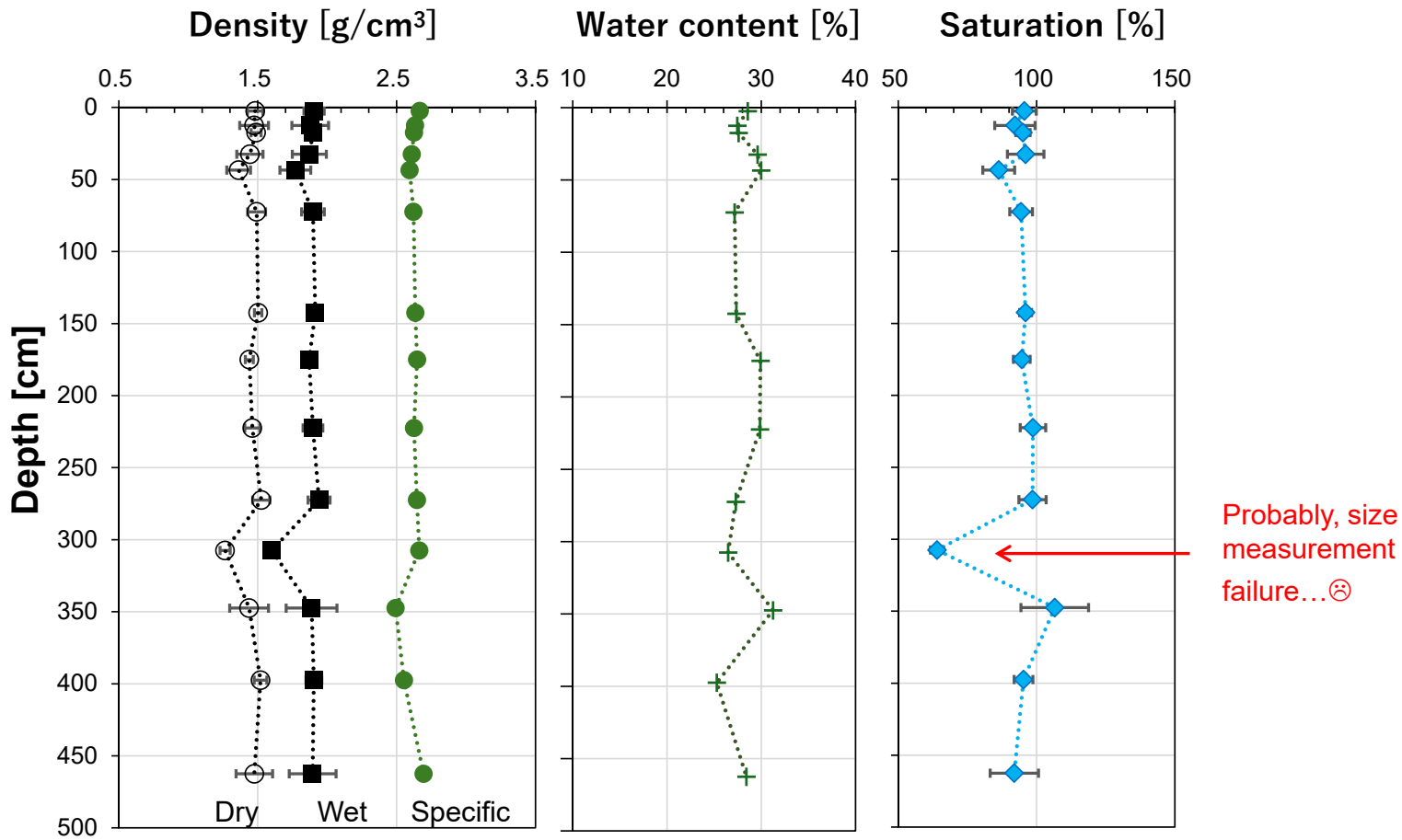


After

Specific density measurement

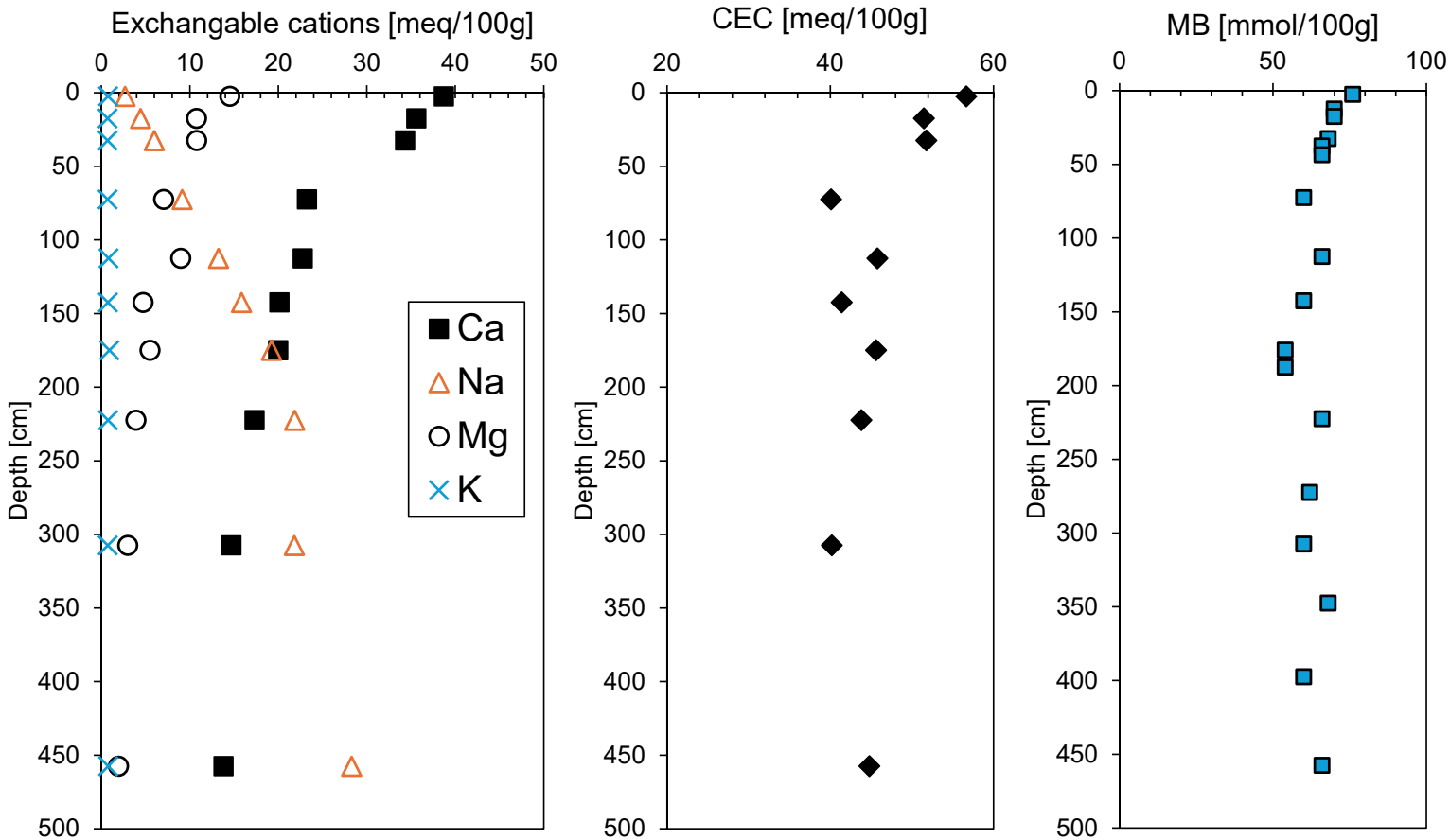
1. Disperse bentonite powder in distilled water.
2. Vacuumed to remove air in pore space (> 3 days at -100 kPa)
3. Weigh the mass after filling pycnometer with water.

Density, water content and saturation (IBL-D10)



- ☐ All data were almost constant along with the depth.
  …about 1.5, 1.7 g/cm^3 of dry/wet density, near 100 % of saturation.
- ☐ No sign of reduced density at the surface.

CEC & MB adsorption test (IBL-D10)



- Ca, Mg-type in the surface, while Na-type in the depth. => Interaction with river water.
- CEC values in the range of 40-56 meq/100g.
- CEC and MB values are slightly high at shallower part, supported the other data (XRF, etc.).

Questions

Q1. Why the riverbed bentonite is unlikely mass-depletion? What is a possible factor to hinder erosion?

A1. Possible factors…

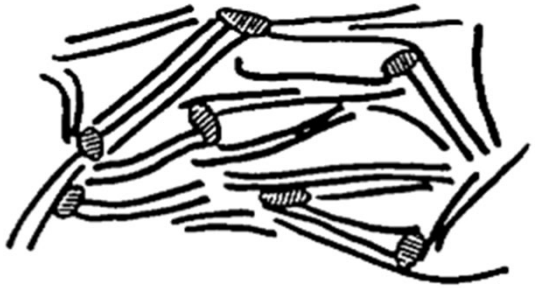
(1) Na -> Ca-type change,

(2) cementation,

~~(3) high ion strength in porewater~~

and the others?

Silica precipitation in bentonite



Pusch et al. (1998)

Questions

Q2. If bentonite's erosion rate is similar to the surrounding rocks (siltstone, tuff, etc.), how much is it?

A2. Estimated in the order of 0.1 – 1 mm/yr

How much the erosion rate in the study area?

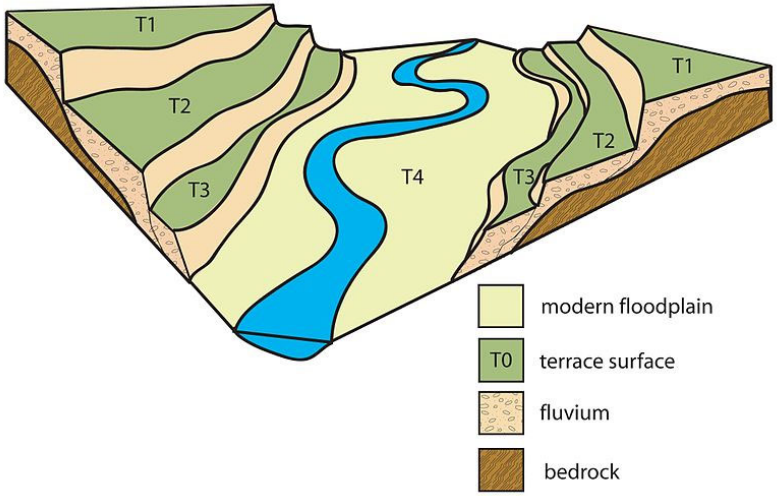
Method 1. Erosion rate correlate to altitudinal dispersion

$$E = \alpha D^{\beta} \quad \alpha = 8.64 \times 10^{-6}, \beta = 2.54, R^2 = 0.957$$

$$\mathrm{E}: erosion\ rate, D: altitudinal\ dispersion$$

Fujiwara et al. (2001) calculated the erosion rate in whole area of Japan for each 6 × 6 km area.

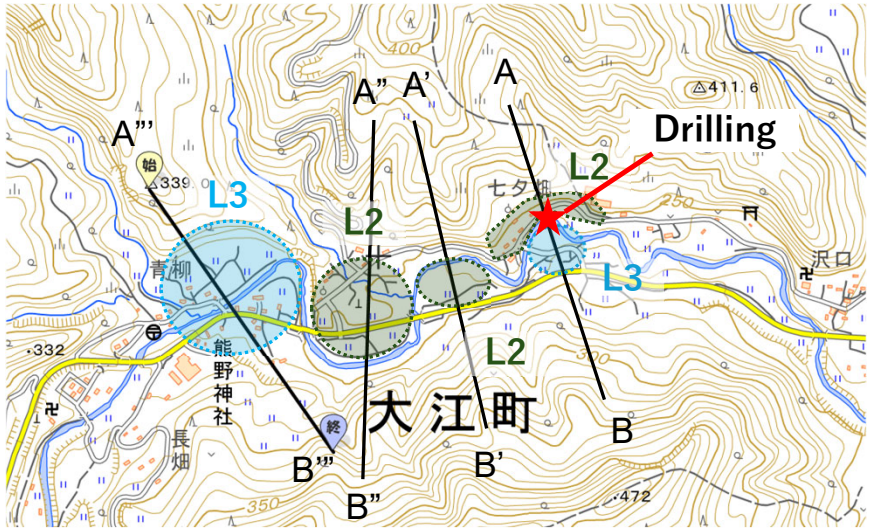
- West side of study area (upstream) => 0.404 mm/yr
- East side of study area (downstream) => 0.281 mm/yr



Method 2. Based on formation age of river terrace and height

- Topographic data: Geospatial Information Authority of Japan maps
- Classification of river terrace：(Hagisu, 2010MS)
- Formation age or river terrace：(Yamagata Pref., 2002)
  ⇒ L2 terrace: 22 – 27 ka, L3 terrace: 10 – 20 ka

Profile	Class	Rate [mm/yr]
AB	L2	0.74 – 0.91
	L3	0.45 – 0.90
A'B'	L2	0.18 – 0.23
A"B"	L2	0.18 – 0.23
A'"B'"	L3	0.10 – 0.20

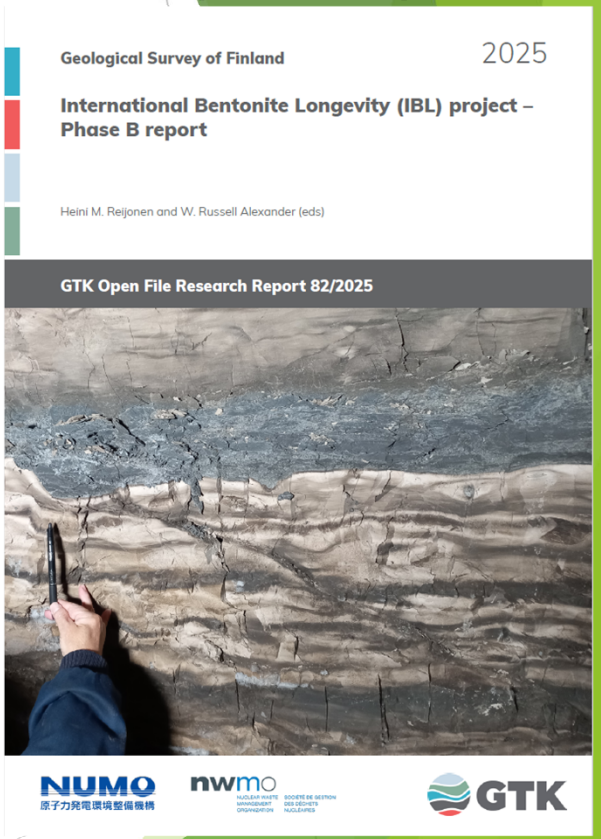


Summary

- Bentonite layer in the Miocene pyroclastic rock are drilled. Two drilling cores with about 5 m length were obtained. All part of core composed of bentonite.
- River water chemistry was rich in Na^+, Ca^{2+}, SO_4^{2-}, Cl^- and diluted condition that chemical erosion may occur (total cation charge ~ 1.2 – 1.5 mM).
- Cores were analyzed by X-ray CT, XRF core scanner, XRD, … etc.
- Density profiles show almost constant values along the depth. About ~95 % saturation state can be seen in whole part of core. No sign of mass depletion from the surface.
- In exchangeable cations, Ca and Mg decreased from the surface to depth, Na increased. => Ion exchange between Ca, Ma-rich river water and Na-type bentonite.
- Na -> Ca-type change and/or cementation, are possible factor limiting erosion.
- Based on geomorphological methods, the erosion rate is estimated to be in the range of 0.1–1 mm/yr.

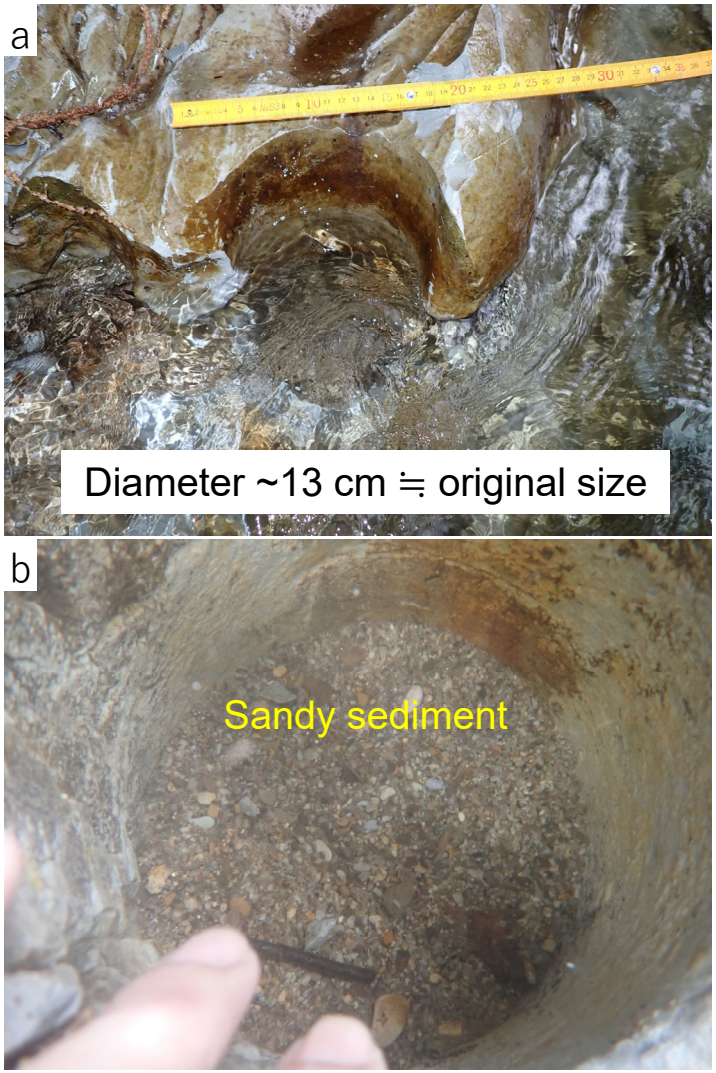
Thanks to IBL project members, NUMO-CRIEPI-HU joint research members, ARIM program, Kochi Core Center staff and you!

IBL phase B report



One year after drilling…

Next target? Self-sealing behavior

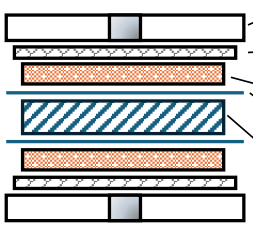


IBL-D10 borehole

Erosion test using riverbed bentonite

Bentonite disk or powder with 1.5 g/cm^3 of dry density

(e)



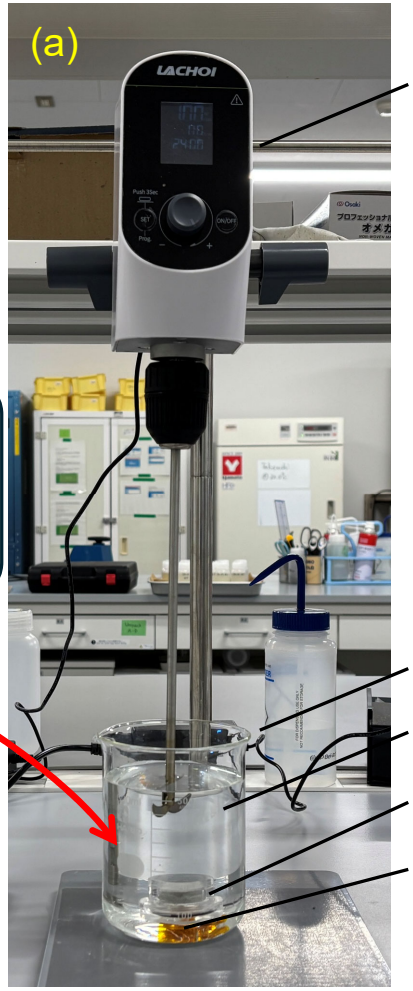
Acryl column（ϕ 5.5 mm hole）

Supporting filter（SUS, 150 um pore size）

Metal filter（SUS, 3 mm, 10 um pore size）

Membrane filter（0.5 um pore size）

Bentonite（4 mm thick）



Rotation mixer（LACHOI, 100rpm）

500 ml beaker

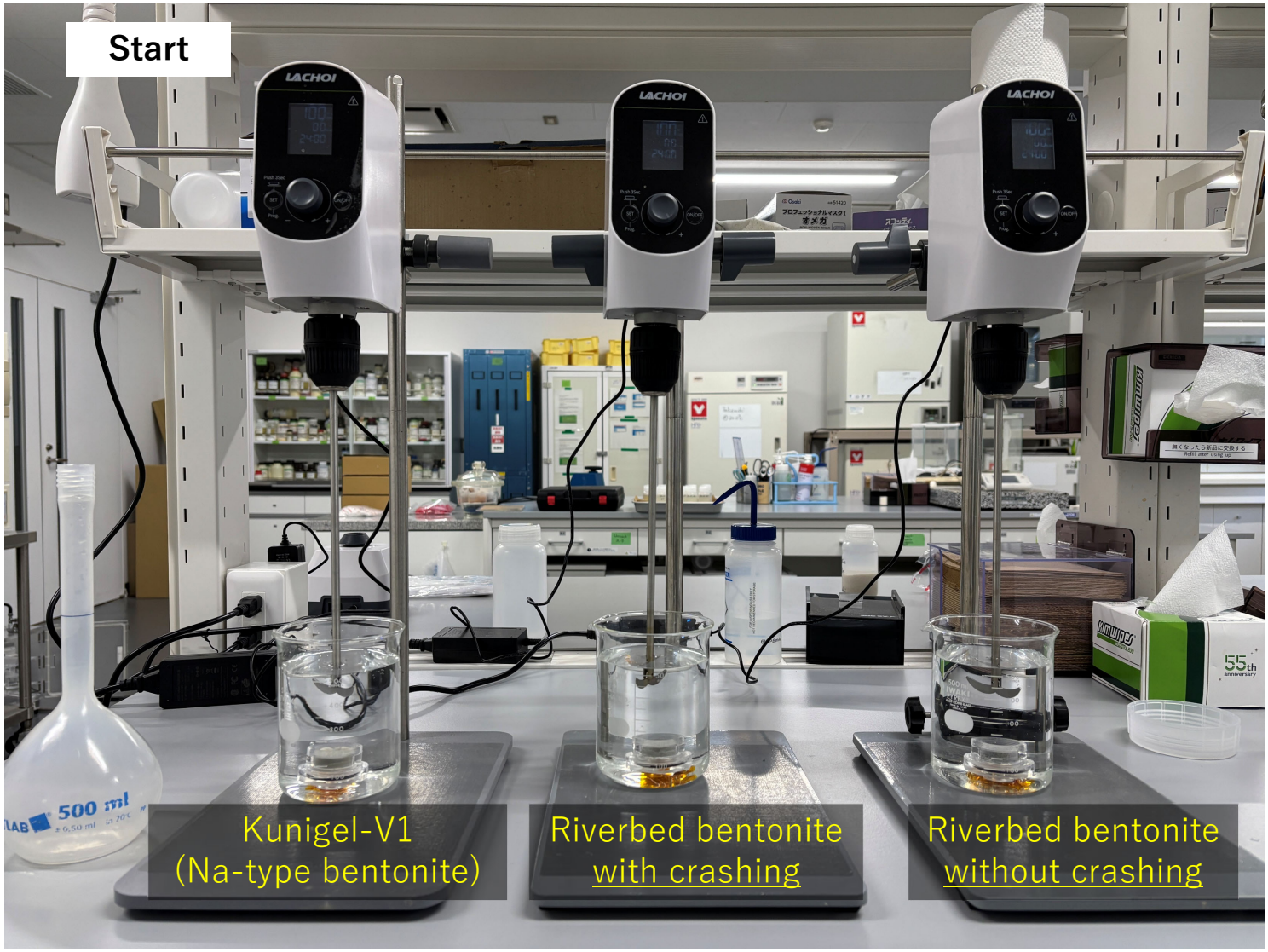
River water

Bentonite disk

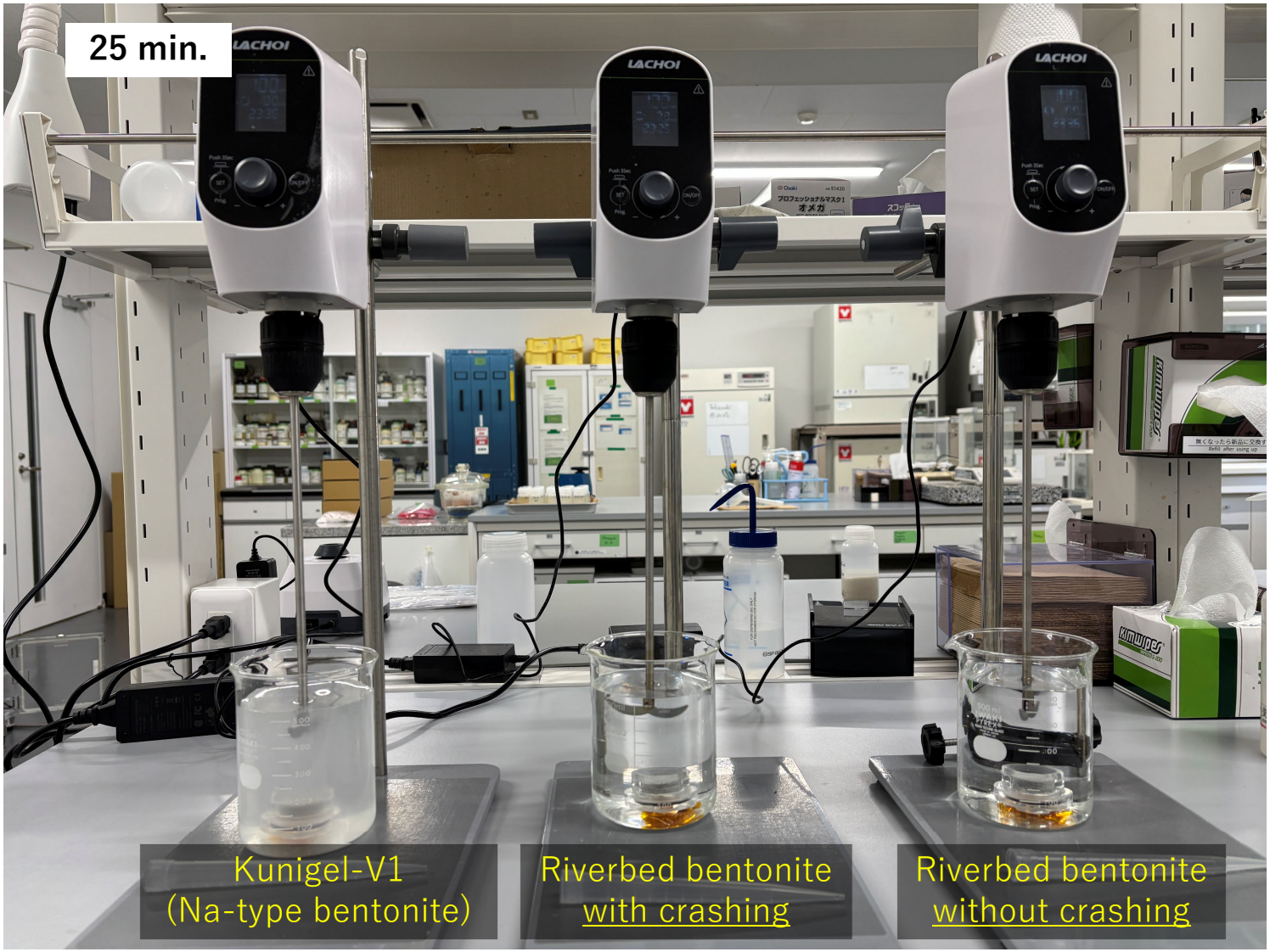
Adhesive tape

Erosion test setup

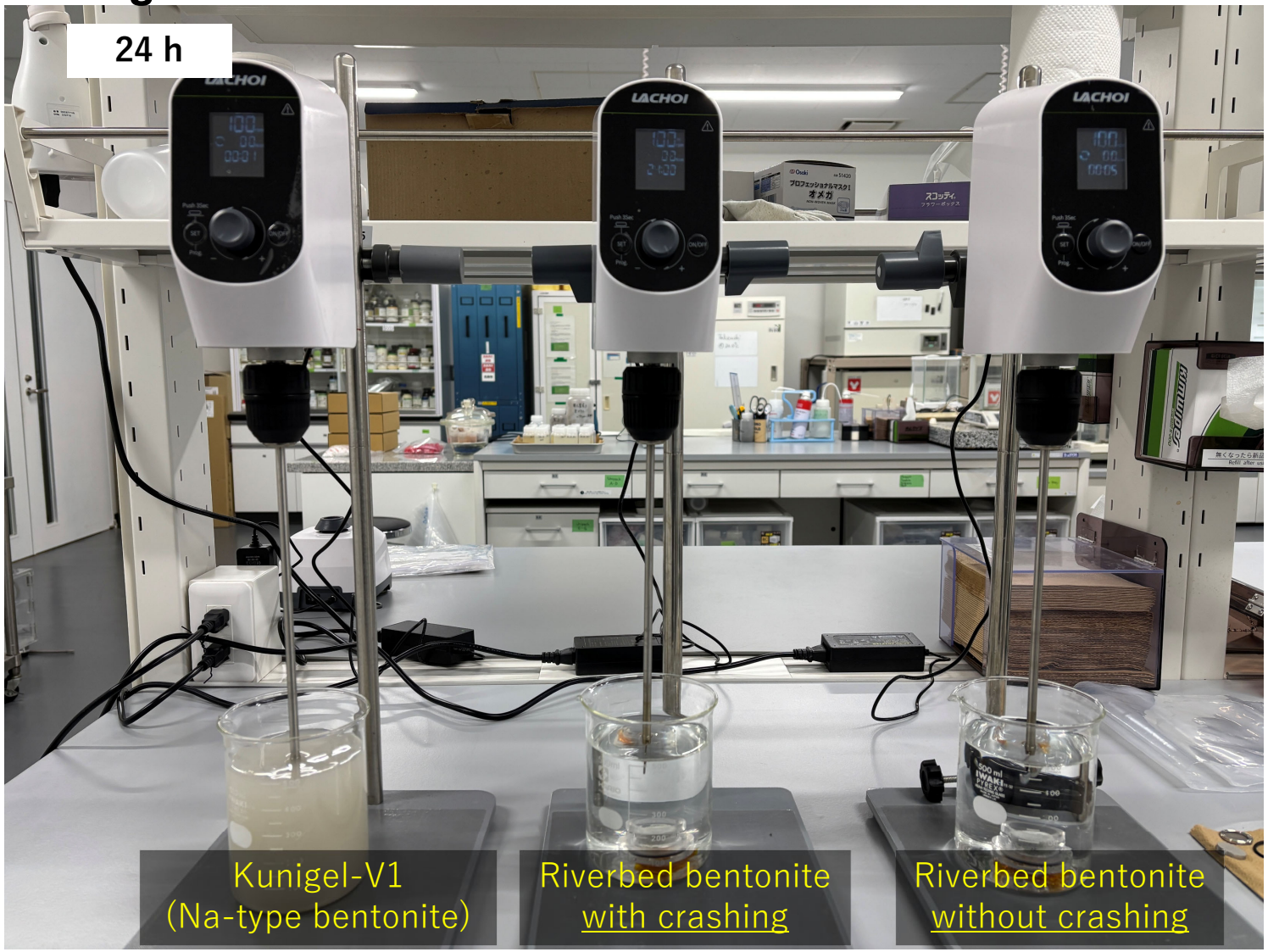
Erosion test using riverbed bentonite



Erosion test using riverbed bentonite



Erosion test using riverbed bentonite



Erosion test using riverbed bentonite

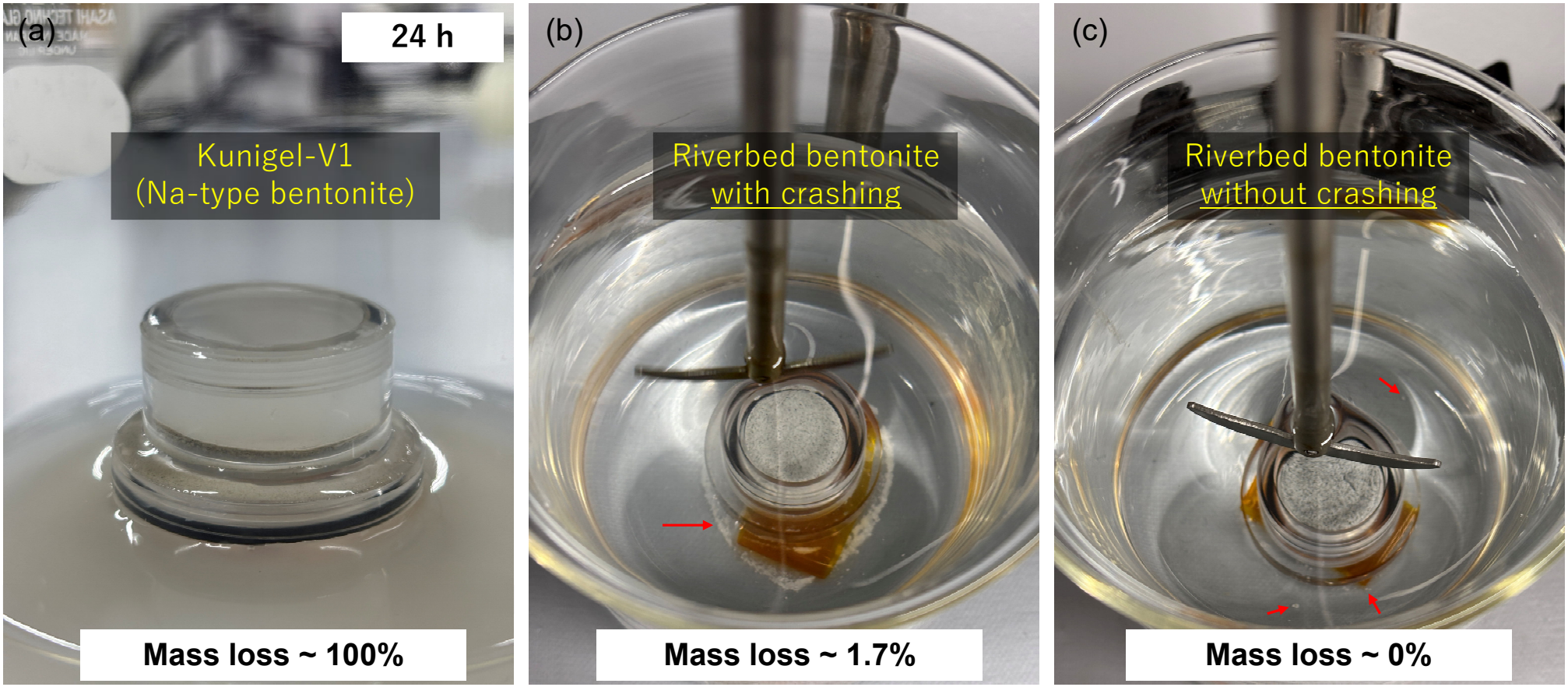


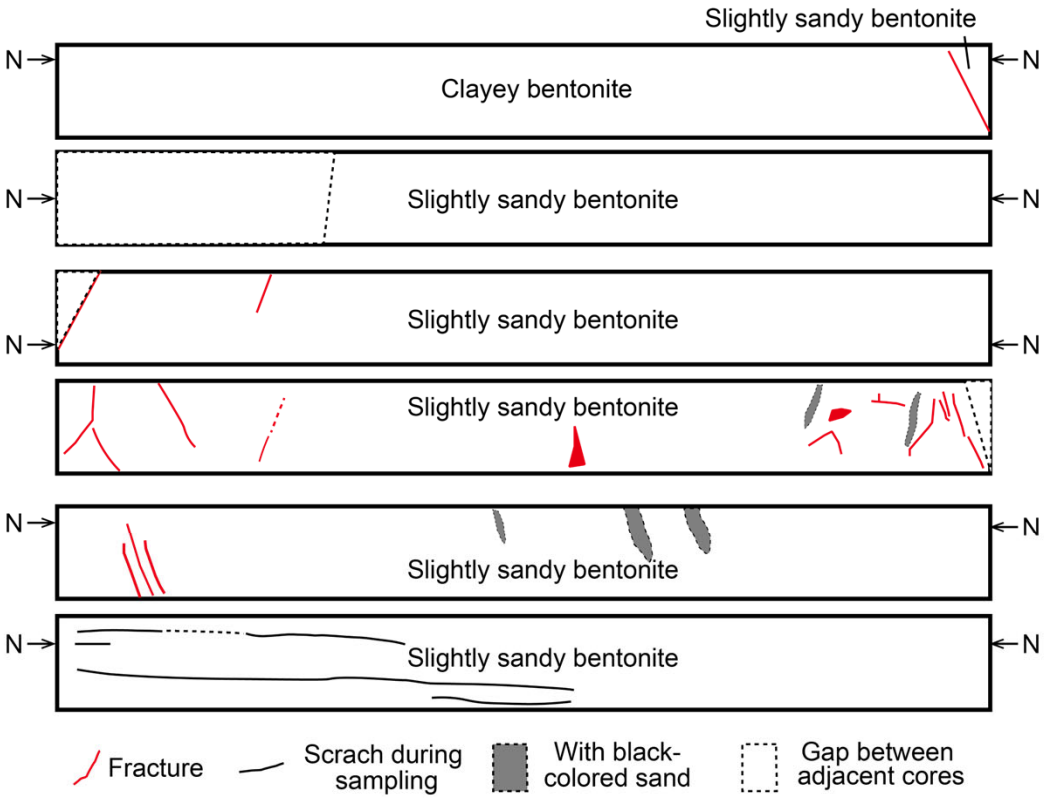
Fig. After 24 hours of the erosion test.
(a) Kunigel-V1, (b) crushed riverbed bentonite, (c) uncrushed riverbed bentonite.
(b) shows that some of the eroded bentonite has settled at the bottom (red arrow).(c) shows a small fragment (red arrow).

First drilling：IBL-1

IBL-1 cores

Each depth: (1) 0.00 m – 0.95 m, (2) 0.95 – 1.60 m, (3) 1.60 – 2.55 m, (4) 2.55 – 3.45 m, (5) 3.45 – 4.45 m, (6) 4.45 – 5.45 m。

・Cores were stored in the acrylic cases (φ10 cm, 1m length).
・Cases were tightly sealed to prevent drying.

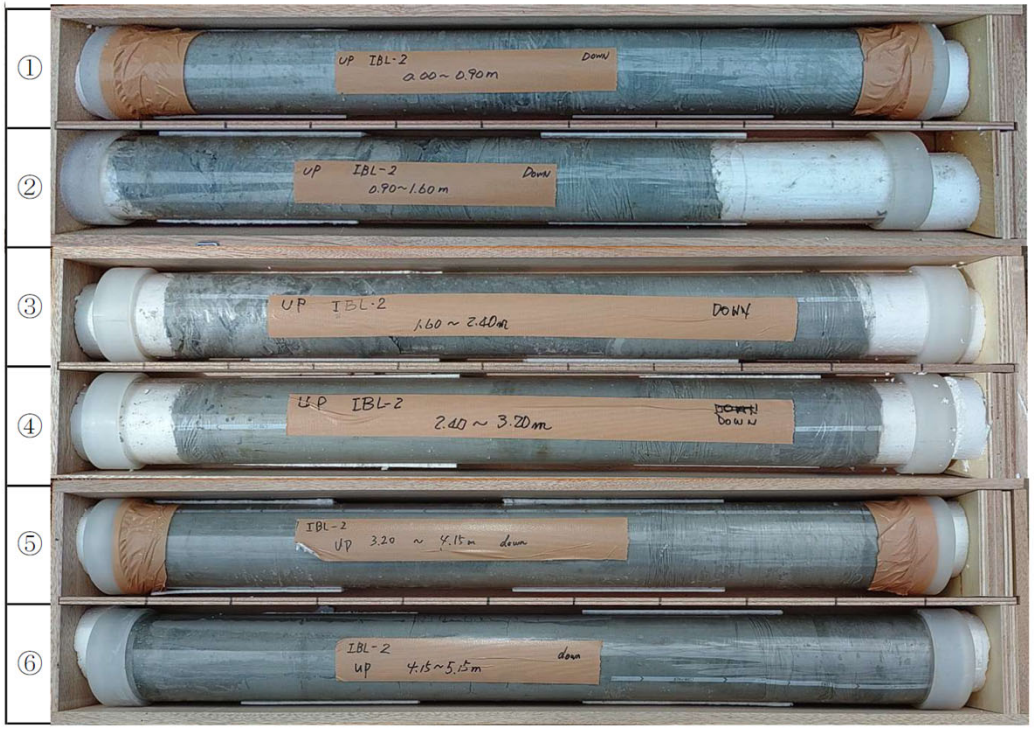


IBL-1 lithology

N: north direction

☑ **All parts were composed of bentonite.**
☑ **Shallow part (< 1 m) was likely rich in clay fraction.**

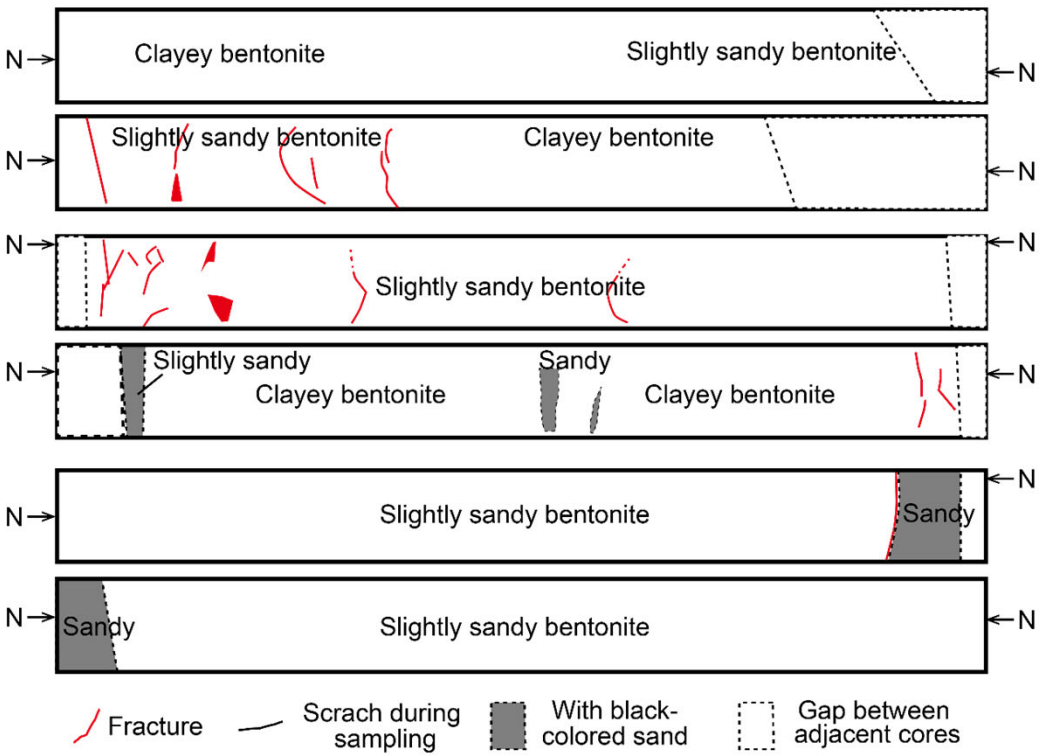
Second drilling：IBL-2



IBL-2 cores

Each depth: (1) 0.00 m – 0.90 m, (2) 0.90 – 1.60 m, (3) 1.60 – 2.40 m, (4) 2.40 – 3.20 m, (5) 3.20 – 4.15 m, (6) 4.15 – 5.15 m。

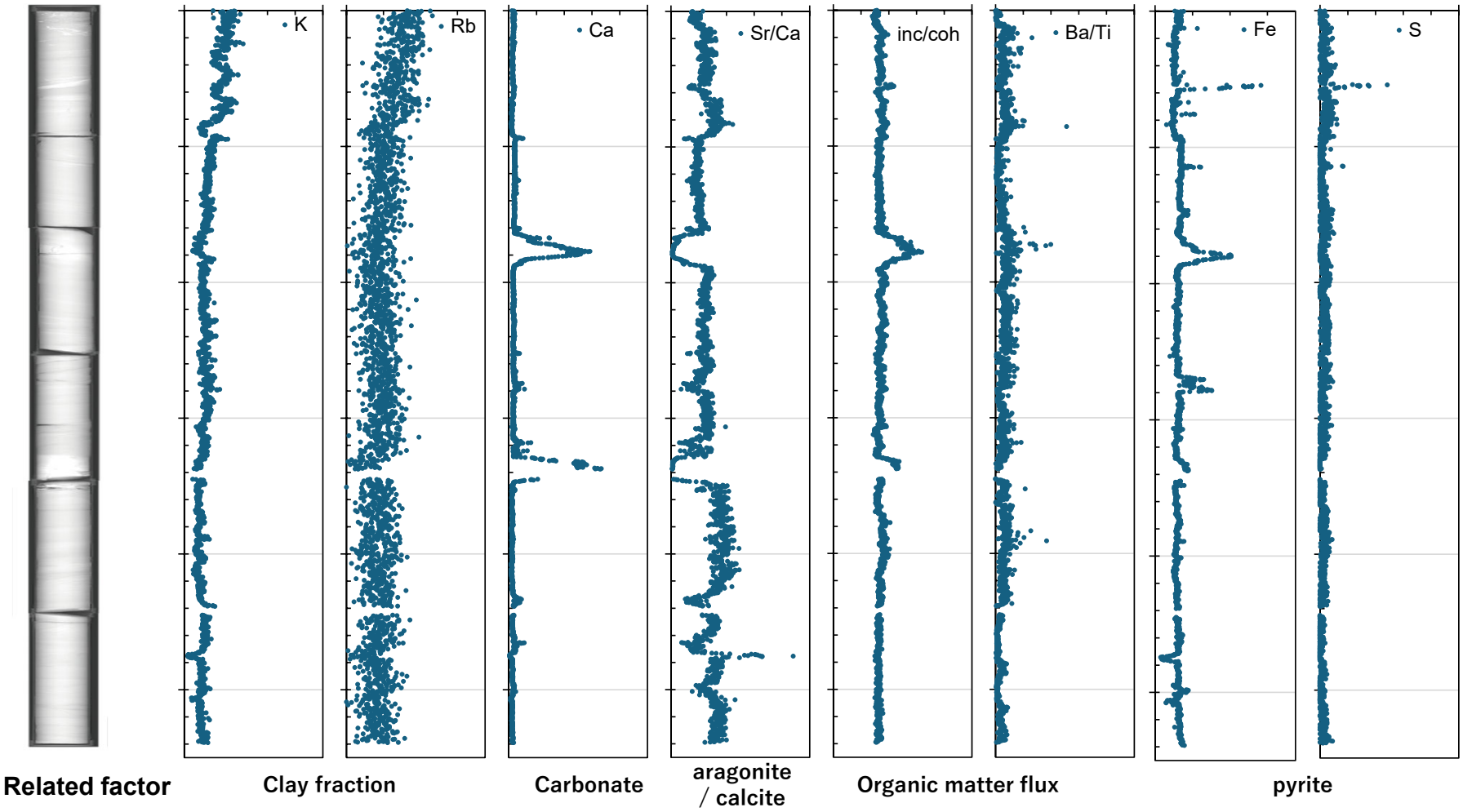
・Cores were stored in the acrylic cases (φ10 cm, 1m length).
・Cases were tightly sealed to prevent drying.



IBL-2 lithology

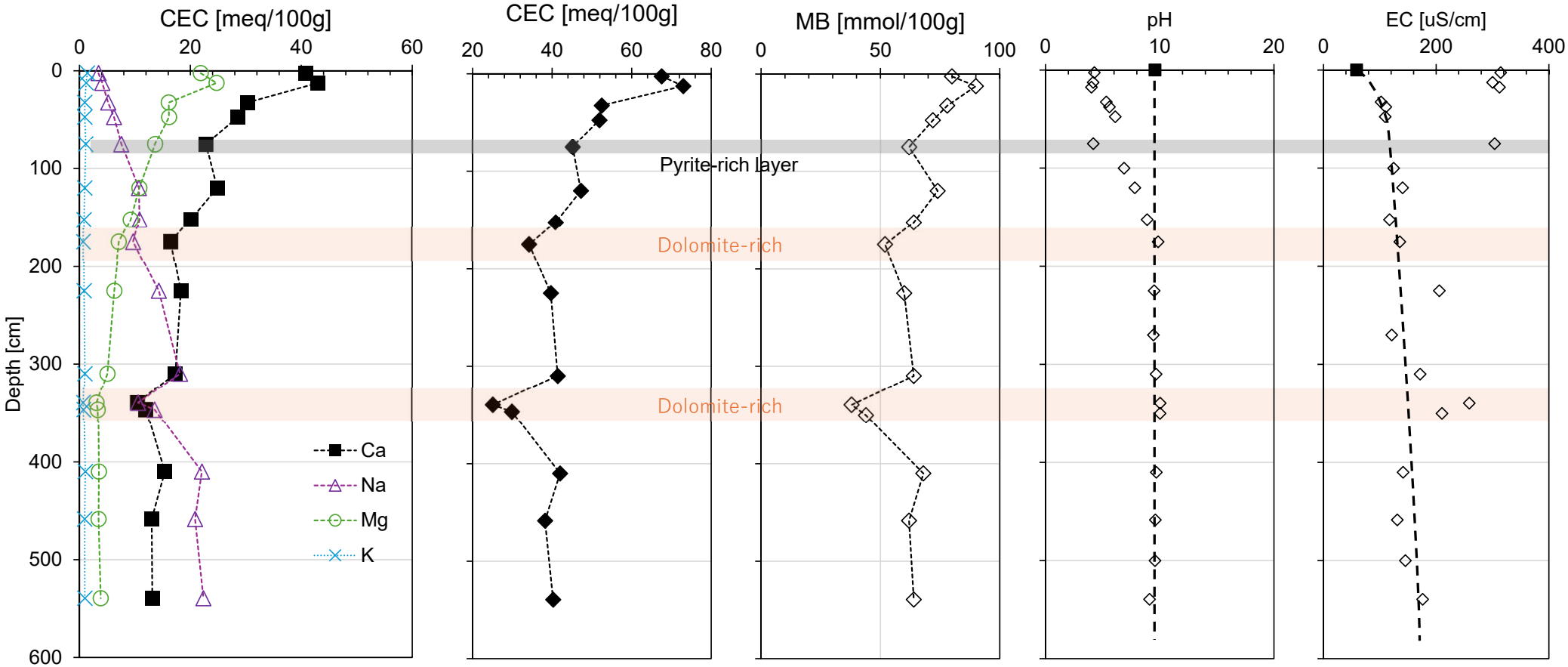
☑ **All parts were composed of bentonite.**
☑ **Shallow part (< 1 m) was likely rich in clay fraction.**

XRF core scanner



(1) Decrease of clay fraction from the surface, (2) some parts are rich in calcite or pyrite

Depth profiles of CEC, MB, pH & EC（IBL-D9）



- 表層はCa-Mg型 ⇔ 深部はNa型となっており、河川水との接触によるイオン交換を示唆。
- 表層の約1 mでCEC, MBがやや低下、1m以深ではほぼ横ばい（炭酸塩部を除く）。
- 1.5 m以深ではpH~9 – 10程度で一定だが、表層に向かって低下。黄鉄鉱の酸化溶解の影響を懸念。

CEC・MB

Depth [cm]	Sample name	Exchangeable cations [meq/100g]				
		Ca	K	Mg	Na	Total
2.5	IBL-2_000-005	38.71	0.75	14.53	2.68	56.67
17.5	IBL-2_015-020	35.59	0.70	10.76	4.42	51.47
32.5	IBL-2_030-035	34.32	0.69	10.77	5.99	51.78
72.5	IBL-2_070-075	23.23	0.69	7.05	9.14	40.11
112.5	IBL-2_110-115	22.74	0.81	8.98	13.24	45.77
142.5	IBL-2_140-145	20.12	0.73	4.72	15.84	41.41
175	IBL-2_172-178	19.98	0.91	5.50	19.23	45.62
222.5	IBL-2_220-225	17.32	0.75	3.91	21.84	43.82
307.5	IBL-2_305-310	14.68	0.71	2.99	21.82	40.20
457.5	IBL-2_455-460	13.80	0.76	1.95	28.29	44.79

Ref：reported CEC values of Kunigel-V1

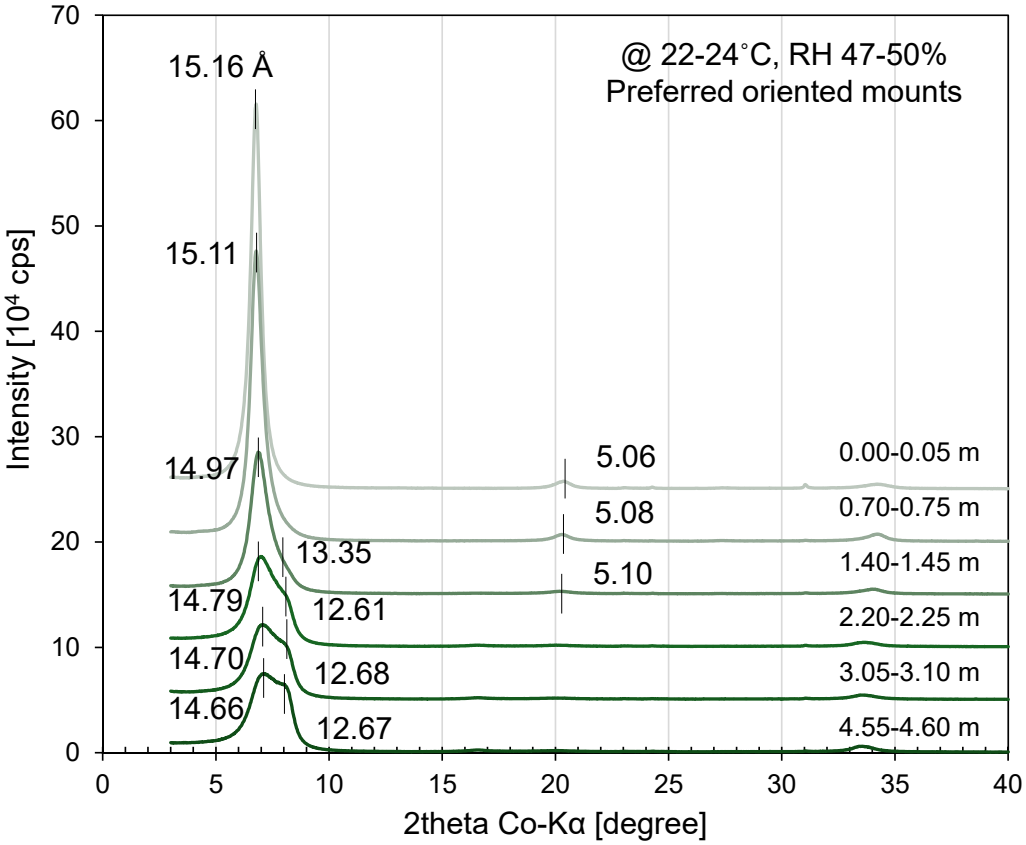
This study	SFSA method	8.46	0.30	0.51	52.83	62.10
NUMO-CRIEPI, 2022	〃	9.3	0.4	0.8	53.4	63.9
Shirakabe et al., 2021	〃	7.8	0.0*	0.4	60.3	68.5
	Ammonium acetate	59.5	3.1	2.5	67.1	74.2**

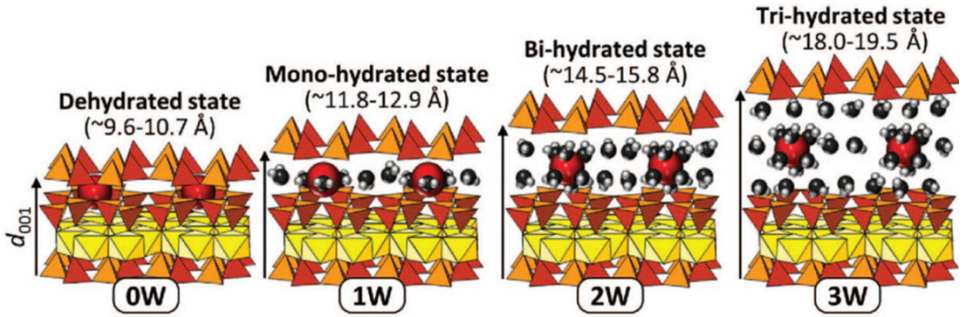
*Below detection limit. **NH_4^+をKClで更にイオン交換して定量。

Depth [cm]	MB [mmol/100g]	Smectite content [%]*
2.5	76	54
12.5	70	50
17.5	70	50
32.5	68	49
37.5	66	47
43.5	66	47
72.5	60	43
112.5	66	47
142.5	60	43
176	54	39
187.5	54	39
222.5	66	47
272.5	62	44
307.5	60	43
347.5	68	49
397.5	60	43
457.5	66	47

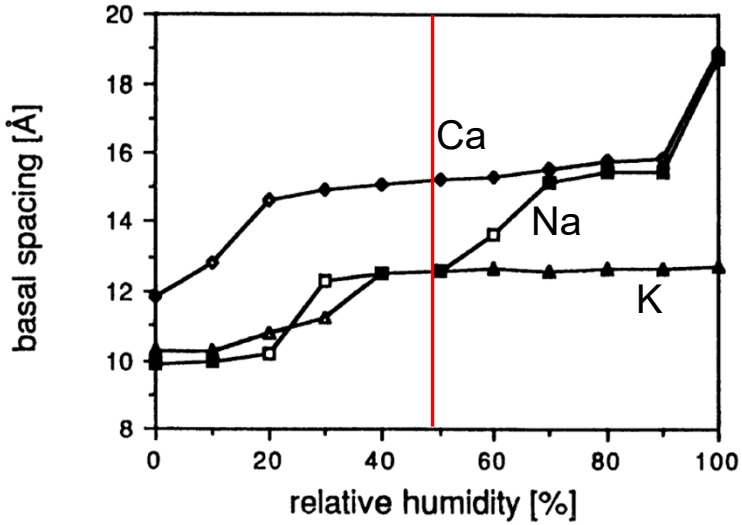
*Assume 140 mmol/100g = smectite 100%

XRD: Clay fractions (0.2 – 2 µm)





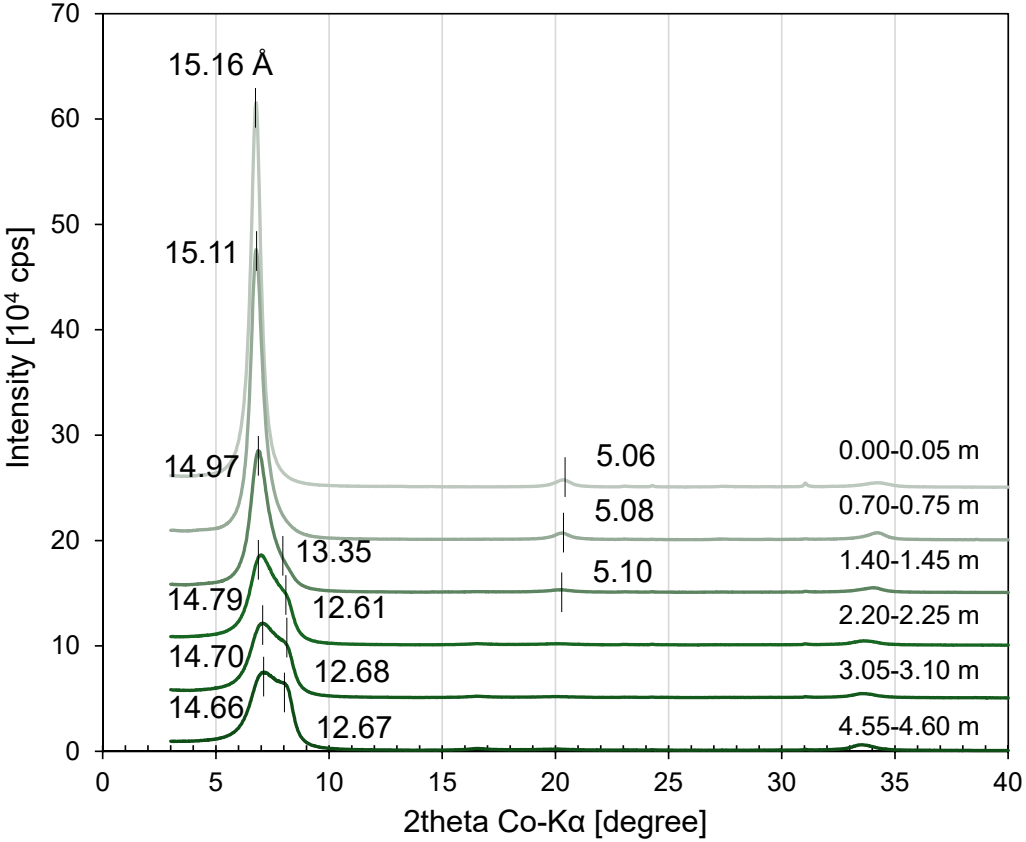
Ferrage et al. (2016)



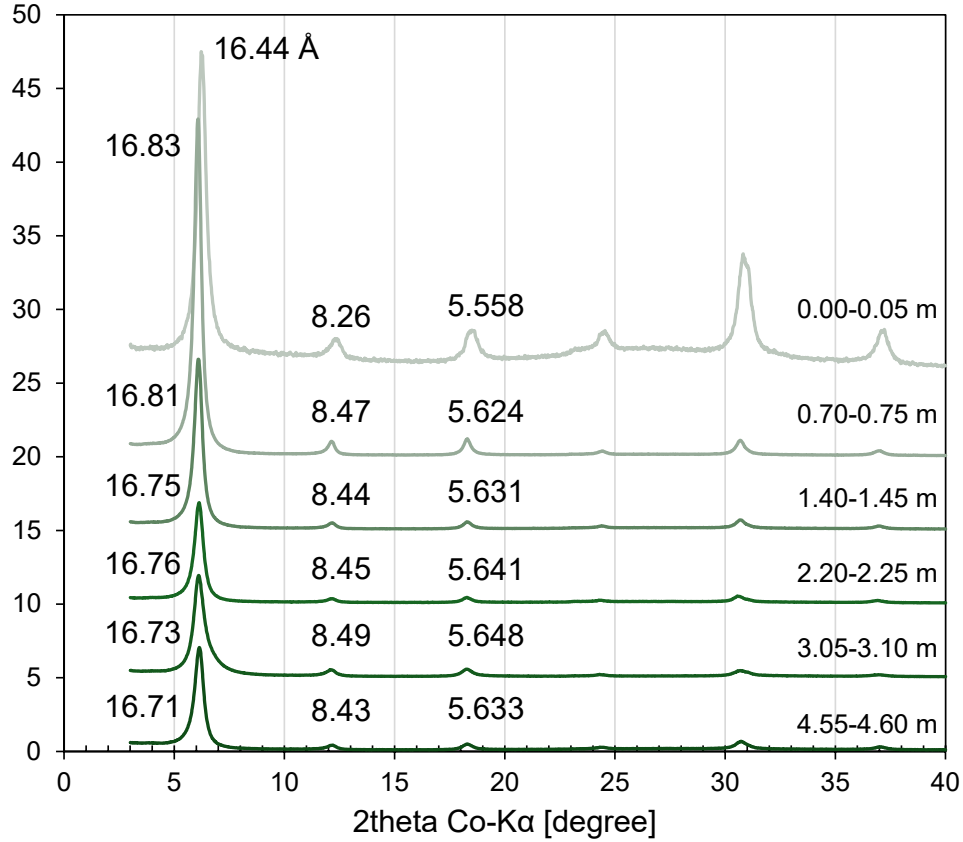
Watanabe, Sato (1988)

XRD: Clay fractions

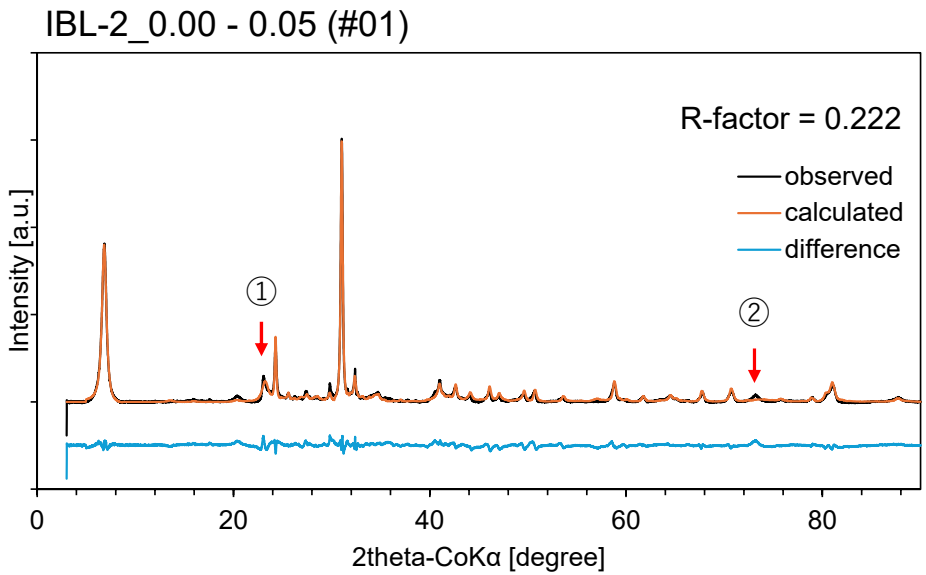
0.2 – 2 um画分10mgを蒸留水0.4mlに懸濁させ、
スライドグラス上に滴下・風乾
22-24˚C, RH47-50%で測定

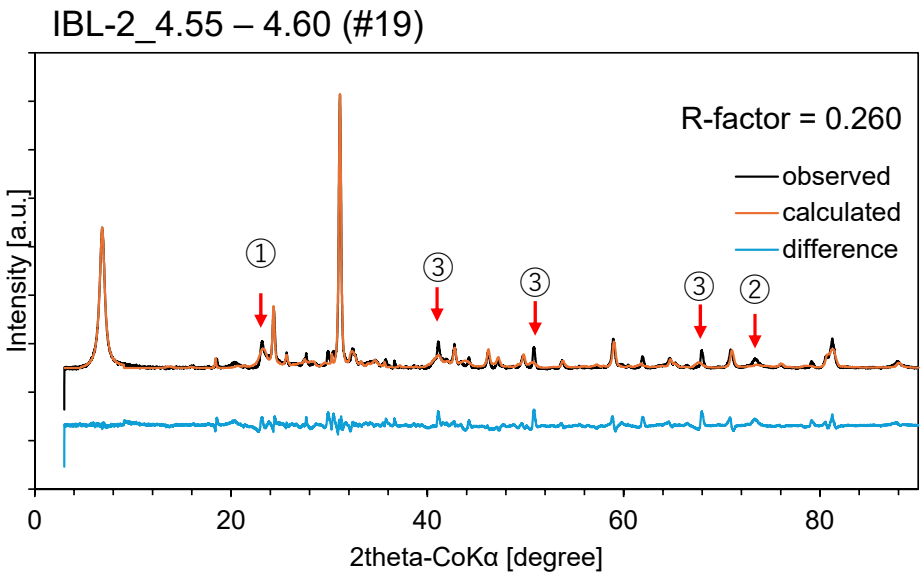


EGを直接定方位試料に滴下（25 µl）し、
半乾き状態で測定



Reitveld解析（241023版）





＜解析の方針＞

- 長石にはlabradoriteを採用。＃19にはanalcimeを鉱物相に追加。
- Step1では、scaleとゼロ点のみ変更。
- Step2では、まず格子定数が大きく変動し得るmontmorilloniteのピーク位置を合わせるためにcell (c, β)のみ変更。他は層間距離が収縮・膨張しても然程変わらないと仮定。a,bとかを自由にさせるとかなり変な値に発散する印象。
- Step3では、montmorilloniteのピーク形状を大まかに合わせに行くために、配向性とWを変更。
- Step4では、他の鉱物相を合わせに行く。cellとWをまとめて変更。この段階ではピーク形状はまだしっくりこないので、次のstepへ。damping factorを少し小さめにすると良いかも。
- Step5では、非対称なピーク形状を合わせるためにasymmetry factorにチェックを。また、Shapeを5wt%以上の主要鉱物について変更する。微量な鉱物を含めるとrefinementが途中で終わる印象。さらに、quartzは高角側と低角側で形状が合いにくい傾向だったので、Vを変更。montmorilloniteも同じくVを変更。

＜フィッティングがズレる部分＞

①mmt 003のピークがややズレる：Na-montmorilloniteのデータからフィッティング開始していて、Ca型と強度比がズレているのが要因の一つかも。また、非対称性パラメータの自由度がもう少し設定できると良いかも。

②mmt 060のピーク強度が全然でない。

③labradoriteのパラメータ設定で改善できそうな印象だった。

Porewater chemistry of surface bentonite

High ionic strength in porewater hinder erosion?

Experimental procedures

- Steel pipes were hammered into the riverbed bentonite to collect cylindrical samples.
- The samples were stored frozen until the experiment to prevent drying.
- Bentonite (33.4% of water content) was dispersed in ultrapure water to extract the pore water.
- Stir for 15 minutes → let stand for 1 hour → centrifuge and filter the supernatant.
- Dilute the filtrate as appropriate and analyze by IC and ICP-AES.

☐ **Relatively diluted chemistry, suggesting mixing with river water**

	Porewater [mM]	**Ref[1] [mM]**	**Ref[2] [mM]**
Na	**1.41**	205	91.5
Mg	**0.097**	0.940	2.48
K	**0.084**	2.31	1.03
Ca	**0.159**	18.2	4.17
Al	**0.063**	-	-
Fe	**0.001**	-	-
Si	**0.420**	-	-
Cl	**0.852**	323	47.6
NO_3^-	**-**	-	-
SO_4^{2-}	**2.36**	0.940	24.8

[1] Bradbury & Baeyens (2002)
Porewater in a compacted bentonite (Kunigel-V1, ρ_d = 1400 kg m^{-3})
[2] Kizka et al. (2023)
Porewater in a Opalinus clay (Jura Ost)

Erosion test using riverbed bentonite

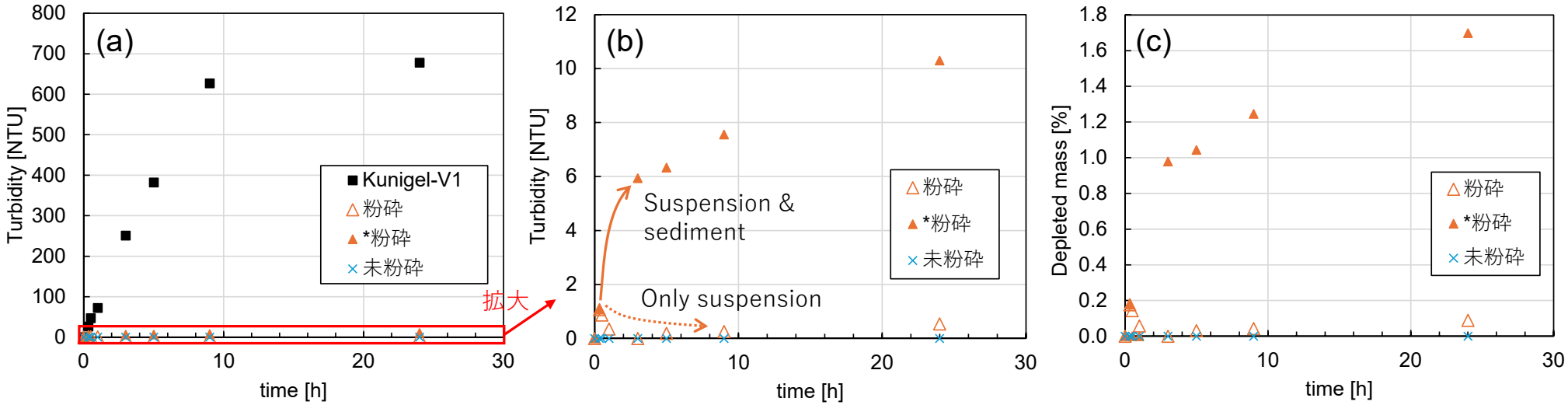
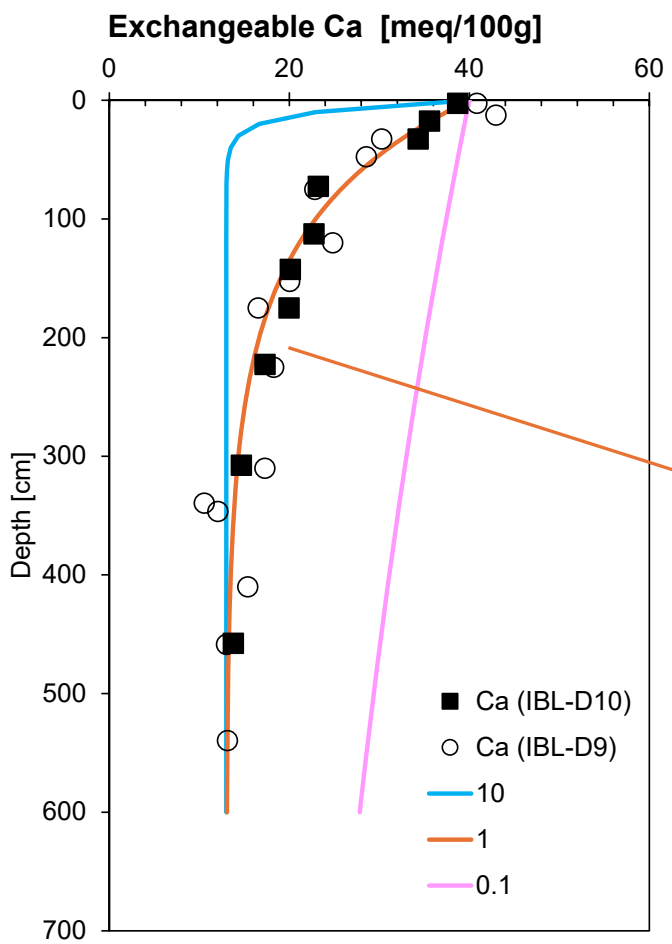


Fig. Turbidity change as a function of time
(a)(b) Turbidity of each sample, and (c) the depleted mass ratio (%) calculated from the turbidity.。
*For the crushed riverbed bentonite, measurements were taken both in a suspended state and after forcibly dispersing the fraction settled at the bottom.

- ☐ Depleted mass loss (%) for 24 hours: Kunigel-V1 ～100%, Crashed riverbed bentonite～1.7%, Uncrashed riverbed bentonite～0％ (under detection)
- ☐ Na ⇒ Ca・Mg-type may hinder erosion rate.
- ☐ Erosion is further reduced when the bentonite was uncrushed.

Erosion rate vs. Diffusion rate

[1] Ochs et al., 2001, [2] Tachi et al. 2014, [3] Kozaki et al., 2010



境界面が一定速度で移動する場合の定常解

$$\xi = x - vt$$

$$C(\xi) = C_i + (C_0 - C_i)\exp(-\frac{v}{D}\xi)$$

x: 固定座標, ξ: 移動座標

v: 侵食速度, D: 拡散係数

C_0: Conc. at interface

C_i: Initial conc.

Key parameter is $\frac{v}{D}$

High $\frac{v}{D}$ = Fast erosion & Short diffusion distance

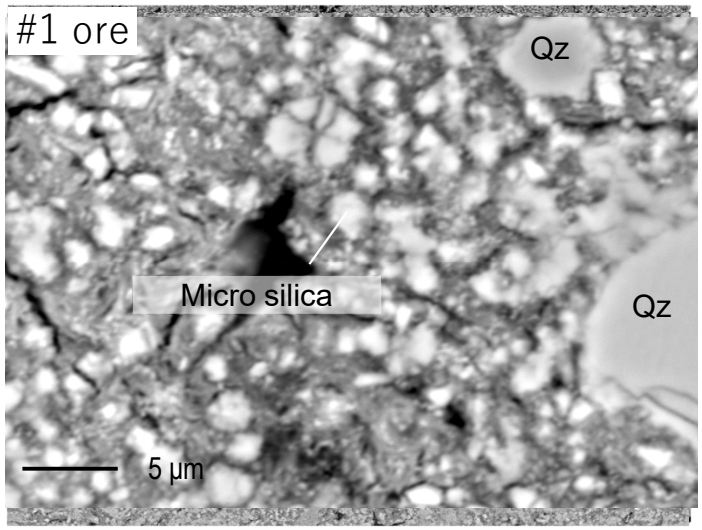
Low $\frac{v}{D}$ = Slow erosion & long diffusion distance

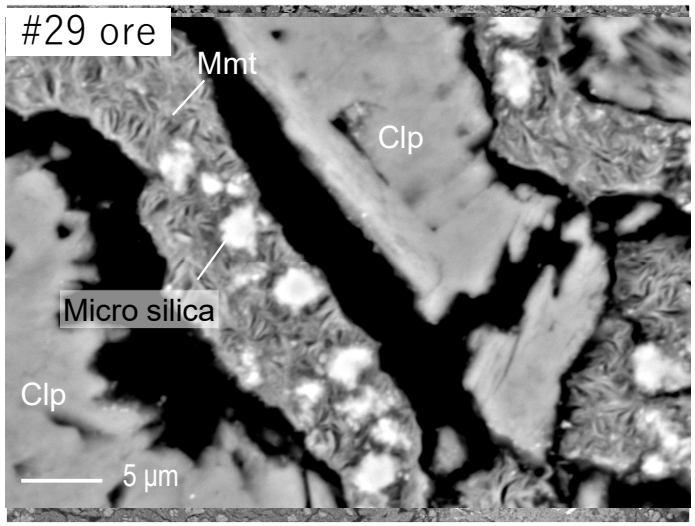
Ca profile agrees well with $v/D \approx 1$.
i.e., Erosion and diffusion rates have the same order

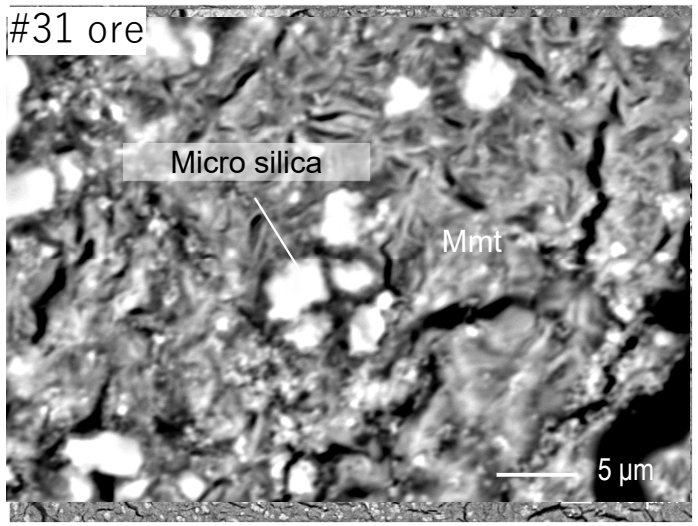
	D_a [m²/s]	v [mm/yr]
Kunigel-V1 (1.6 g/cm³)[1]	Sr: ~ 8.0×10^{-11}	**2.52**
Kunigel-V1 (1.6 g/cm³)[2]	Cs: ~ 4.0×10^{-12}	**0.13**
Kunipia-F（1.0 g/cm³, Na-Ca型）[3]	Ca: ~ 1.6×10^{-11}	**0.50**

Micro silica particles in bentonite

Qz:quartz, Mmt: montmorillonite, Clp: clinoptilolite





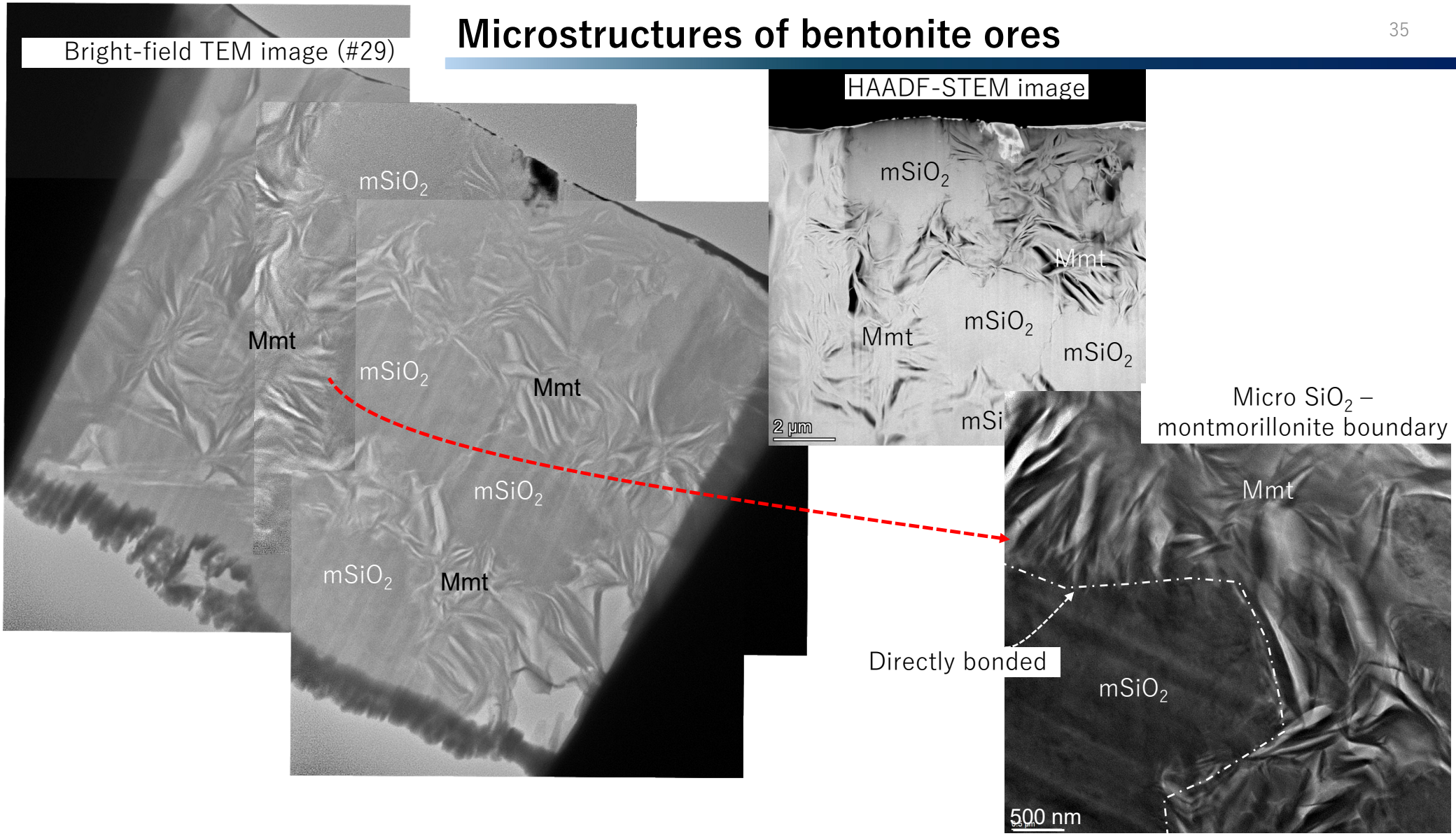


The distribution of micro silica
- **discrete grains**
- **short chain of grains**
- **small cluster of grains**

Consistent with authigenic micro-sized quartz in shale rocks (Thyberg et al., 2010)

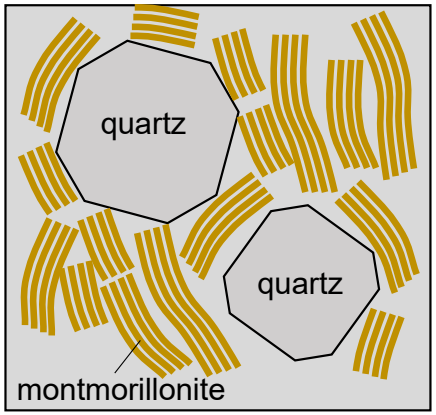
Formed under closed system diagenesis and with a low mobility of silica in clayey matrix

Microstructures of bentonite ores

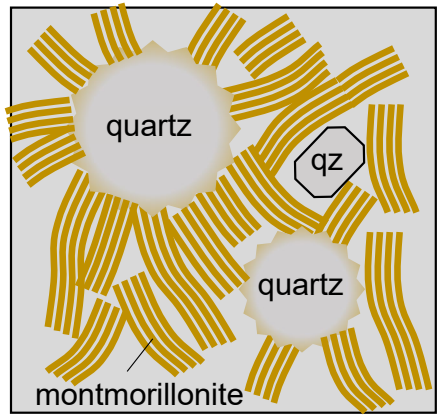


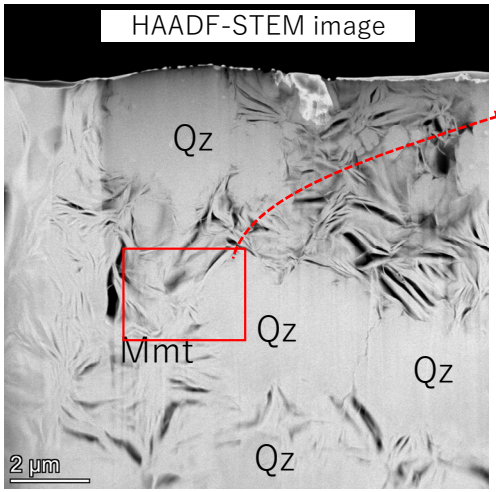
Microstructures of bentonite ores

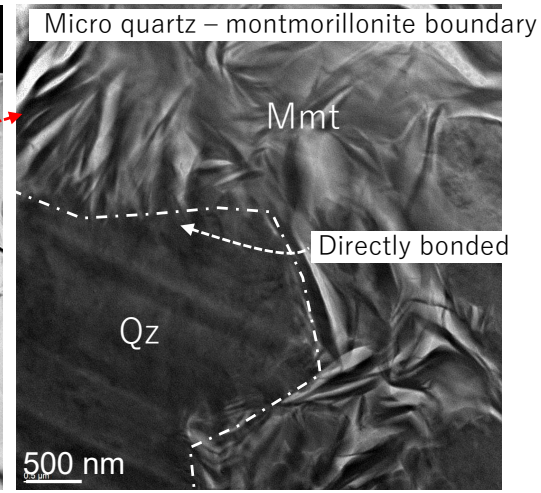
Conceptual texture of compacted bentonite



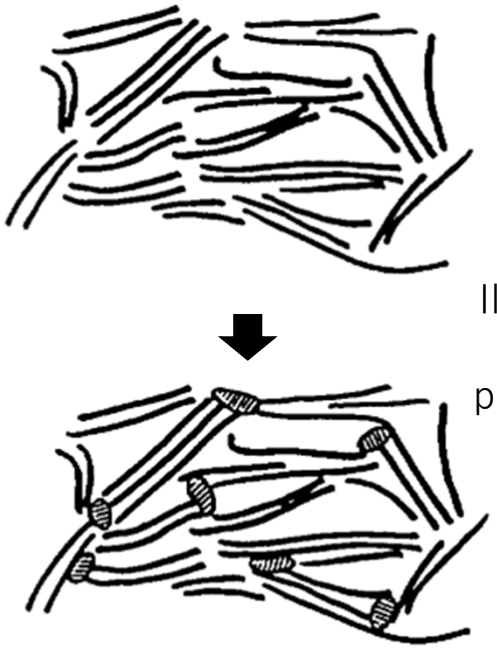
Observed texture of bentonite ores







Proposed model for bentonite cementation



Illitization & Silica precipitation

Pusch et al. (1998)

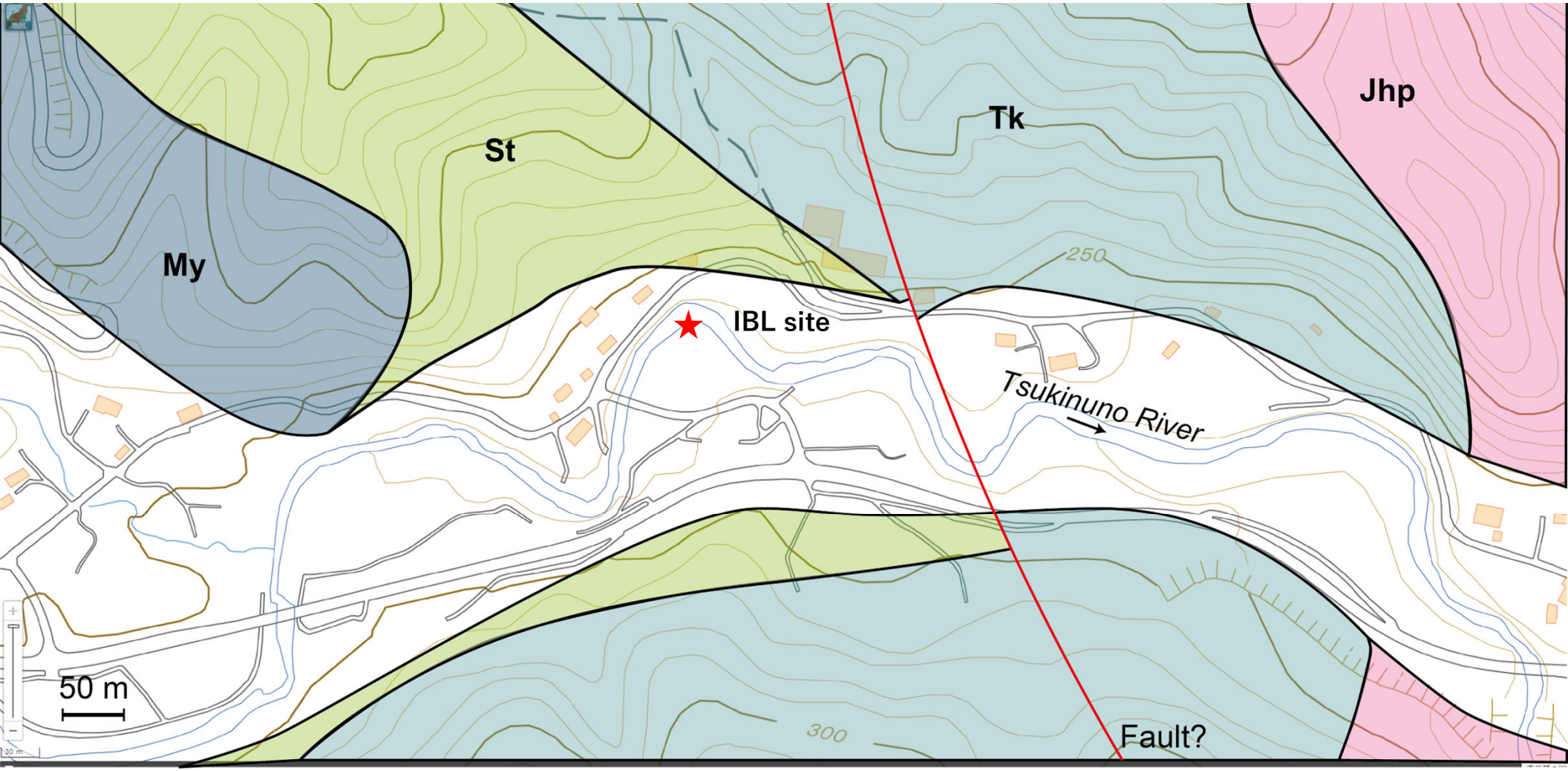
International Bentonite Longevity (IBL) project

Riverbed bentonite will provide…

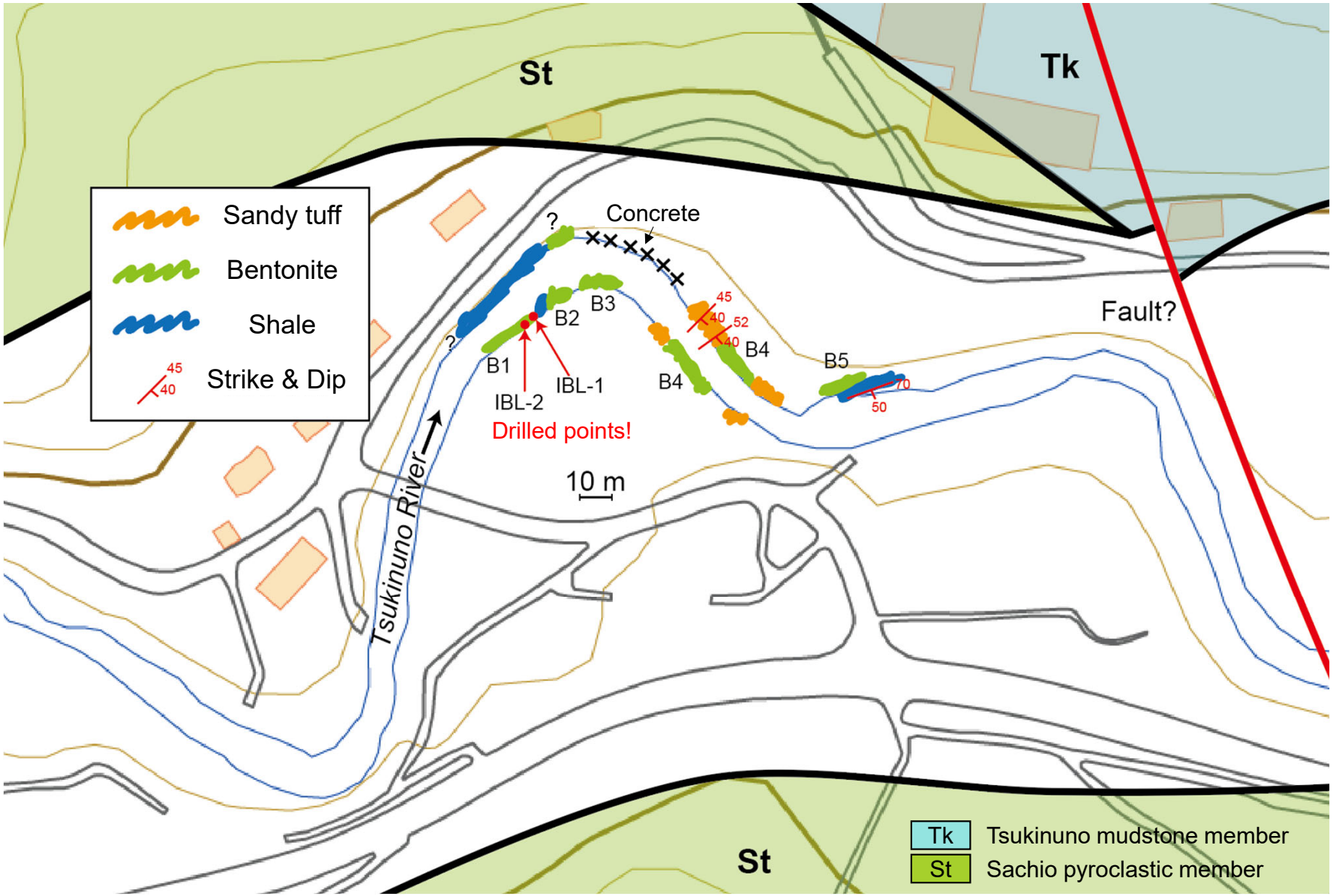
The mine and its environs are ideal for studying long-term, safety-relevant bentonite processes, including:

- *saturation* – natural saturation states of bentonite in differing environments (on the surface and at varying depths underground, dry and wet host rock conditions) for comparison with ongoing short-term, laboratory and underground rock laboratory (URL) tests
- *bentonite density changes* (swelling and heave) – due to exposure to groundwaters/meteoric waters
- *bentonite water interaction processes with fresh and deeper groundwater chemistries* – for example, changes in cation exchange capacity (CEC) and exchangeable cation composition (EC)
- *bentonite erosion* – both under repository-relevant conditions at depth in the tunnels where water conducting features contact the bentonite and under extreme conditions (river erosion at the surface)
- *bentonite reaction* – with mudstone and siltstone host rocks (of relevance to borehole seals)

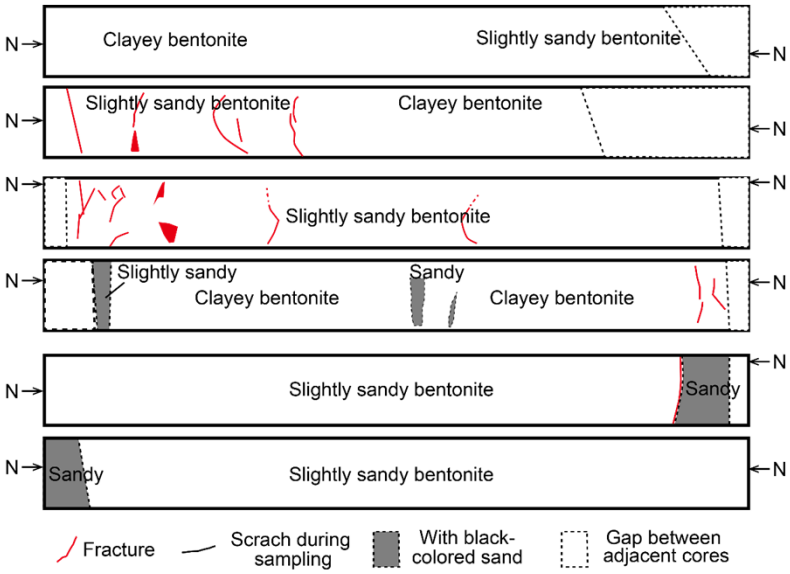
from IBL website



My 水沢泥岩部層　St 幸生火砕岩部層　Tk 月布泥岩部層　Jhp 十八才火砕岩部層

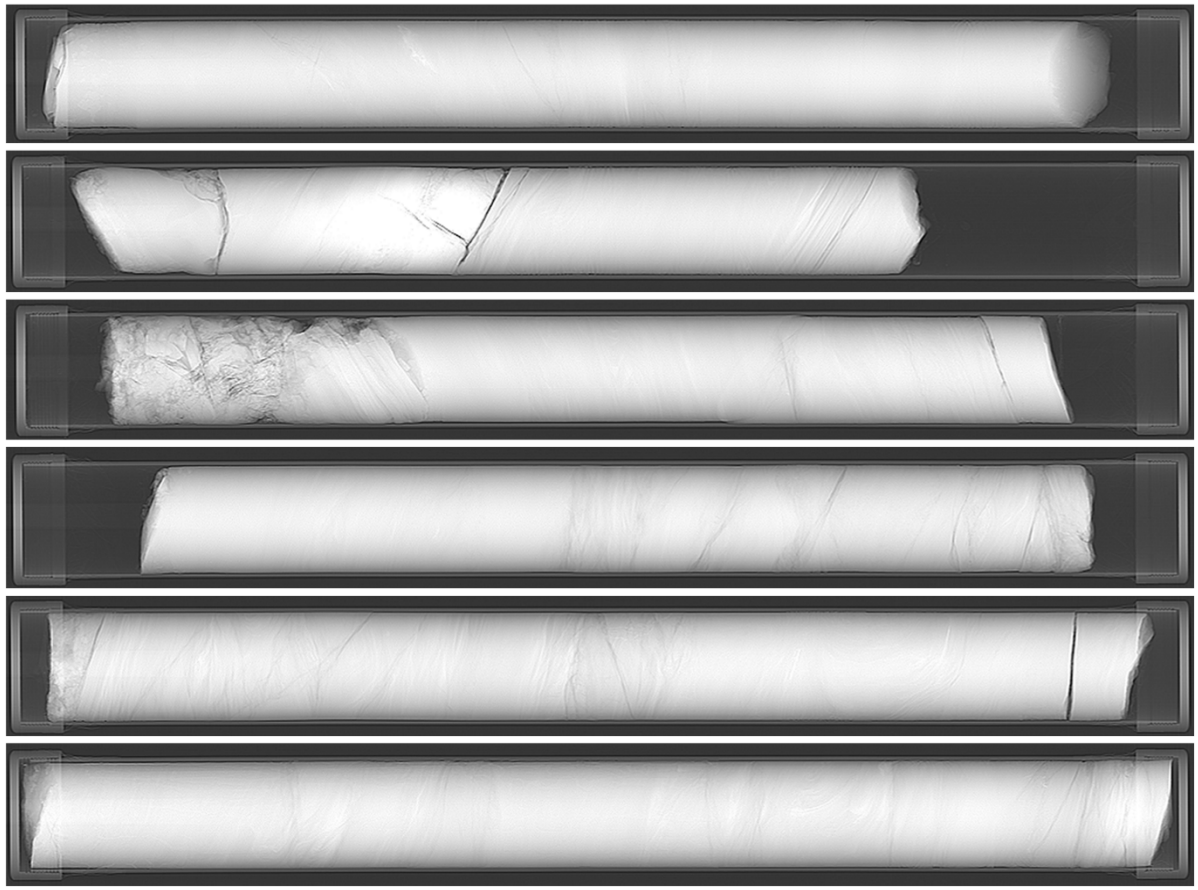

St
Tk
Sandy tuff
Bentonite
Shale
Strike & Dip
45
40
?
Concrete
B1
B2
B3
B4
B4
B5
IBL-1
IBL-2
Drilled points!
45
40
52
40
70
50
Fault?
10 m
Tsukinuno River
St
Tk
Tsukinuno mudstone member
St
Sachio pyroclastic member

X-ray CT image (IBL-2)

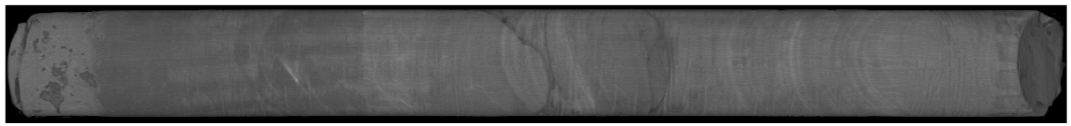


(1) 0.00 m – 0.90 m, (2) 0.90 – 1.60 m, (3) 1.60 – 2.40 m, (4) 2.40 – 3.20 m, (5) 3.20 – 4.15 m, (6) 4.15 – 5.15 m。

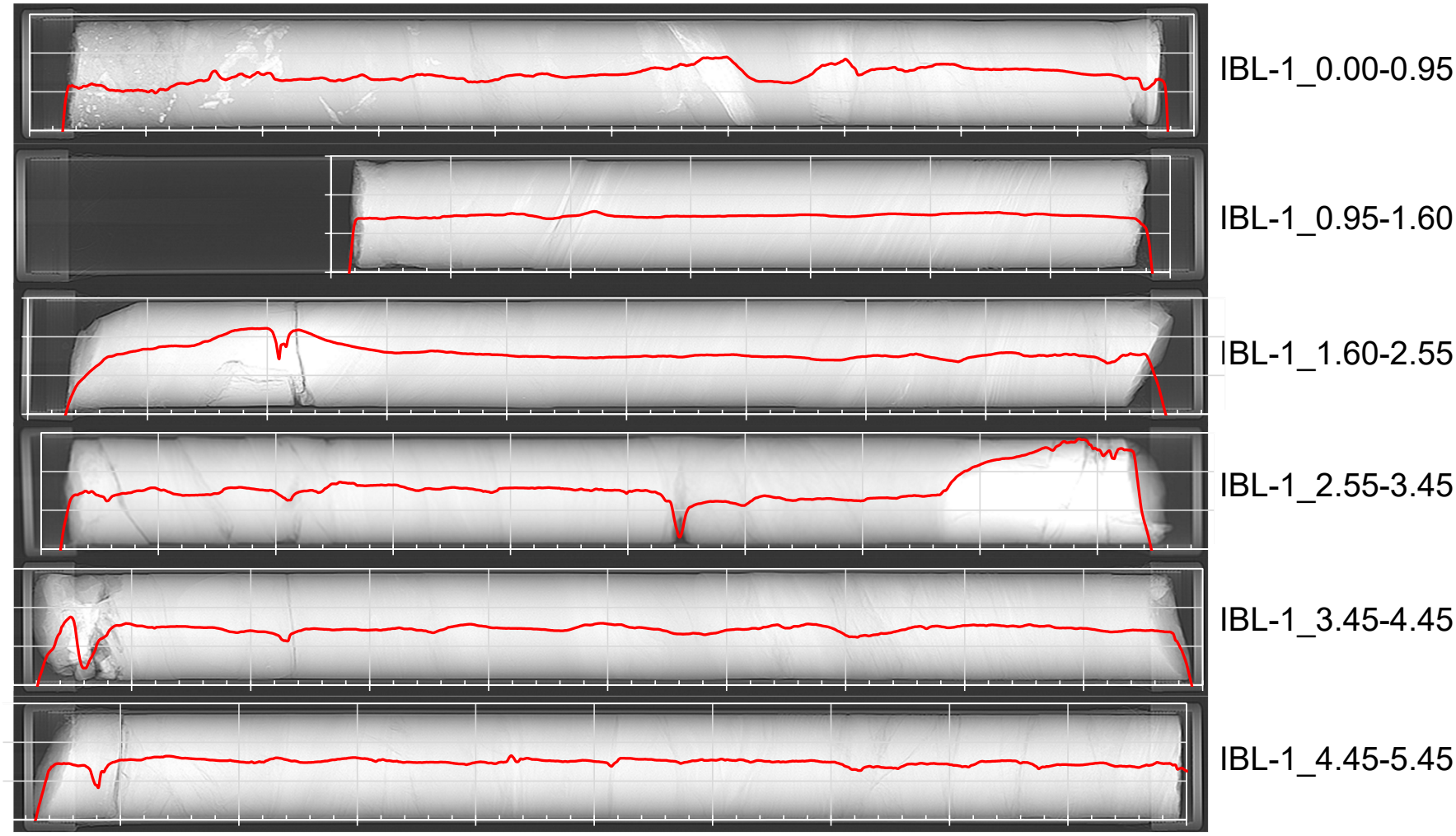
Helical CT image (quick log)

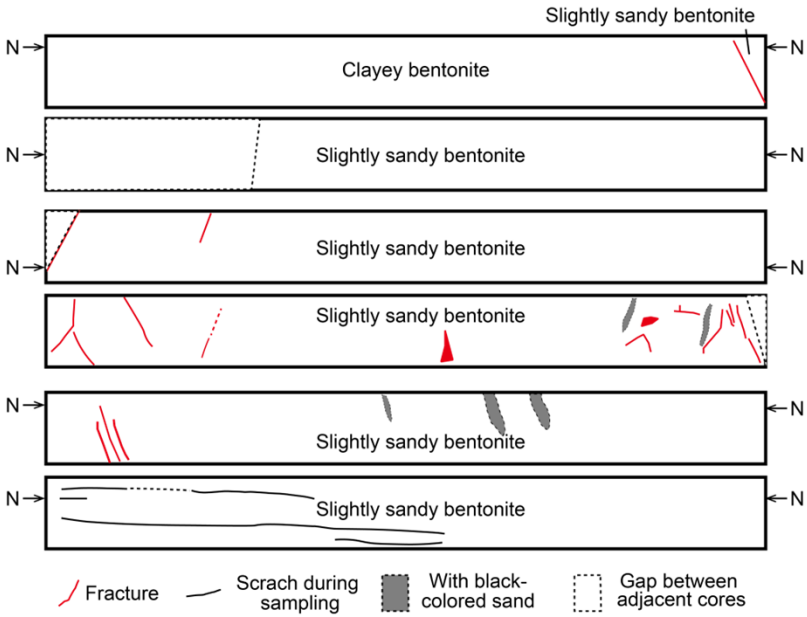


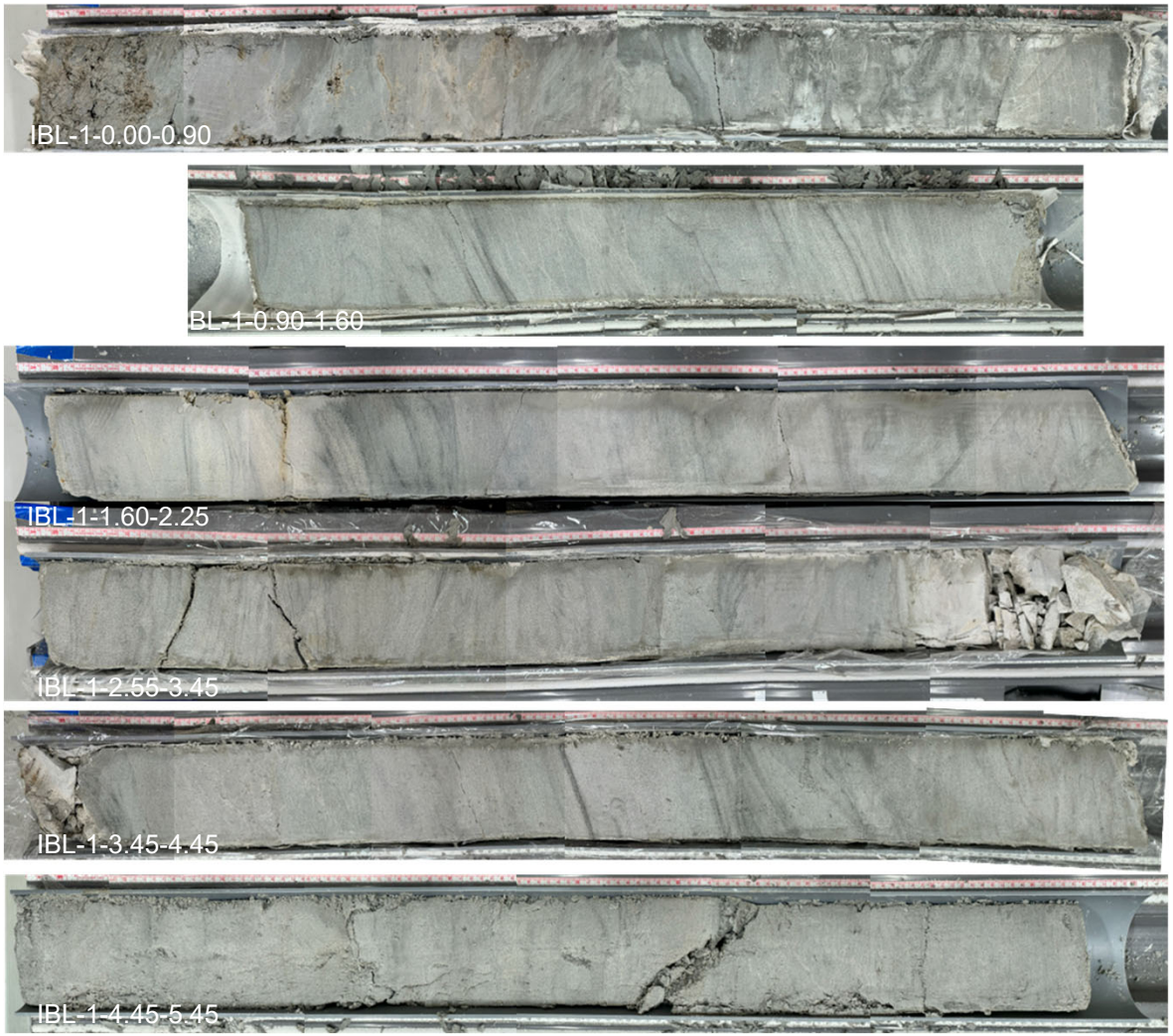
Slice CT (detail 3D log)



X-CT：Line profile of brightness (∝ density)







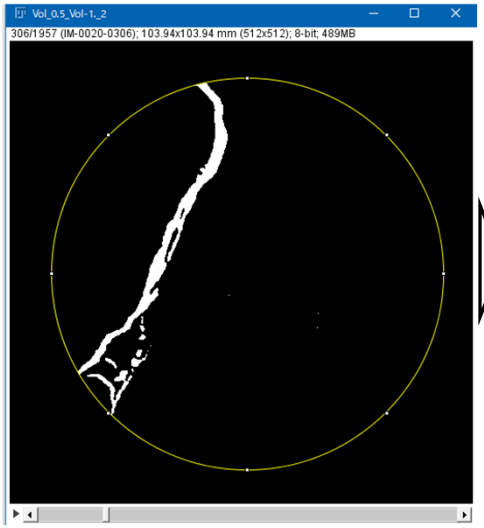
IBL-1 halves after surface trimming

X-ray CT images

e.g., IBL-1_1.60-2.55

Slice images and 3D model

Finding cracks



スライス像中の亀裂・空隙部分を抽出するフィルター（Phansalkar threshold）を~2000枚に適用

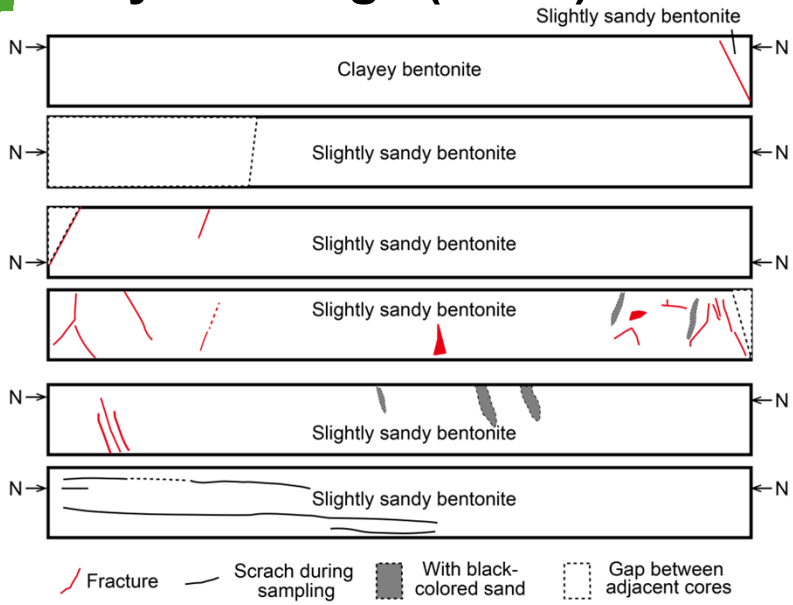
Cracks and pores

Progress so far

◎Done, △Planning

	IBL-1	IBL-2
CEC	△	◎
XRD（bulk, random oriented）	△	◎
XRD（clay fraction, preferred）	△	◎
X-ray CT	◎	◎
XRF core scanner	◎	-
XRF	△	-
Microscope observation（optical, SEM）	△	△
Density, saturation	-	◎
Amount of remaining sample	• Whole half-split were stored. • The other side of halves were kept in the pieces of ~10 cm long. • Sufficient stock of powder.	• Samples from the particular depth (density measurement) were kept in pieces 5 -10 cm long. • Sufficient stock of powder.

X-ray CT image (IBL-1)

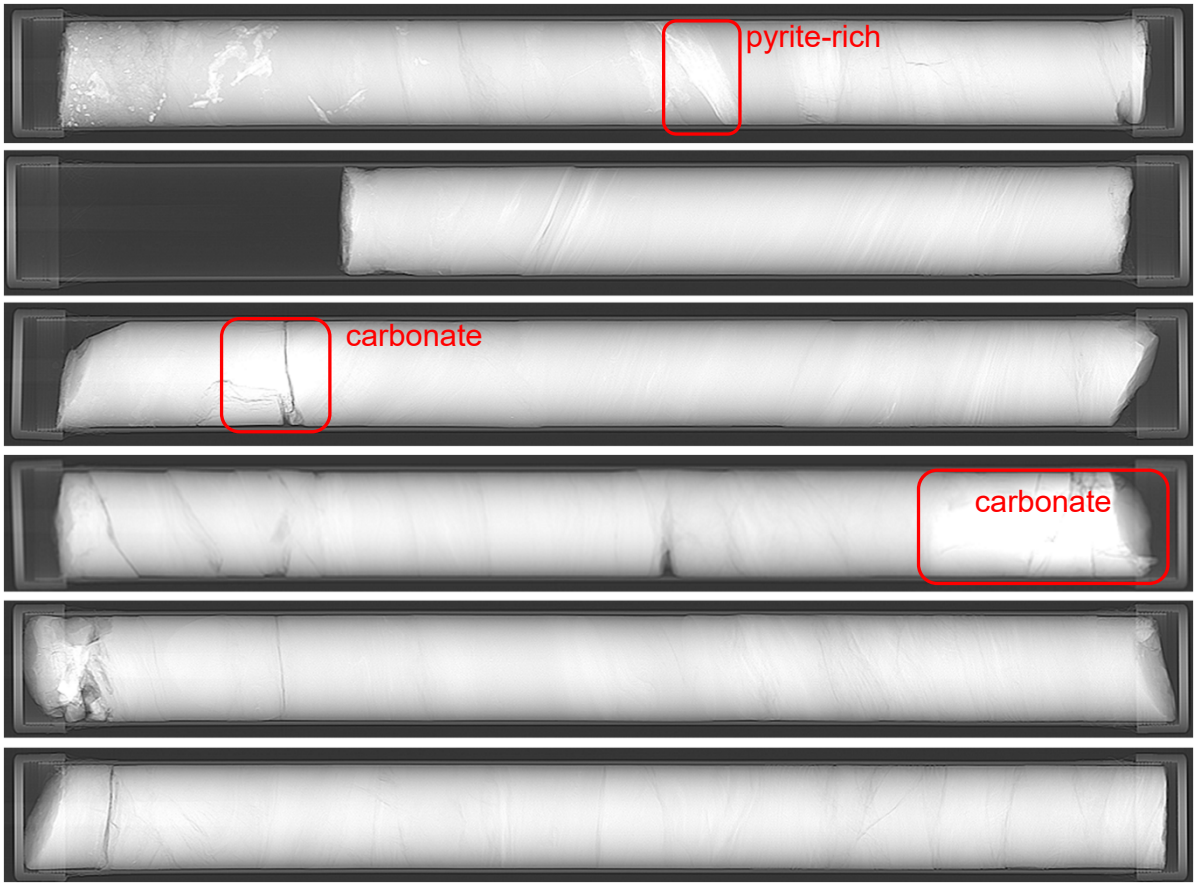


(1) 0.00 m – 0.95 m, (2) 0.95 – 1.60 m, (3) 1.60 – 2.55 m, (4) 2.55 – 3.45 m, (5) 3.45 – 4.45 m, (6) 4.45 – 5.45 m。

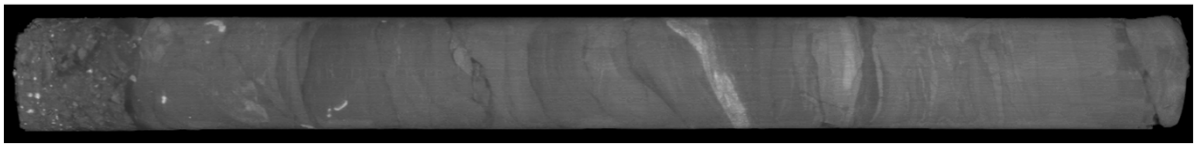
Measurement condition

- Aquilion PRIME Focus Edition (Canon medical systems)
- X-ray source: 120 kV, 100 mA
- Slice step: 0.5 mm,
- Exposure time for 1 slice: 0.5 s
- Spatial resolution: 512 × 512 pixels (0.20 × 0.20 mm^2/px)

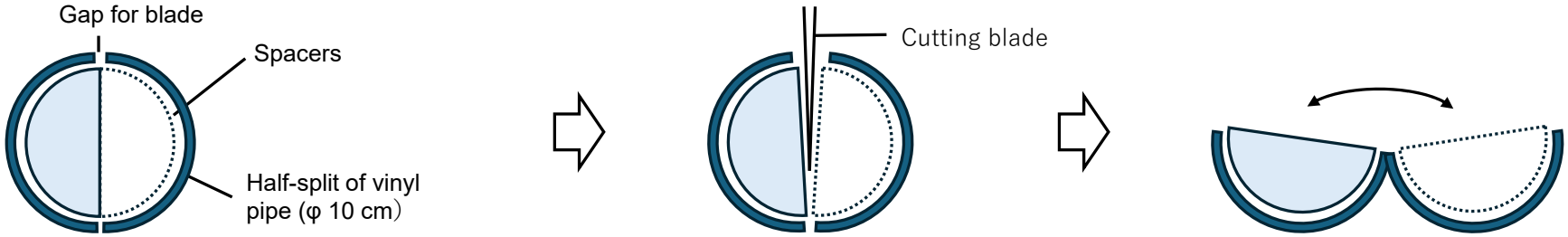
Helical CT image (quick log)

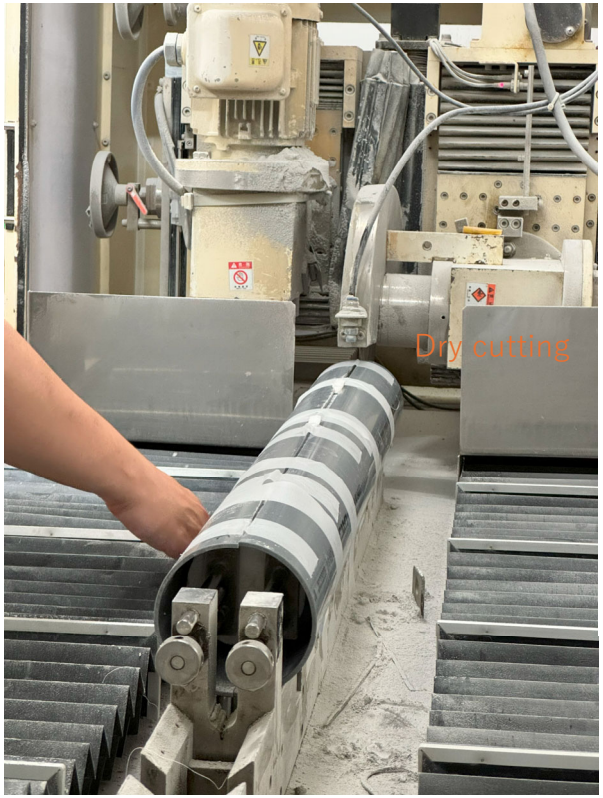


Slice CT (detail 3D log)

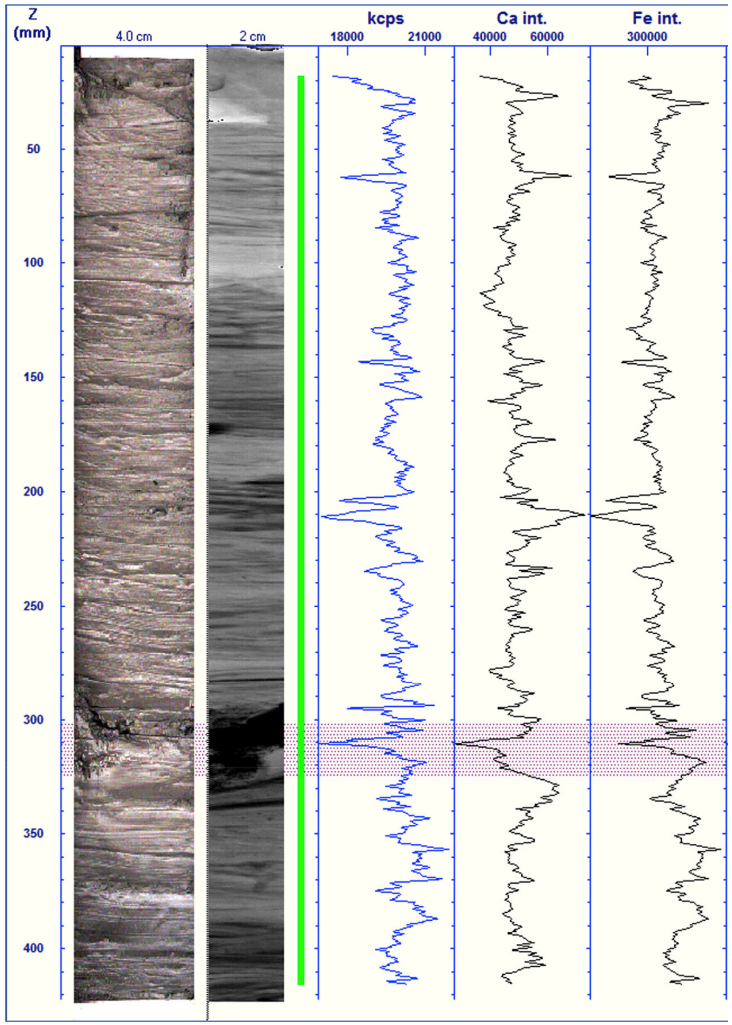


Half cutting of IBL-1 cores





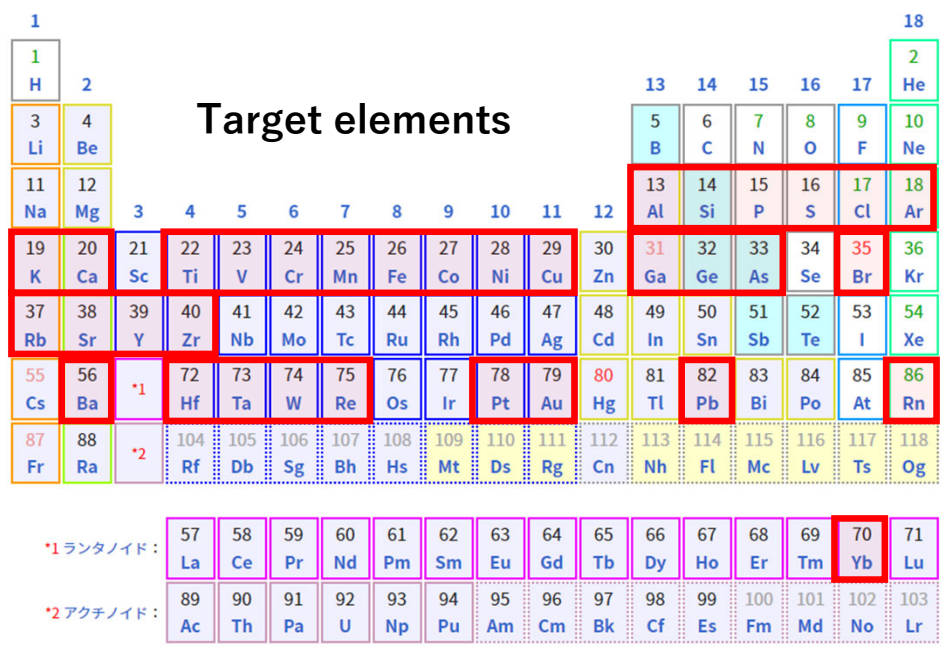
XRF core scanner



(Croudace et al., 2012).

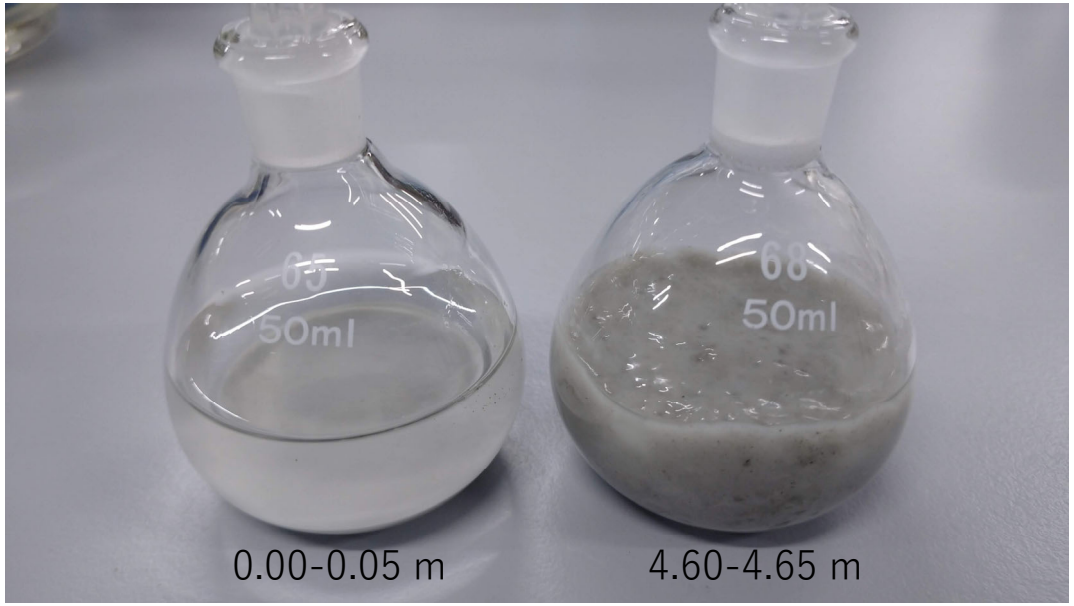
Measurement condition

- Itrax XRF Core-scanner (Cox Analytical Systems)
- Conditions: 40 kV, 10 mA, Step 2.0 mm, Exposure time：100 ms
- Scanning on the surface of each halve.



CEC&MB

表層と深部の試料で膨潤性に大きな違い＝Ca型 vs Na型？



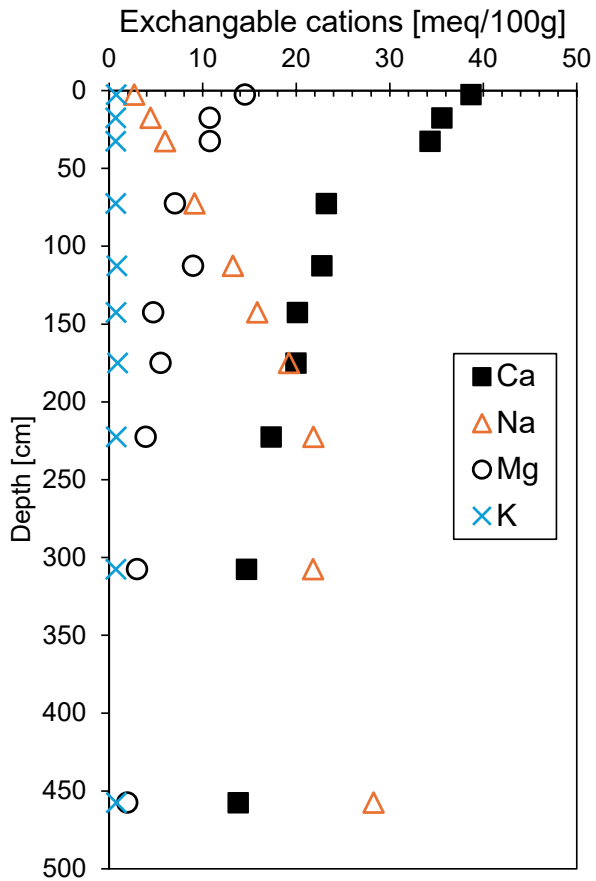
＜CECの測定方法＞

- ベンジルトリメチルアンモニウム溶液（BTM）を用いた抽出方法（白河部ら, 2022）
- BTM60.0gを超純水1Lに溶かし、6%溶液を調製
- メノウ乳鉢で微粉砕したベントナイト0.5 g（110°Cで24時間乾燥後）にBTMを50 ml添加
- 20分間の超音波分散と1時間の静置
- 0.45 umフィルターで濾過後に適宜希釈し、ICP-AESで各元素濃度（Na, K, Mg, Ca）を測定

＜MBの測定方法＞

- クニミネ工業に測定を依頼

侵食速度 vs 拡散速度



- 乾燥密度1.4 – 1.6 g/cm^{3}のベントナイト（珪砂30 wt%混合）の見かけの拡散係数: 4.6 – 10*10^{-13} m^2/s ~ 平均拡散距離 5.4 – 7.9 mm/yr
- Ca濃度が横ばいとなる深度3 m程度までCaが拡散のみで移動
  ⇒浸食速度 0 なら、1.43 – 3.10 × 10^{5}年要する。

(1) 浸食速度が拡散速度に対して無視できるほど小さい場合は上述の値に相当する長期の相互作用が起きている可能性
(2) 浸食速度が十分に大きい場合は、例えばベントナイト中の亀裂を通って早い拡散が起きるといった現象が並行して起こっている可能性

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \quad c\,(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

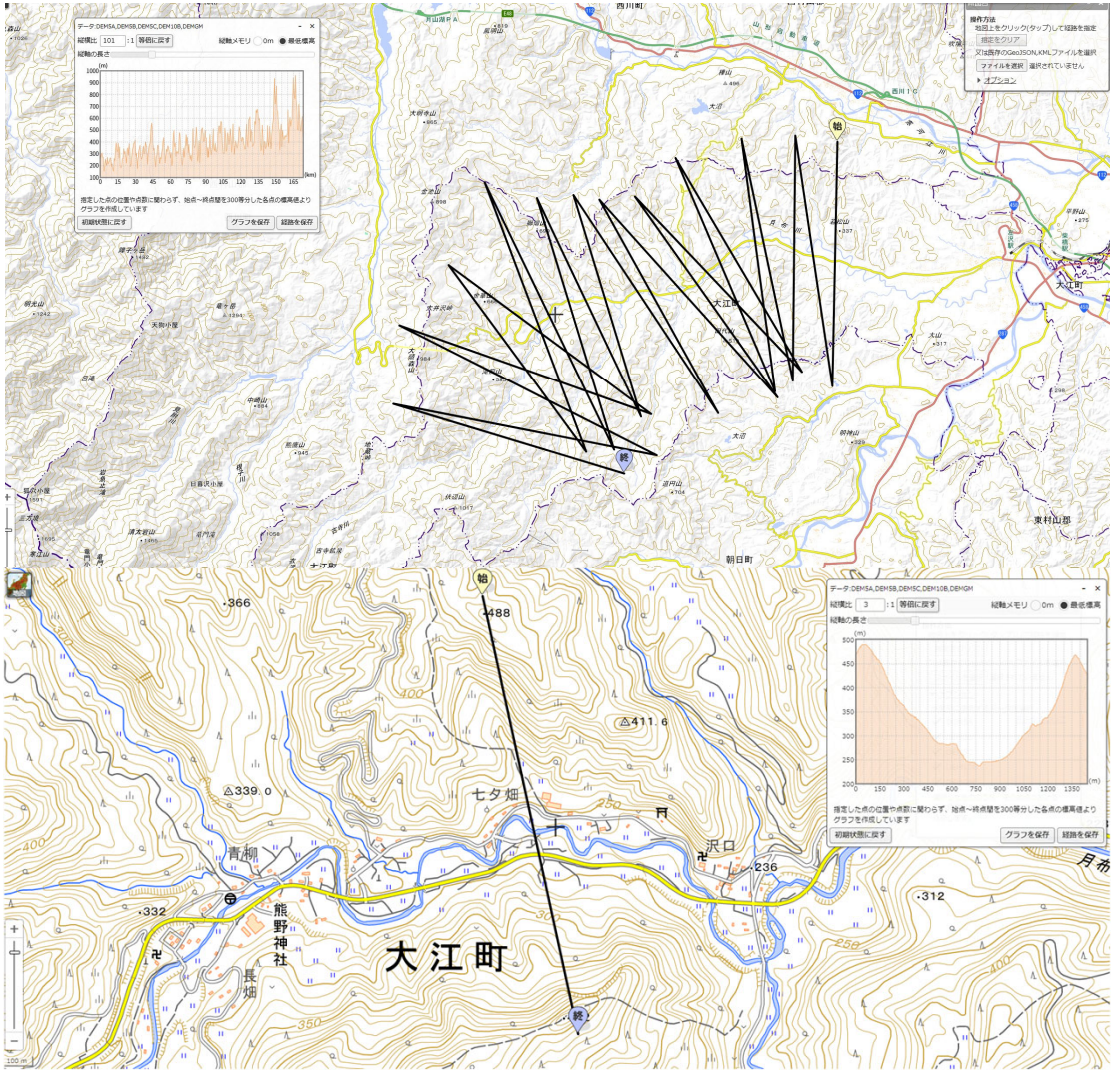
C_0: 河川水中のCa濃度
D：拡散係数

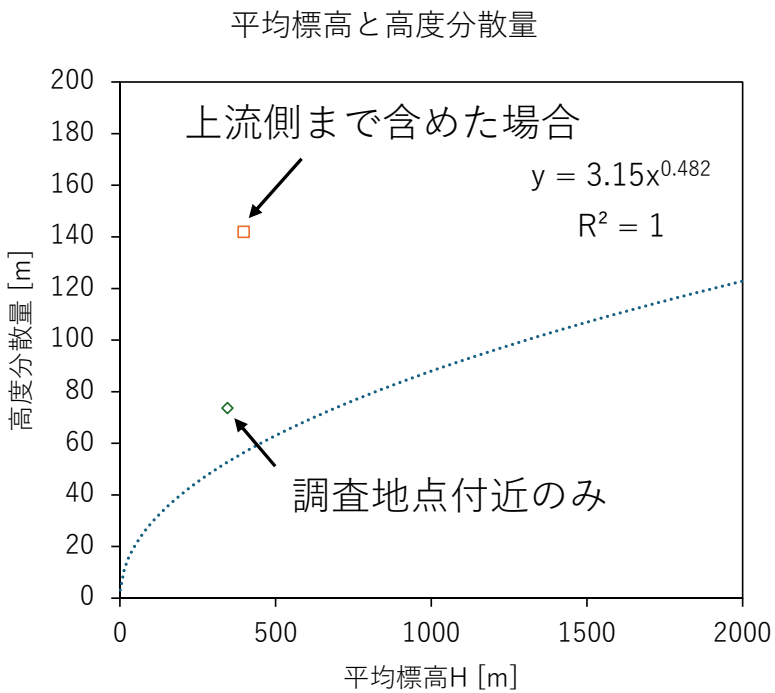
$$\frac{\partial c}{\partial t} = \frac{E}{\rho}\cdot\frac{\partial c}{\partial x}$$

E: 削剥速度 (g m-2 yr-1)
ρ : 地形構成物質の密度 [g m-2)

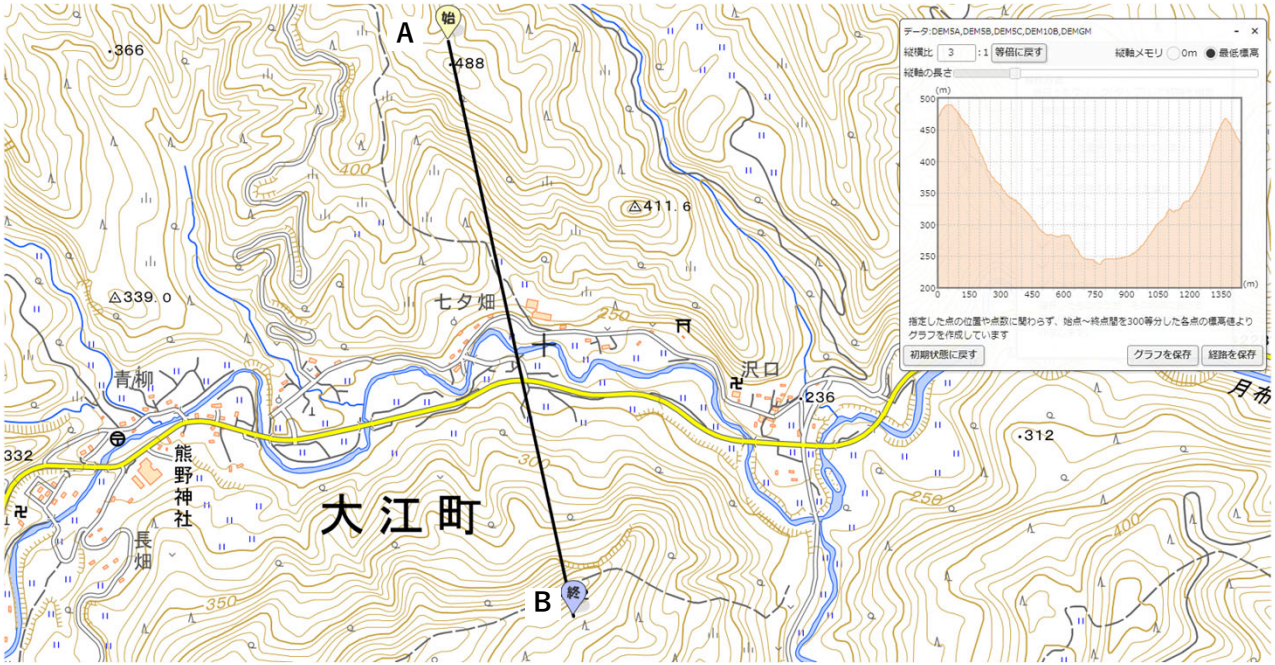
侵食速度の検討①：平均標高から推定

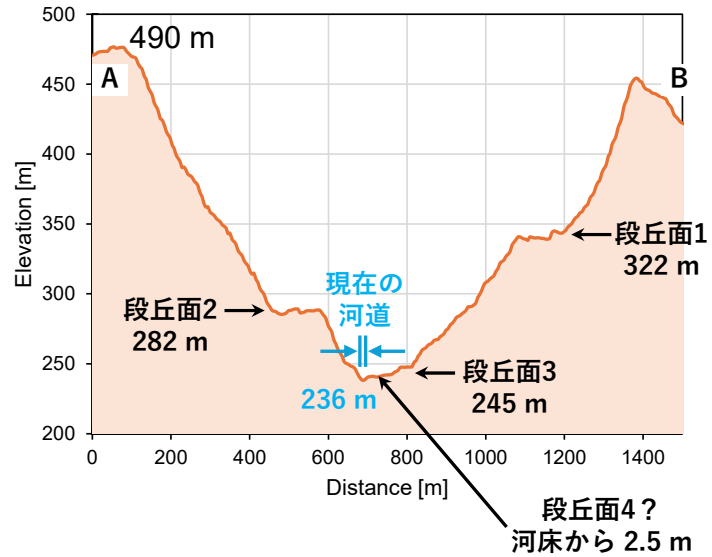
平均標高・高度分散量の出し方はどうしたら良い？





侵食速度の検討②：段丘面の形成年代から推定





関東地方の段丘形成時期：50 - 70 ka（大森ら, 1986）
東北地方の段丘形成時期：阿武隈川沿いや会津地域の編年表だと20 – 30 kaが多い？（生出ら, 1989）
山形盆地の堆積物は中期更新世（126 – 781 ka）に堆積したもの

段丘面3が中期更新世以降の浸食で出来たものであれば、9 m ÷ 126 or 781 ka ~ 0.01 – 0.07 mm/yr（以上）？
段丘面4が完新世以前　　〃　　2.5m ÷ 12 ka ~ 0.21 mm/yr（以下）？

分析項目

◎実施済み、△実施中、-未実施

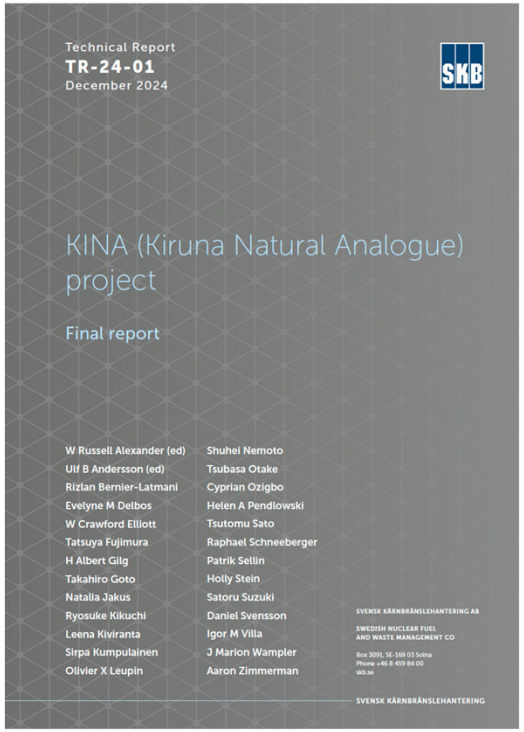
	IBL-1	IBL-2
交換性陽イオン量・組成	△	◎
XRD（不定方位）	△	◎
XRD（定方位）	△	◎
X線CT	◎	◎
XRFコアスキャナー	◎	-
XRF	△	-
薄片観察（OM, SEM）	△	△
密度・飽和度の測定	-	◎
残りの試料量	半割を丸ごと保管中。半割したもう片側は、10cm間隔で小分けにした状態で保管。	密度を測定した深さのサンプルは長さ5~10 cmに小分けして保管。それ以外の深さの試料はほとんど残っていない。
物性試験にまわせる試料の大きさ？	最上部と最下部のコア（直径10cm, 長さ3cmくらい？）は半割していないものを冷凍保管中。粉末は十分な在庫有り。	3,4cm角の塊として残っているものはあるが、円柱状で残っているのは深度25-30cmの部分のみ。粉末は十分な在庫あり。

キルナ鉱山でのNA研究

[1] Gilg & Andersson. (2020), [2] Gilg et al. (2015)

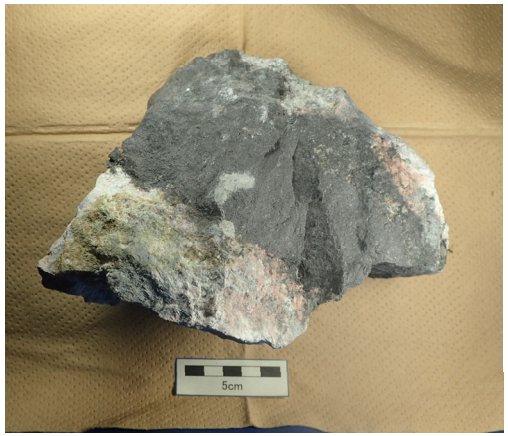
オーバーパックと緩衝材の界面で起きうる相互作用の類似例として、磁鉄鉱ーベントナイトが長期間接触している事例の調査

2023年度までの成果



KINA project Final report (2023, TR-24-01, SKB)

- ヨーロッパ最大級の磁鉄鉱の鉱山（地下1300 m付近まで採掘）
- 地下1200 m付近にベントナイトが一部存在：母岩中のケイ酸塩鉱物の熱水変質で生成し、広い範囲で磁鉄鉱鉱石の近傍に見られる
- 変質に関連した熱水の温度は50~80°C程度[1, 2]
- 磁鉄鉱の周囲のスメクタイトに変質は確認されず
- ベントナイトのK-Ar年代は**3.52(±0.17)億年**



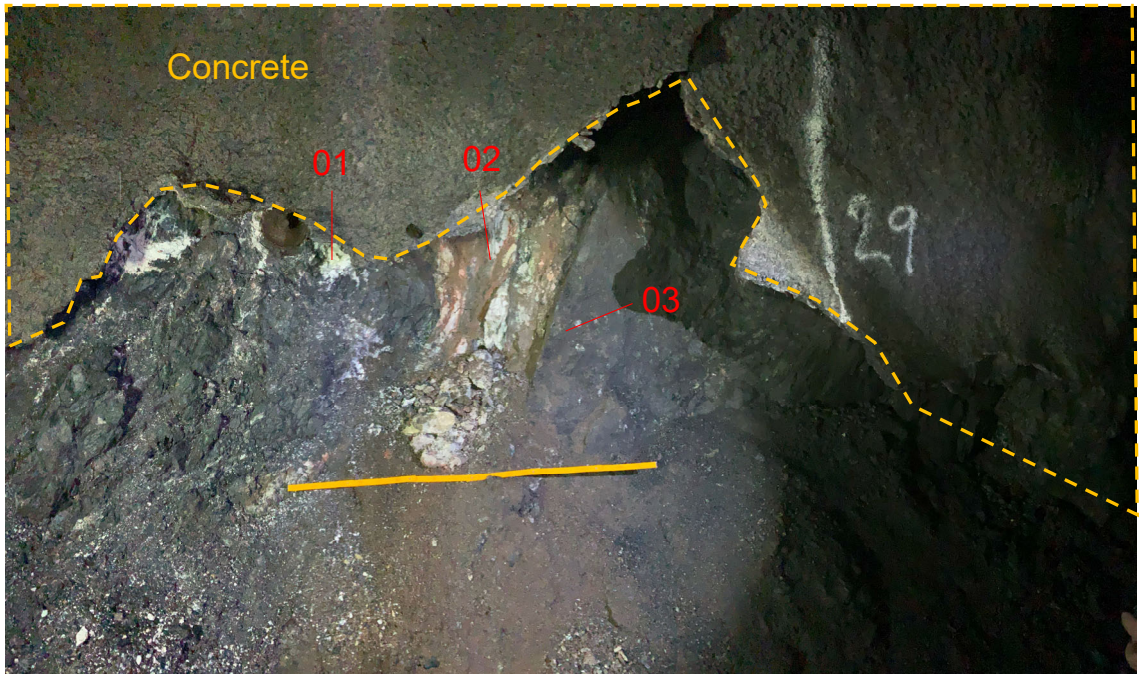
磁鉄鉱ーベントナイト接触試料

懸念点

転石試料を観察・分析。観察された界面が3.52億年もの間保存されていた根拠に乏しく、極めて短い時間スケールの現象を見ている可能性が否定できない

露頭から直接採取された試料でさらに検証

採取試料



384/1137-1b-03

Magnetite hand specimen

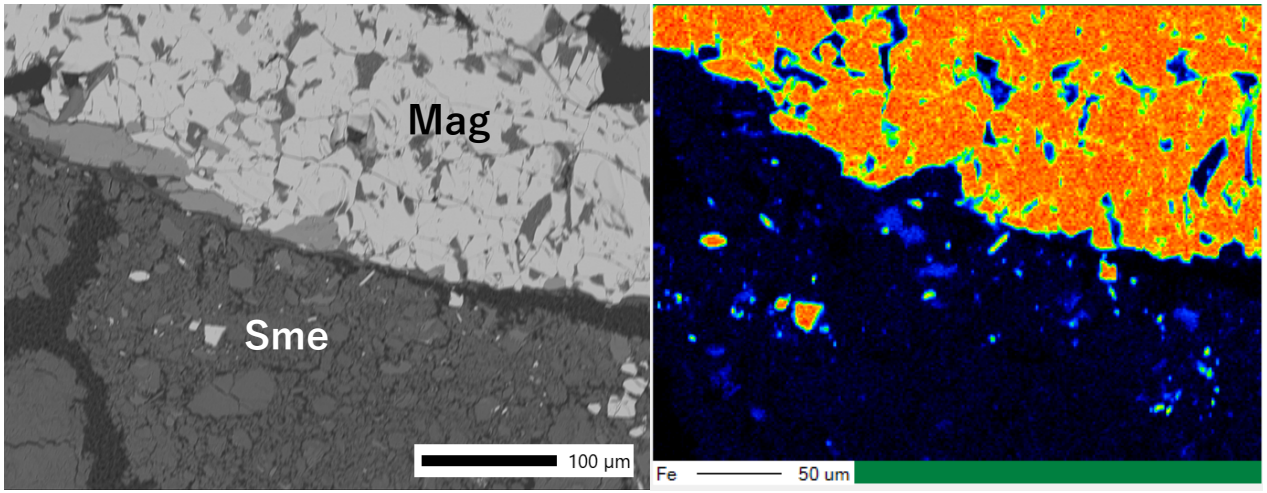
384/1137-1b-01

White (bentonite) – black (magnetite) interface.

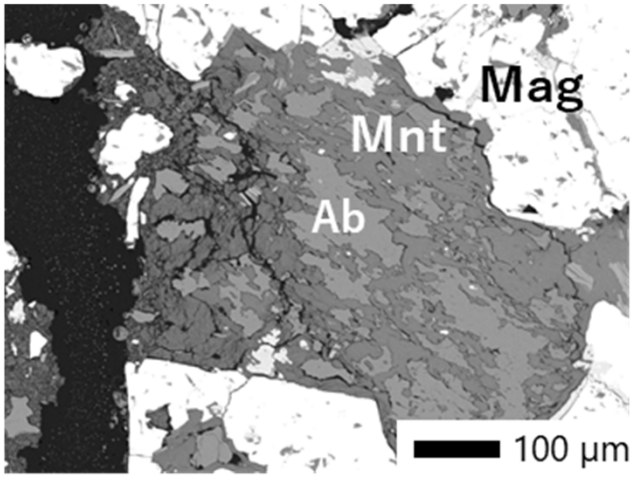
384/1137-1b-02

White (bentonite) – reddish brown (oxidized sulfide?) – black (magnetite) interface

磁鉄鉱－ベントナイトの相互作用



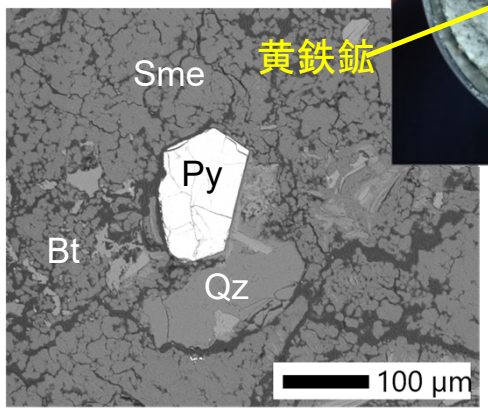
磁鉄鉱ーベントナイト境界の反射電子像(左)と鉄濃度マッピング(右)
Mag: 磁鉄鉱　Sme: スメクタイト



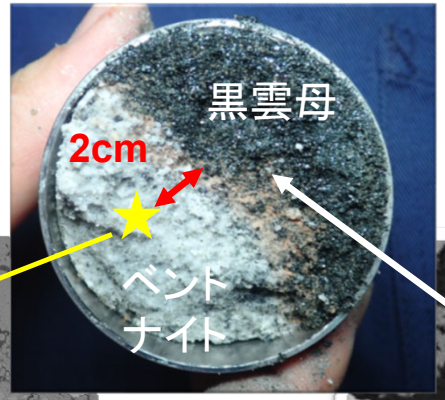
変質途中の長石の組織
磁鉄鉱の亀裂で，長石（Ab）が熱水変質
⇒モンモリロナイト（Mnt）の形成

- スメクタイトのK-Ar年代～3.32（±0.23）億年
- 磁鉄鉱の微量元素組成は，鉱床本体（約18.8億年前）よりも後期の熱水活動での形成を示唆
- ベントナイト中の磁鉄鉱，ベントナイトと接触している磁鉄鉱鉱体は同じ起源である可能性が高い
- ベントナイトは、断層運動などによって別の場所から流入した訳ではなく、磁鉄鉱と接していた長石が低温の熱水変質でモンモリロナイト化することで形成されたことを示す岩石組織＝長期の相互作用を担保

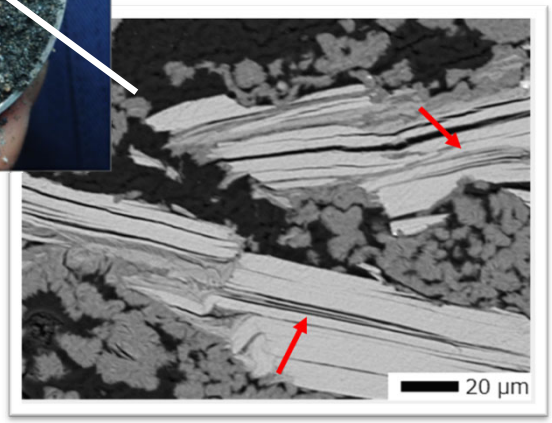
黄鉄鉱－ベントナイトの相互作用



風化していない自形の黄鉄鉱



岩相境界の様子



風化してFeやKが溶脱した黒雲母

Py: 黄鉄鉱　Sme: スメクタイト　Bt: 黒雲母　Qz: 石英

- スメクタイト・黒雲母のK-Ar年代～それぞれ1.86（±0.07）億年、6.7（±0.13）億年
- ベントナイトと接する砂質の黒雲母部分では黒雲母の風化、境界面付近での鉄水酸化物の沈殿が見られる
- 一方、ベントナイト中の黄鉄鉱には酸化溶解の痕跡が認められず

⇒坑道掘削後（～100年前）の酸化的環境への変化は、透水性の高い部分に限定される
⇒ベントナイトの形成（1.86億年）～掘削前（100年前）では、ベントナイト内の黄鉄鉱の変質は抑制される

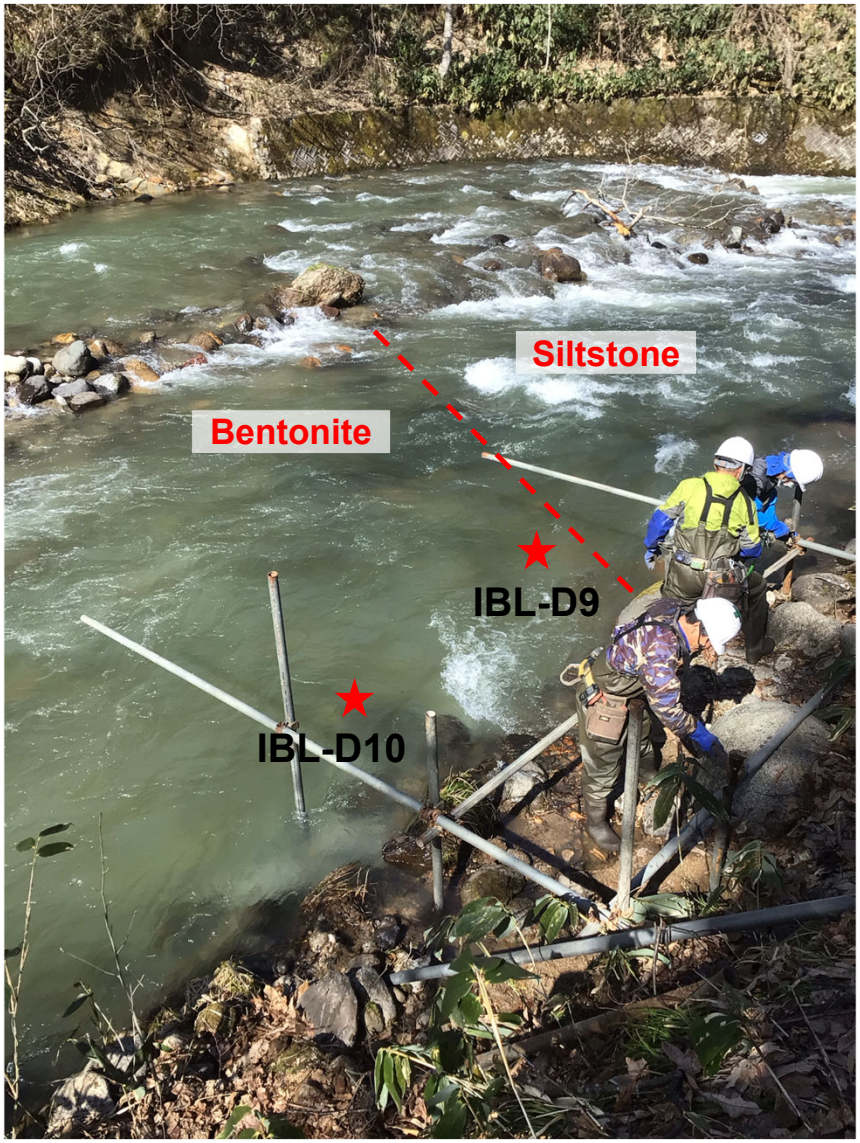
NUMO-電中研-北大 NA共同研究キックオフ 2026.6.3 Wed.

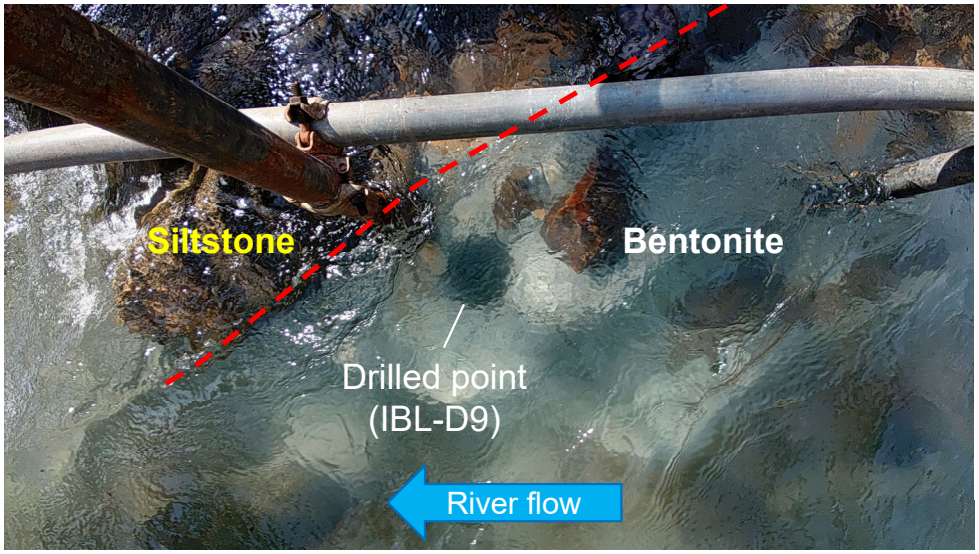
月布川河床のベントナイトにおける膨出現象　第1回打合せ

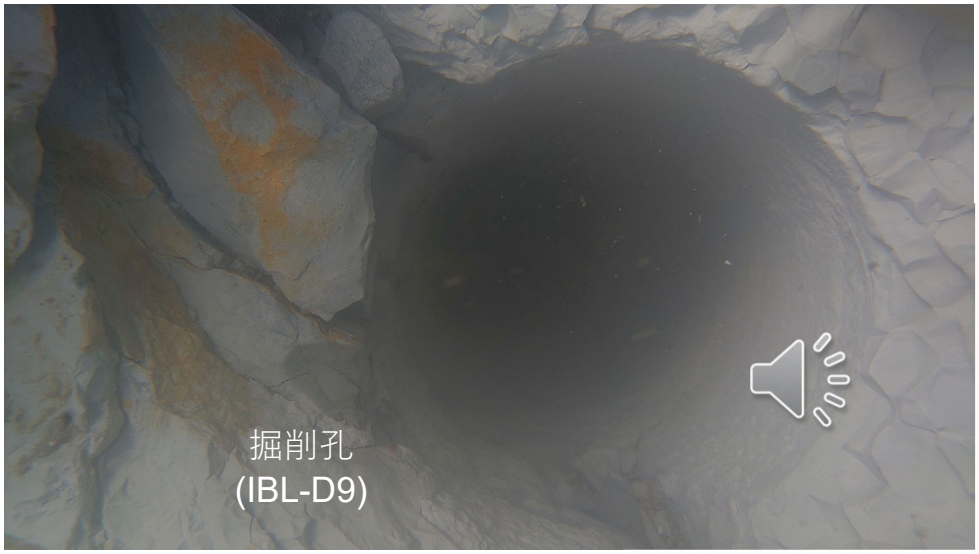
- 去年度までの振り返り
- 今年度の計画

IBL　HOKKAIDO UNIVERSITY　CRIEPI Central Research Institute of Electric Power Industry　NUMO 原子力発電環境整備機構　KUNIMINE INDUSTRIES

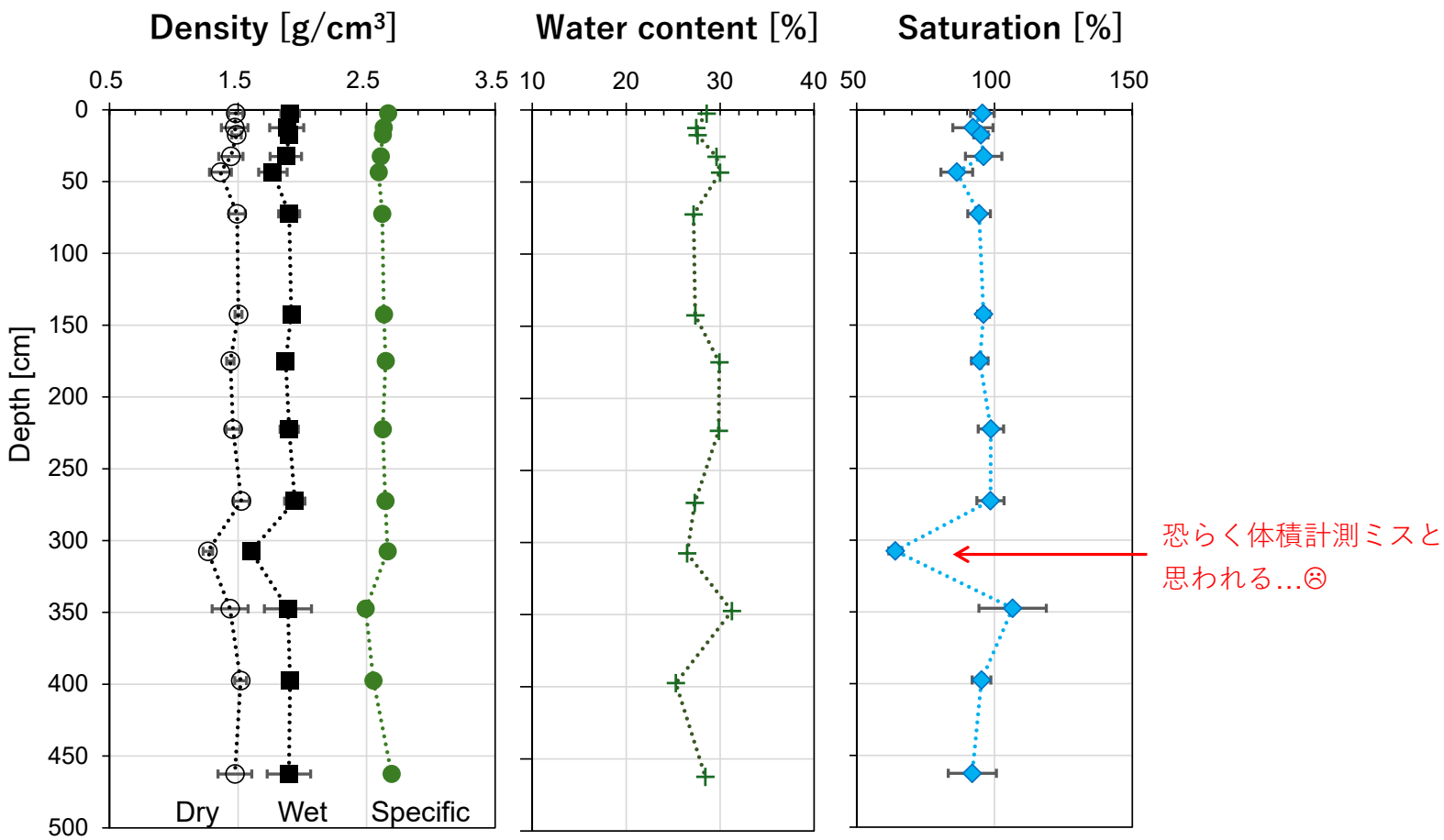
掘削地点


Siltstone
Bentonite
IBL-D9
IBL-D10


Siltstone
Bentonite
Drilled point
(IBL-D9)
River flow

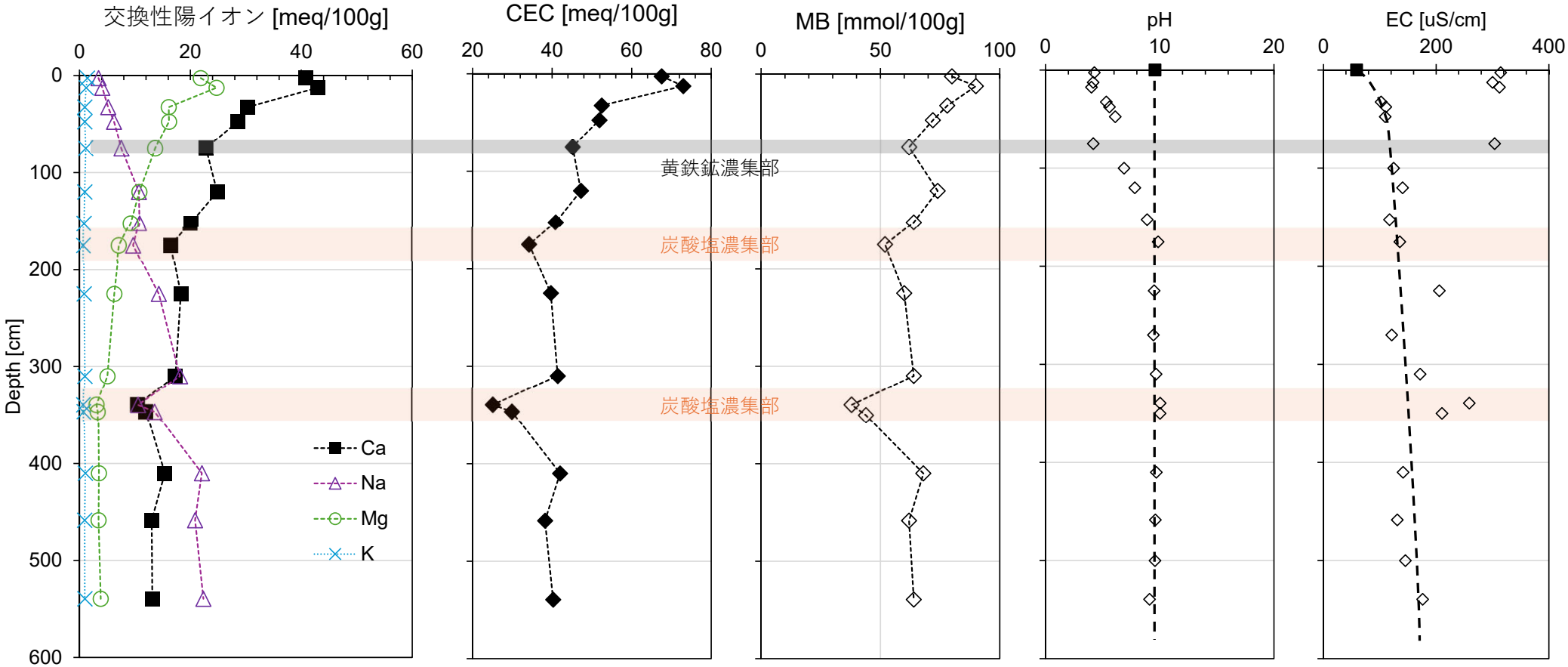

掘削孔
(IBL-D9)

密度・含水比・飽和度の深度分布（IBL-D10）



- 深度に依らずほぼ一定の密度（乾燥・湿潤・比重）と飽和度
  …乾燥密度～1.5、湿潤密度～1.7 g/m³、飽和度～95 %.
- 表層側で流出による密度低下の兆候は見られず

交換性陽イオン・MB吸着量・pH&ECの深度分布（IBL-D9）

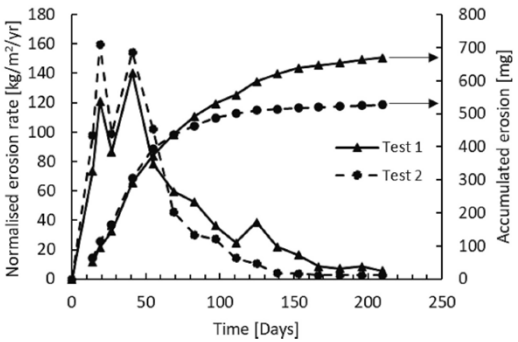


- 表層はCa-Mg型 ⇔ 深部はNa型となっており、河川水との接触によるイオン交換を示唆。
- 表層の約1 mでCEC, MBがやや低下、1m以深ではほぼ横ばい（炭酸塩部を除く）。
- 1.5 m以深ではpH~9 – 10程度で一定だが、表層に向かって低下。黄鉄鉱の酸化溶解の影響を懸念。

Questions

Q1. どうしてベントナイトは流出していないのか？　抑制の要因は？

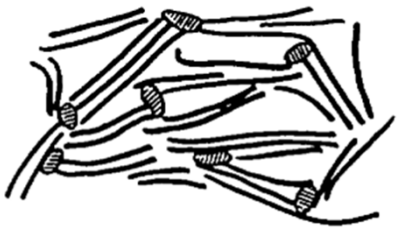
A1. 候補として… (1) Na型⇒Ca-Mg型への変化, (2) セメンテーションの影響、(3) 高濃度の間隙水組成



一般的に、Na型はNa/Ca型やCa型よりも膨出しやすい傾向.

室内試験では時間経過に従って膨出量がほぼゼロになる現象が見られているが、メカニズムは不明 (Hedström et al., 2023)

Silica precipitation in bentonite



Pusch et al. (1998)

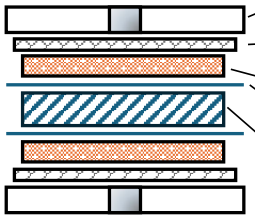
Q2. ベントナイトの侵食速度はどれくらい？　周囲の堆積岩と同じくらい？

A2. 地形学的手法からは、0.1 - 1 mm/yrのオーダーと推定。
拡散プロファイルからは1 mm/yrのオーダーと推定。

河床ベントナイトを用いた膨出試験

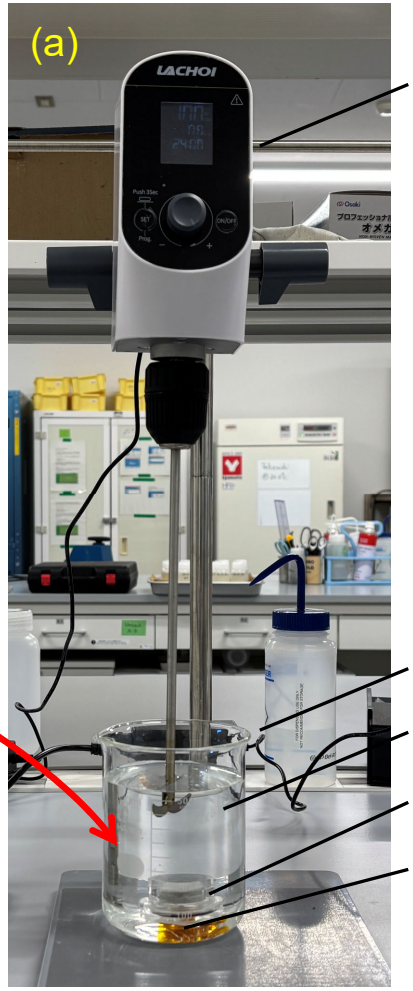
・未粉砕の試料
・粉砕した試料
・クニゲルV1
1.5 g/cm^{3}で同様に作成

(e)



アクリル製カラム（ϕ5.5 mm孔付き）
サポートフィルター（SUS，150 um濾過径）
金属焼結フィルター（SUS, 3 mm厚, 10 um濾過径）
メンブレンフィルター（0.5 um濾過径）
ベントナイト（4 mm厚）

図．供試体の作製



電動攪拌機
（LACHOI製, 100rpm）

500 mlビーカー
模擬河川水
ベントナイト供試体
固定用カプトンテープ

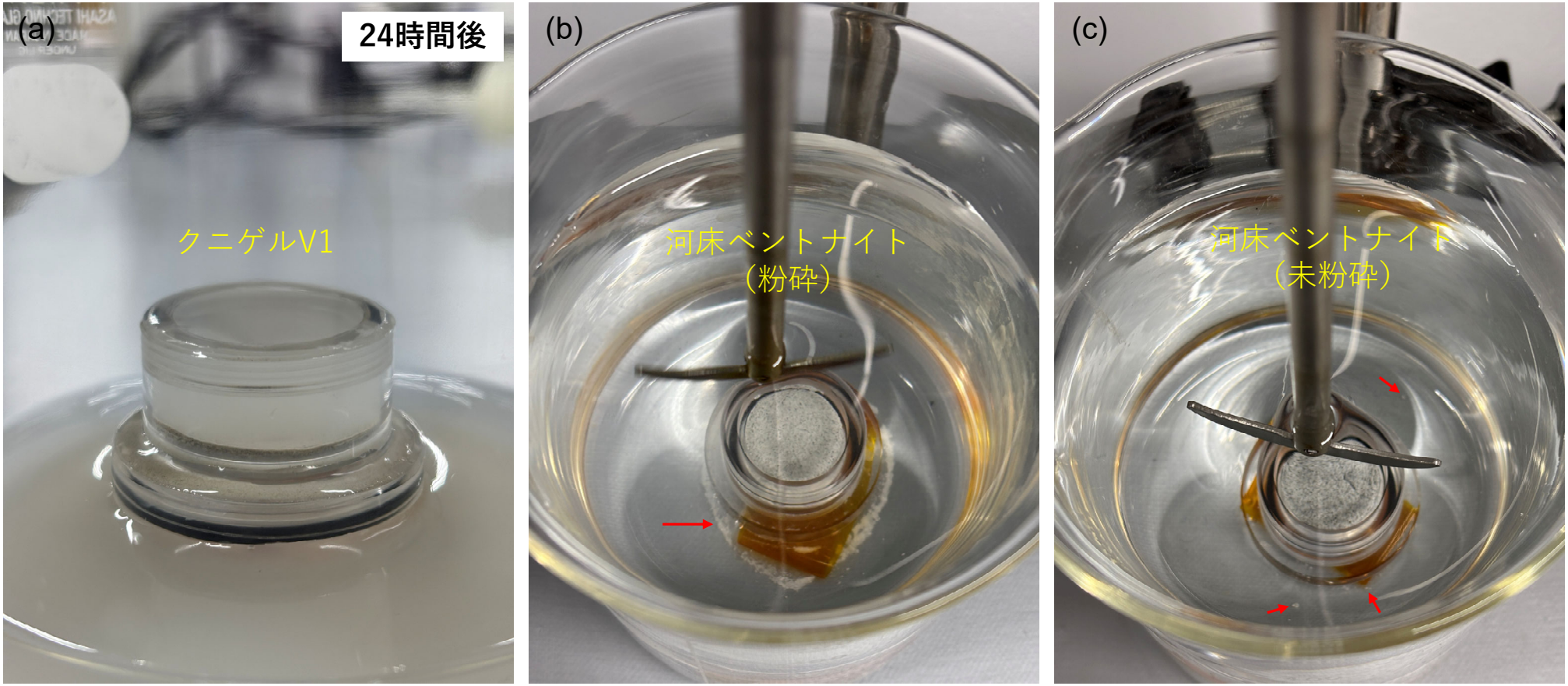
図．膨出試験の構成

河床ベントナイトを用いた膨出試験

河床ベントナイトを用いた膨出試験

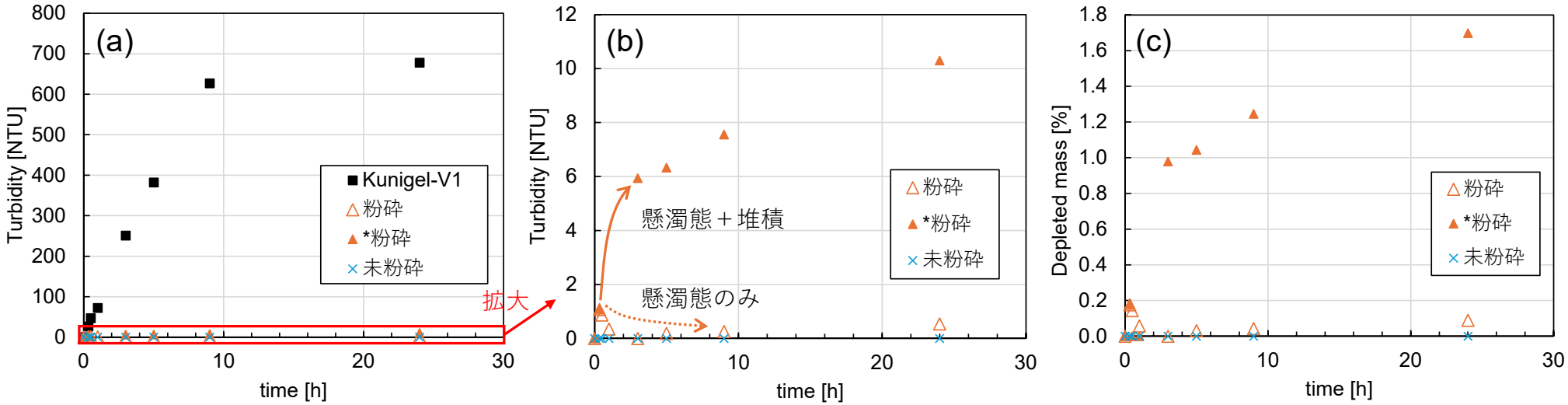
河床ベントナイトを用いた膨出試験

河床ベントナイトを用いた膨出試験



図．膨出試験24時間経過後の様子．
(a) クニゲルV1，(b)粉砕した河床ベントナイト，(c)未粉砕の河床ベントナイト．
(a)はセル内のベントナイトがほぼ全て流出している．(b)は一部の流出したベントナイトが底に堆積している（赤矢印）．
(c)でもベントナイトの欠片が僅かに堆積している（赤矢印）。

河床ベントナイトを用いた膨出試験



図．膨出挙動の時系列変化
(a)(b)各試料の濁度および(c)濁度から算出したベントナイトの膨出率（%）。
粉砕した河床ベントナイトについては，懸濁態のみの状態と，底部に溜まった分を強制的に分散させた状態でそれぞれ測定.
懸濁液中のベントナイトの分散量と濁度の間での検量線を予め作製しておき、膨出率の算出に用いた。

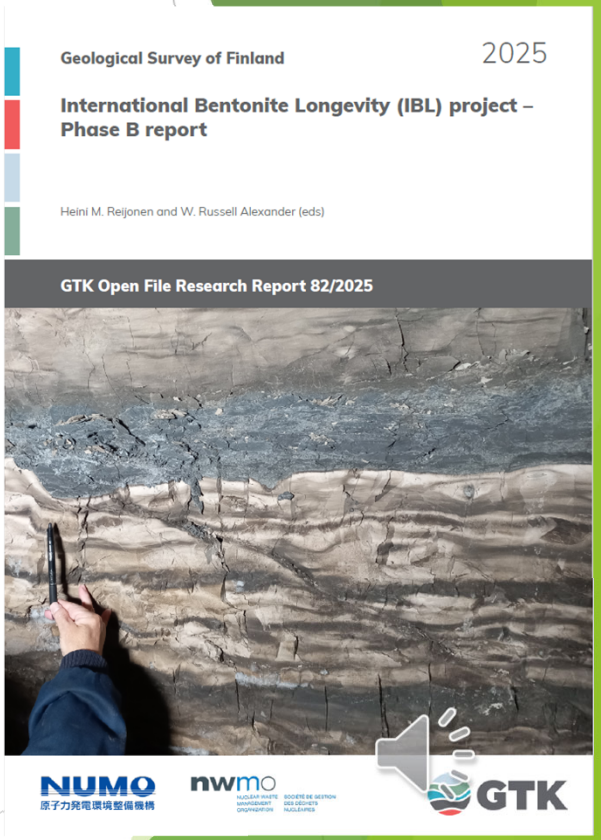
- 24時間の膨出率を比較すると、クニゲルV1 ～100%、 粉砕した河床ベントナイト～1.7%、未粉砕の河床ベントナイト～0%（検出不可）。
- Na型⇒Ca・Mg型への変化で膨出が抑制。特に懸濁態となる細かい粒子の発生が抑制。
- 未粉砕の状態では膨出が更に抑制。短期間では評価不能。

まとめ

- 月布川河床にて2点のボーリングコア（それぞれ約5 m）を2024年度から調査を開始。どちらもほぼベントナイトから成る岩相。
- 河川水は膨出現象が起こりうる希薄な組成を示す。
- **ベントナイトの密度は深度に依らずほぼ一定。飽和度も深度に依らず95%前後を推移。表層での膨出の兆候は見られず。**
- **深部はNa型なのに対して、表層側はCa,Mg型化している。河川水によるイオン交換を反映していると考えられる。**
- その他、鉱物学的・化学的特徴は⇒IBL project Phase B Reportを参照

- 周囲の堆積岩と同程度の侵食速度を持つと考えられる。地形学的な手法から0.1 - 1 mm/yrオーダーと推定される。同様に、交換性Caの分布からも同程度の侵食速度と推定される。
- 表層のベントナイト間隙水は希薄な傾向を示し、膨出抑制の要因は別にあると考えられる。
- **河川での侵食を模擬した室内試験において、Na型ではないくCa型であること、セメンテーションのどちらも膨出を抑制する効果がある**ことが示唆された。

月布のNA（2024年度までの成果）



2026年度の課題設定

月布川河床NA

A. ボーリングコア試料の分析（継続）

- SEMおよびFIB-TEMによる組織観察・セメント物質の性状

B. 膨出の抑制要因を絞り込むための膨出試験（継続）

- イオン交換（Ca⇔Na）で膨出しやすくなるかの検証

C. 河床ベントナイトの掘削後の経過観察

- 掘削孔のその後の寸法変化など：それ以外には？

D. 河川水と長期間の相互作用を経たベントナイトの物性は？

- 物性の中でも比較的短期で評価できる膨潤圧など：不攪乱試料の成型が課題

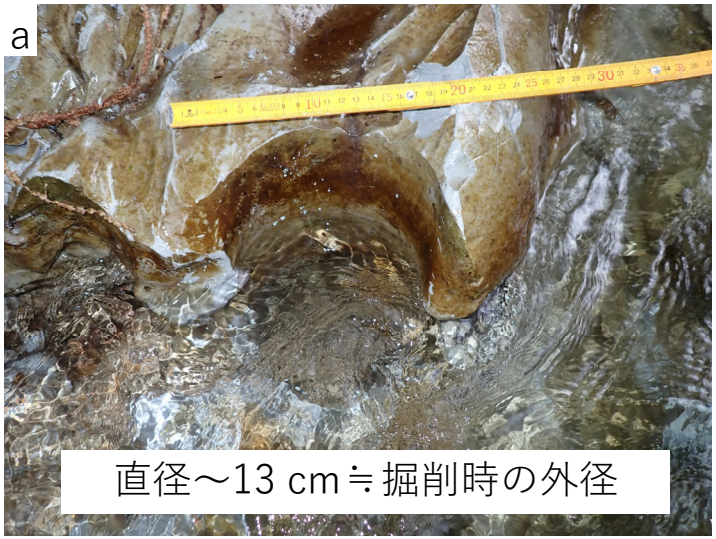
試験スケジュール

	4 - 6月	7 - 9月	10 - 12月	1 - 3月
	NAWG-18 ▼		委員会（中間）▼	委員会（最終）▼
コア分析（前年から継続）	→	→	→	
膨出実験（前年から継続）	→	→		報告書作成 →
掘削地点の追加調査・サンプリング			→	
膨潤圧試験？			→	→

ボーリングサイトの追跡調査（2025.7）

昨年掘削した場所と同じ地点

a



b

IBL-D10の掘削孔の痕