NATURAL ANALOGUES IN SUPPORT OF THE SWISS SAFETY CASE (NTB 24-10)

WITHIN THE GENERAL LICENSE APPLICATION FOR NÖRDLICH LÄGERN SUBMITTED IN 2024

NAWG Presentation

Manchester, June 9, 2026

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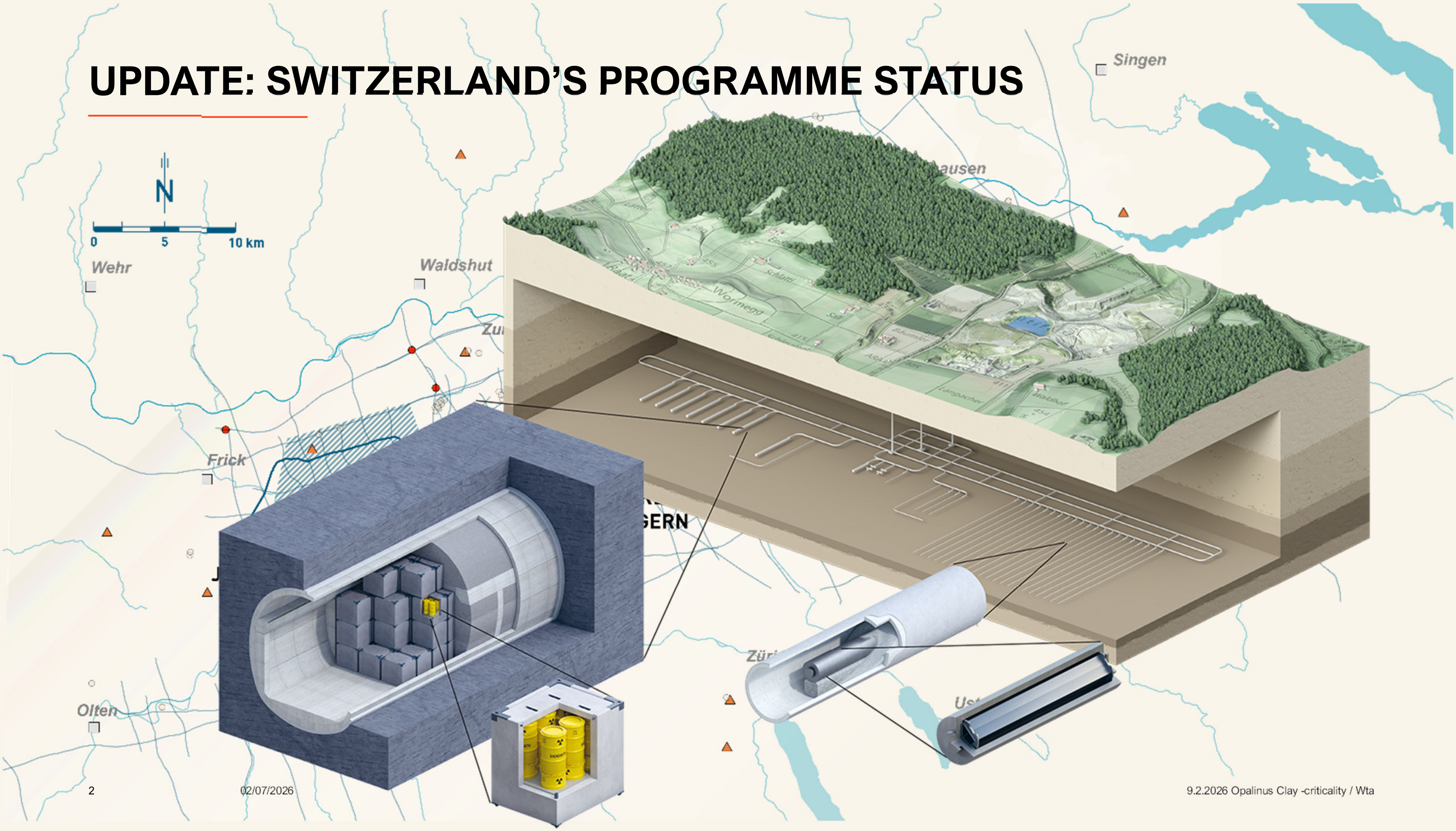
UPDATE: SWITZERLAND’S PROGRAMME STATUS



NATURAL ANALOGUES (NAs) IN THE SWISS SAFETY CASE

Importance for long-term deep geological repository (DGR) safety?

- NAs provide evidence for barrier performances and validation of processes/properties for engineered & natural barrier systems in DGR's over long, geological timescales (i.e. >> experimental limits)
- Strengthens robustness, transparency, and stakeholder confidence

Swiss DGR programme context (www.drbg.ch)

- Long-standing integration of NAs in Nagra's safety cases (NTB 93-03, NTB 02-05, NTB 24-10)
- **2024:** Submission of General Licence Application for HLW and L/ILW repository at Haberstal in Nördlich Lägern
- ***Shift of use/importance of NAs*** *in the Swiss SC from a generic analogue use to targeted, process-specific evidence to support the Claims-Arguments-Evidence structure*

NAs IN THE SWISS SAFETY CASE 2024: NTB 24-10 REV.1

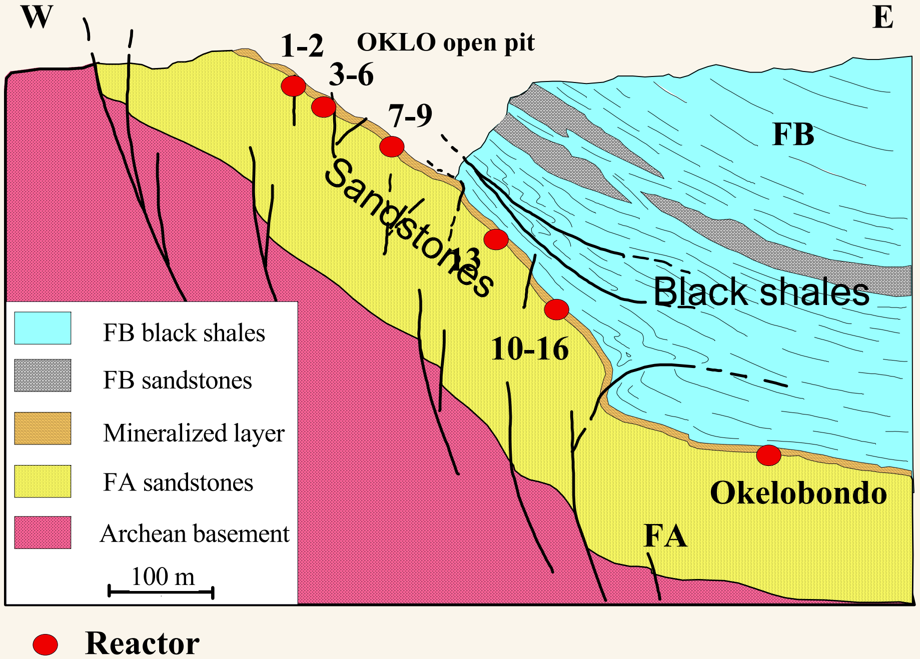
Key contributions in the Swiss SC

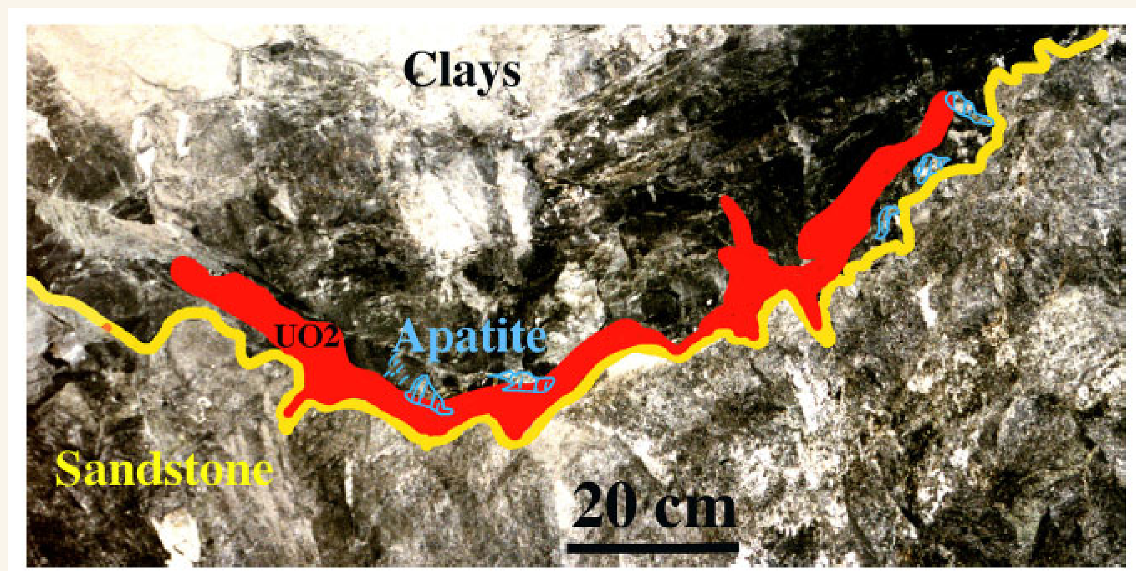
- **Spent fuel:** extremely slow dissolution rates (Oklo, Cigar Lake)
- **Steel canisters:** corrosion processes and low long-term rates
- **Vitrified waste:** durable, diffusion-controlled alteration
- **Bentonite and cement:** long-term stable interfaces, limited interactions, alterations within expected role of material

- *Increasing focus on digitalisation and traceability*
- *NAs confirm slow, self-limiting system evolution and long-term process understanding, and add value even in a data-rich, site-specific context (Opalinus Clay) (i.e. validation of model assumptions)*

NATURAL ANALOGUE – OKLO REACTORS (GABON) ~2 Ga AGO

System stability over geological timescales of 1 Ma to 1 Ga – even under changing geochemical settings (i.e. porewater)

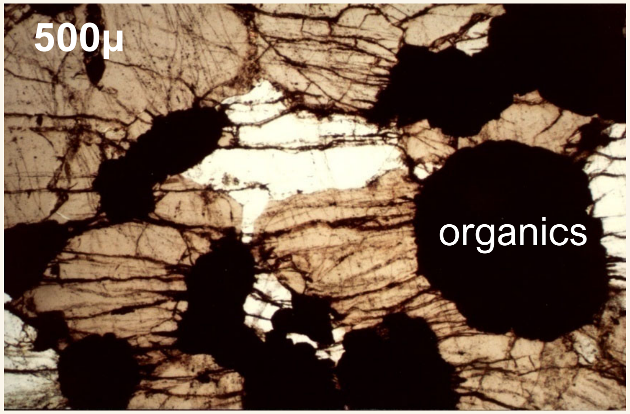


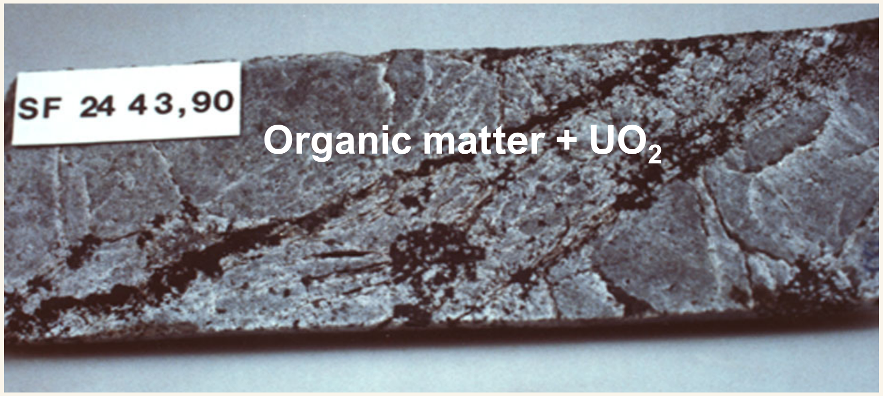


Vertical structure of reactor 10 seen in the mine of Oklo. The core of the reactor is depicted in red. It is surrounded by sandstone (yellow) and clays (above). Note the occurrence of calcium phosphate (Apatite, in blue), which trapped plutonium during or soon after fission operation.

ARGUMENTS DERIVED FROM OKLO

- Reactor zones; 300–400 °C - significant quartz dissolution in the sandstone but **clays** (kaol, chl, ill) **remained stable** due to low thermal conductivity and localized heat
- Reactor **self-regulated** and shutdown when water boiled off (3 hr cycles). Where strata collapsed, reactions were terminated (i.e. importance of abundant water for moderation)
- Reactor zones remained **closed systems for most fission products** (precipitation within mineral phases formed).

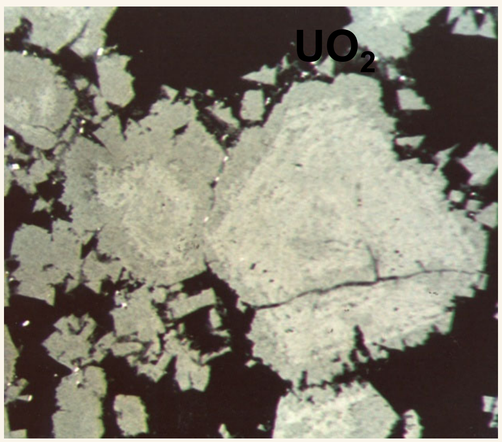




NATURAL ANALOGUE – OKLO REACTORS – RECORDS & LOSSES

Very low dissolution rates of UO_2/uraninite
=> RN release from SF is extremely slow

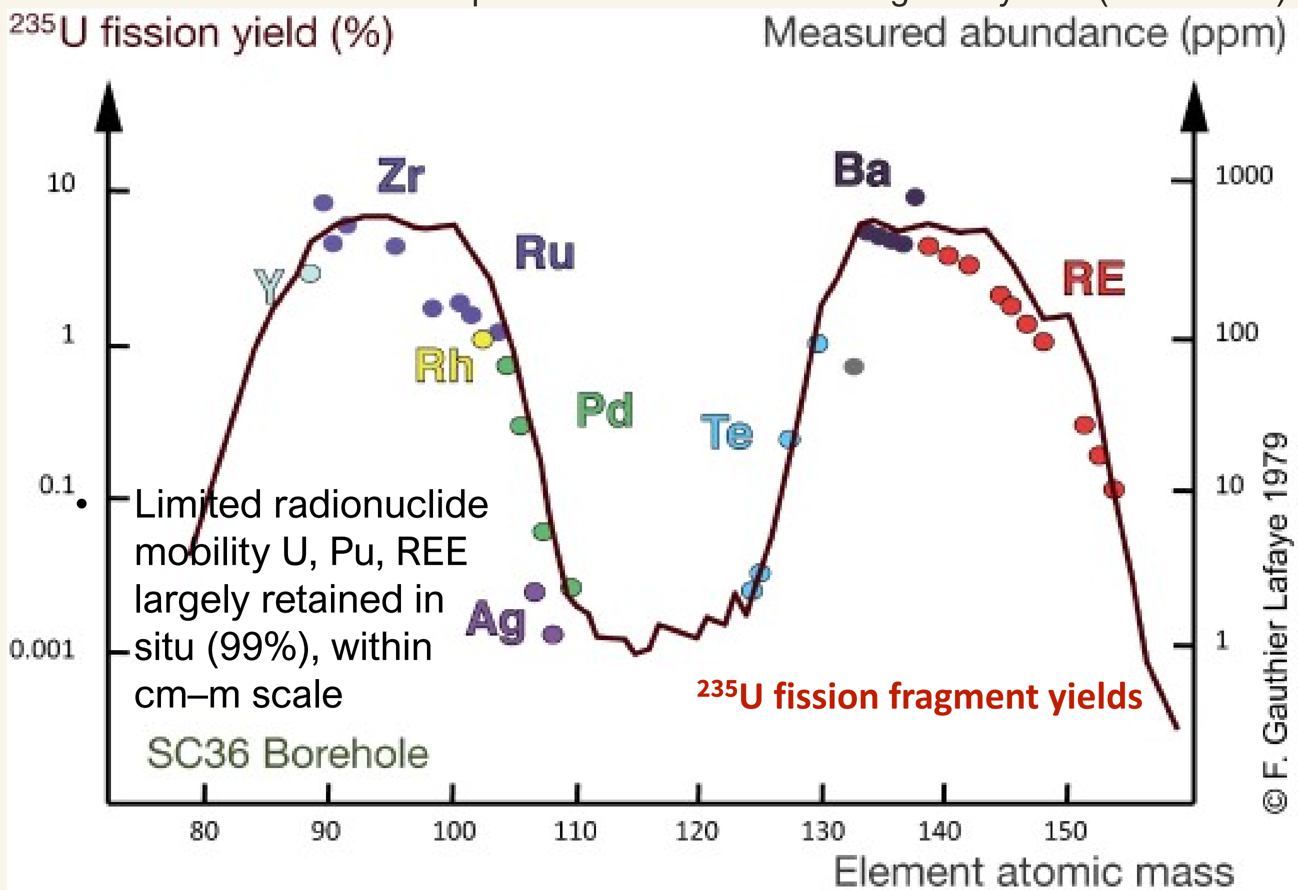
Some elements allow dating the events: Nd, Ru, Xe (age 2 Ga)



Stability of : (U, Pu, Th), REE, Zr, Ru, Pa, Rh, Pa

Migration of : Kr, Xe, I, Ba, Sr

Natural sustained fission data (dots) from borehole SC36 (RZ2, in comparison with ^{235}U fission fragment yields (solid curve).

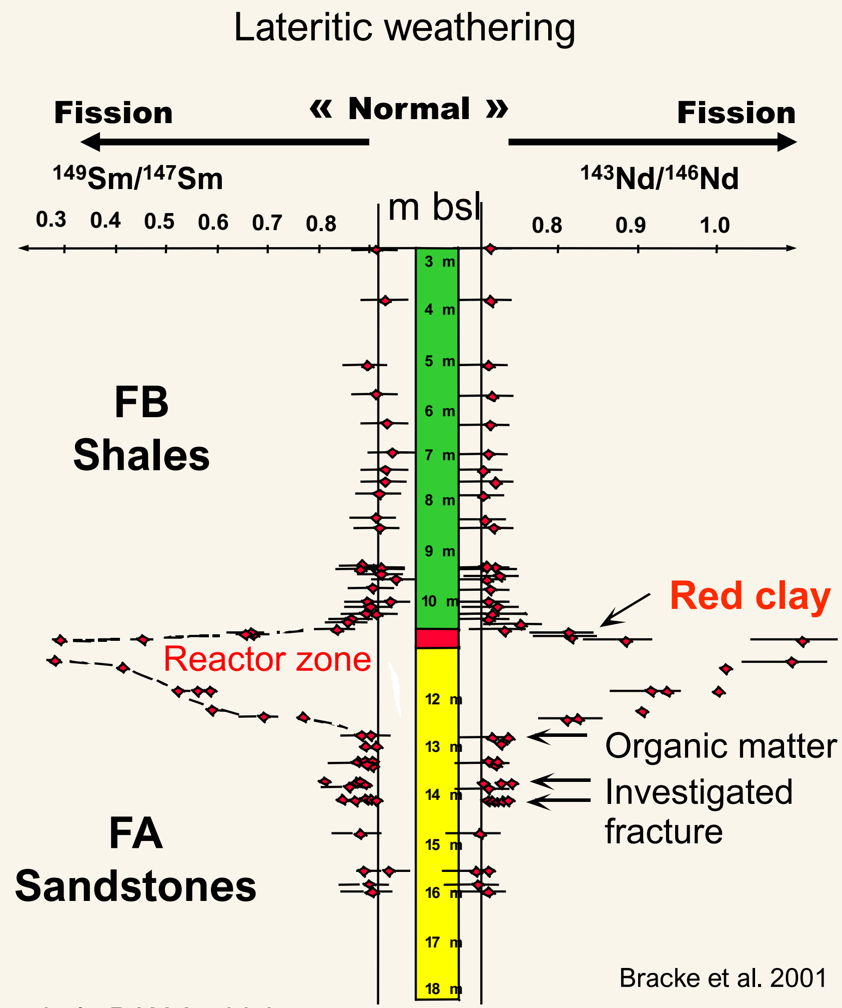


- Limited radionuclide mobility U, Pu, REE largely retained in situ (99%), within cm–m scale

BANGOMBE REACTOR

- Bangombe reactor (5 m long, 1 m wide and 5 -20 cm thick layer of uraninite embedded in illite and chlorites). The **uranium** content of the core ranges between **40 and 60%.**
- Fission reactions started in **high-grade uranium ore in sandstone** (U>10%) –> T increase -> convective hydrothermal system.
- Fission products concentrated in minerals formed (incl. **apatite**, clays, etc.) and organic matter (**sorbed**).
- Diffusion-dominated transport – despite higher permeability host rock conditions than Opalinus Clay

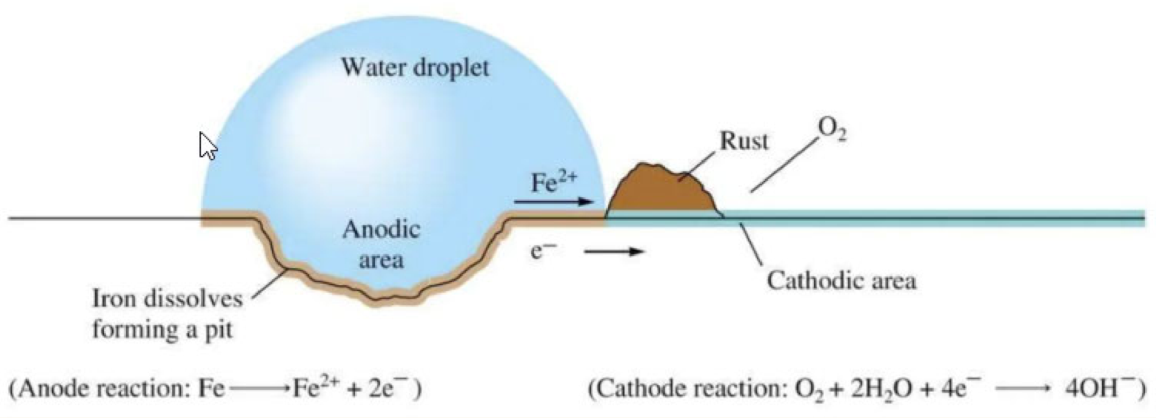
Confirms slow matrix degradation + strong retardation (NAs much slower release than models assume)



Distribution of fissiogenic Sm and Nd in the bore hole BAX 8 which cross-cut the reactor of Bangombé. Norm.Sm and norm.Nd refer to Sm and Nd having normal isotopic composition, not influenced by the fission products.

STEEL CANISTERS - CORROSION

- Natural analogue examples have self-limiting Fe corrosion in clay environments. Upon formation of dense Fe(II) corrosion layers (magnetite, siderite), further metal loss under anoxic, diffusion-limited conditions is **slowed down**
- Archaeological preservation (incl. Roman nails) over centuries-millennia confirms very slow, self-limiting corrosion rates
- Data support conservative Safety Case corrosion rates (NTB 24-10): gradual degradation, initial containment, and manageable gas generation



VITRIFIED WASTE - EVIDENCE FROM GLASS ANALOGUES

- Obsidian & ancient glass artefacts show long-term stability (>100 ka - 1 Ma)- with alteration under water-rock interaction, variable pH, and geochemical conditions. Often high initial alteration with rapid transition to very low residual rates (strong slowdown over time) and diffusion-limited.
- ***Formation of silica-rich gel layers*** create diffusion barriers, together with secondary minerals (clays, zeolites) stabilise the system
- **Implications for safety (NTB 24-10):** conservative dissolution rate models are confirmed with slow RN release, controlled by alteration layers & solubility. Mostly congruent release – i.e. RNs retained or decayed before migration

Glass analogue evidence confirms that vitrified waste is highly durable, with slow, diffusion-limited dissolution providing robust long-term containment

BENTONITE AND CEMENT: NATURAL AND FIELD EVIDENCE

Bentonite stability and transport properties & retention

- Kina project: Natural smectites preserved over >60 Ma years in Fennoscandian systems, deep alteration zones show smectite stability at 50 to >150°C with minimal mineral alteration and property modifications = > **Buffer remains functional even with interaction**
- Bentonites exposed to alkaline waters comparable to low-pH cement systems (Philippines, Cyprus) show minimal smectite alteration over 100ka to 1 Ma time-scales
- FEBEX Experiment Grimsel Test Site: Fe-bentonite interaction typically mm to cm scale (≈1–10 cm) Reactions depend on fluid supply and diffusion constraints
- SKB AMB 2 and 5 Test: minor alterations when heated to 250°C with slight reduction in LC and CEC

CEMENT: NATURAL AND FIELD EVIDENCE

- **Cement Systems** of Maqarin, Khushaym Matruk: cm to dm-scale alteration zones (local veins ~25-40 mm). C-S-H, carbonates and Mg phases => Porosity reduction near interfaces and reduced permeability, diffusivity.
- Hyperalkaline fluids (pH >12) interacting with sediments: limited plume extent. Formation of C-S-H phases and zeolites, carbonates (long-term mineral stability)
- Field experiment (Mont Terri CI): In situ cement-clay interaction since 2007 (ongoing): Clay alteration: few mm, Cement alteration: ≤ 25–30 mm after ~17 years. No large-scale degradation of Opalinus Clay
- **Strong anion transport reduction in field experiments**

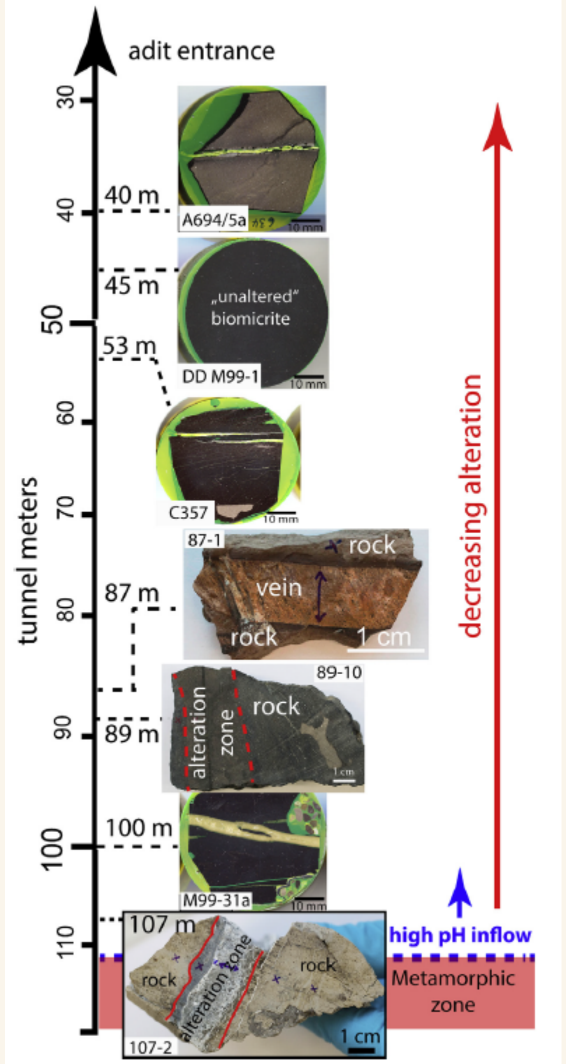
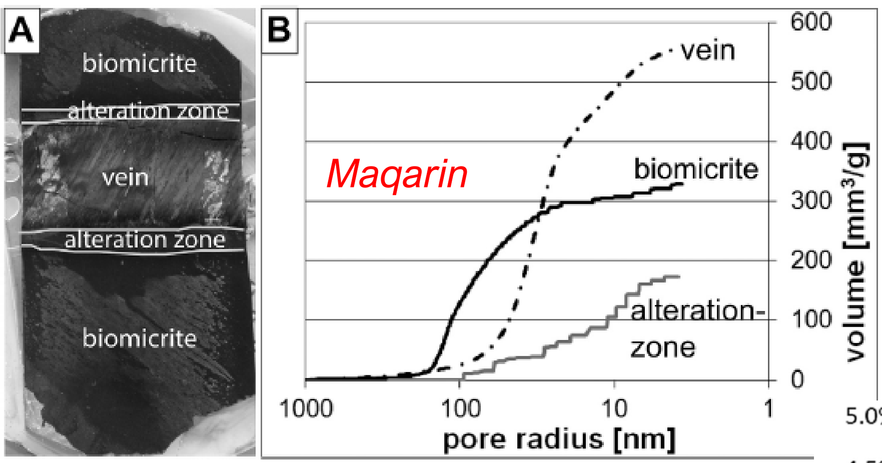


Fig. 1. Schematic cross-section through Adit A6 with sample localities and photographs of the investigated samples.

Martin et al. 2016, Applied Geochemistry 71 (2016) 20e34

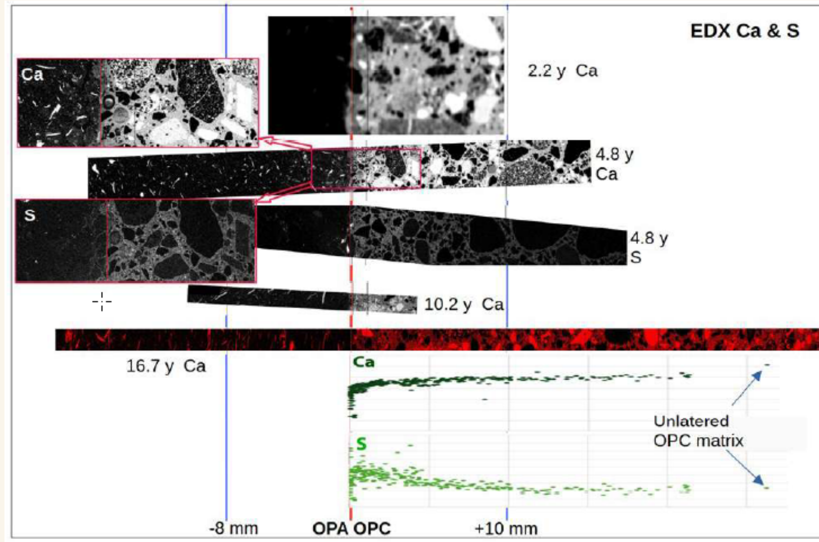
CEMENT: NATURAL AND FIELD EVIDENCE



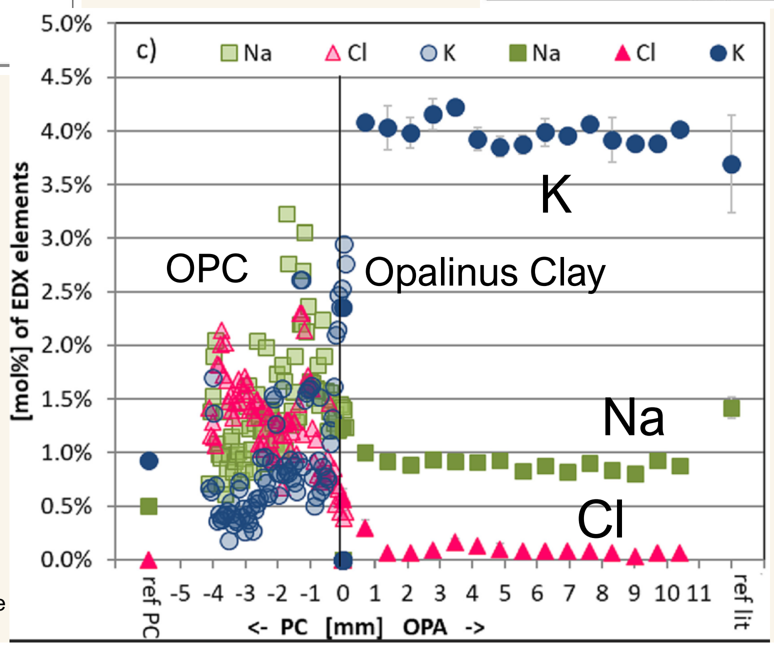
Martin et al. 2016, Applied Geochemistry 71 (2016) 20e34

A) Sample 87-1 showing the vein, alteration zone and biomicrite (for a colour image, see Fig. 1). B) Porosity measured by mercury intrusion porosimetry of the vein, the biomicrite and the alteration zone.

SEM-EDX element map for Ca across concrete (OPC)-Opalinus Clay (OPA) interface after different times of interaction, and two maps for S **after 4.8 year**



Mäder et al., 2026, MTTM – CI-D Experiment



Bernard et al., 2023 Cement and Concrete Research, 170, August 2023, 107180

Mont Terri- CI & CI-D

Element concentration profiles determined by EDS across the interface Portland paste in contact with OPA after **10 years.**

NEXT LICENSING PHASE: CONSTRUCTION LICENCE & NA NEED?

Nördlich Lägern: Opalinus Shale at 850-900 m depth and 48°C

- Which NAs could provide more quantitative (duration, T, etc) input?
- Direct coupling to repository conditions (i.e. pH, T, p, chemistry, etc)
- Can data be integrated or used in processes of performance or safety models?
- Better THMC linkages?
- Stronger argument integration – into the Claims-Arguments-Evidence structure?
  - stability over geological timescales? Geochemical conditions? T-ranges?
  - influence of glacial cycles?
  - link to field experiments? FEBEX and Fe zonation/migration – coupled processes reduce transport capacity over time

CONSTRUCTION LICENCE & NA NEED?

- NA or materials for anion retention or slow diffusion
- Longevity of cements and stability of their chemical conditions (i.e. pH)
- Solute transport through natural shale systems
- Geochemical stability/retention of fissile materials in shale environments (criticality safety assessments/argumentation)
- SF solubility and mobility
- Metal corrosion and gas production