DEEP GEOLOGICAL KIIRUNAVAARA SMECTITES, NORTHERN SWEDEN: A NATURAL ANALOGUE OF **LONG-TERM STABILITY** OF CLAY MINERALS

NAWG, June 2026

Raphael Schneeberger, Raphael Wüst

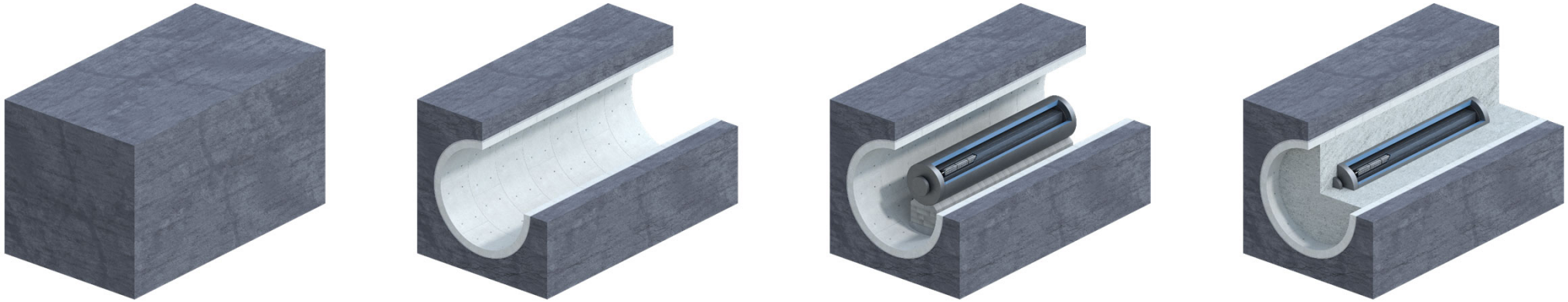
nagra.

LONG-TERM STABILITY OF CLAYS: WHY THIS MATTERS

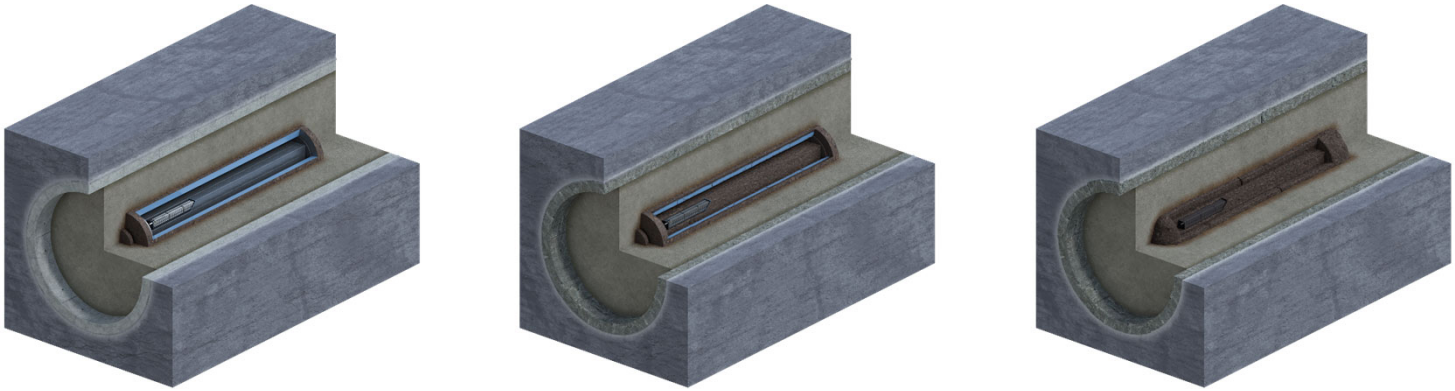
- Issue for WMO's: Can bentonite remain stable over geological time-scales? i.e. tens to hundreds of thousands of years?
  - KIRUNA's clays demonstrate that:
    - Bentonite remains stable over geological time-scales (millions of years)
    - Repository-relevant properties of the smectites are maintained
    - Iron-ore (magnetite) and clay interaction is minimal (Fe-poor smectites)
    - No evidence for erosional/sedimentational behaviour under relevant conditions
    - In-situ bentonite at Kiruna preserves microbial life

➢ => Provides confidence in long-term stability of buffer material and hence properties – which directly support repository safety and performance assessments

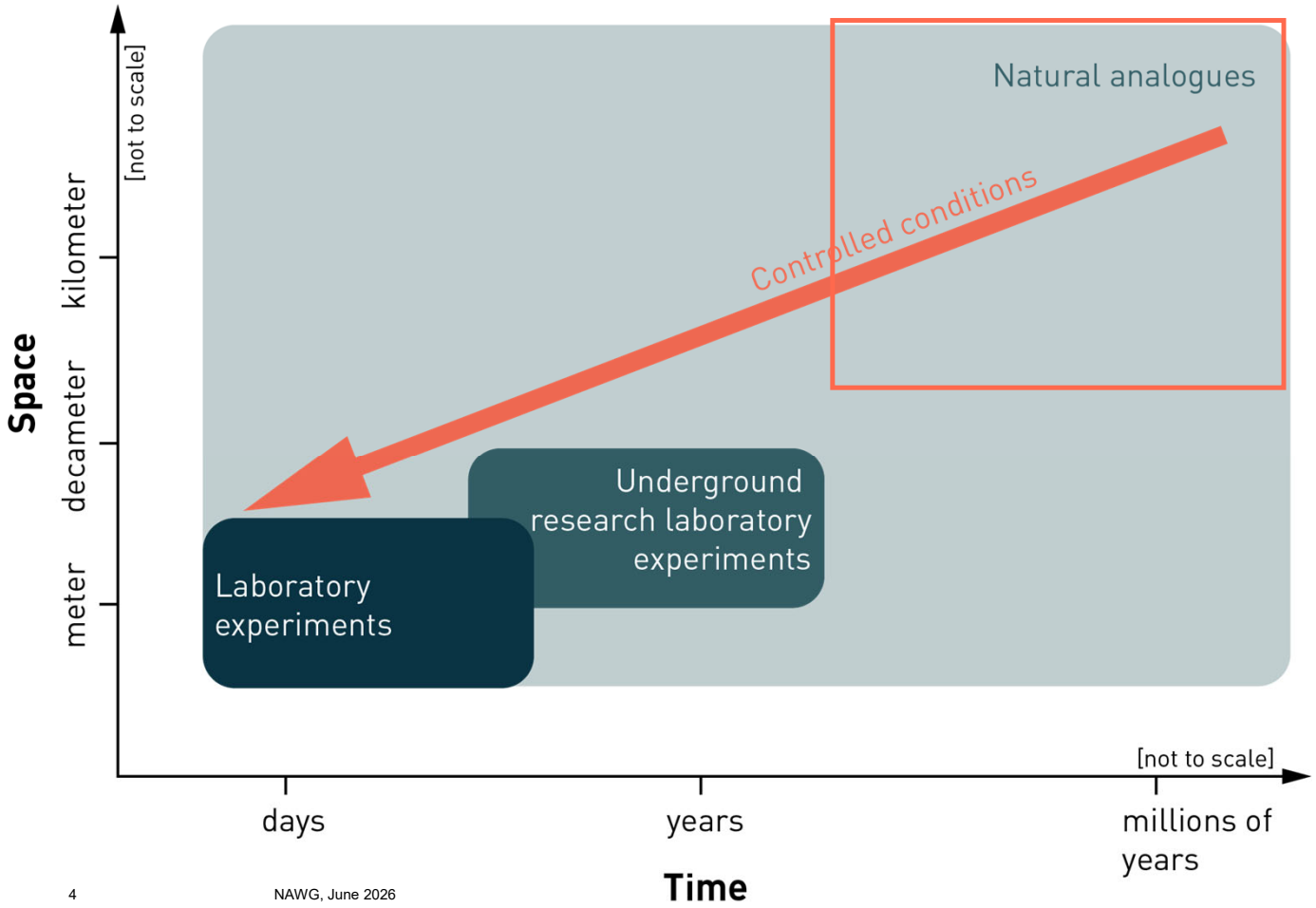
REPOSITORY EVOLUTION OVER GEOLOGICAL TIME



Barrier performance must be maintained over >100,000 years.

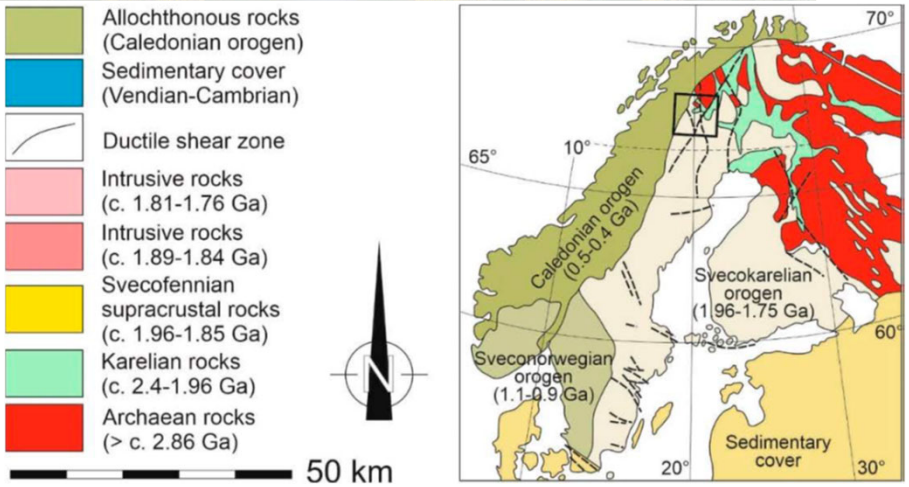


WHERE DO WE GET KNOWLEDGE FROM?



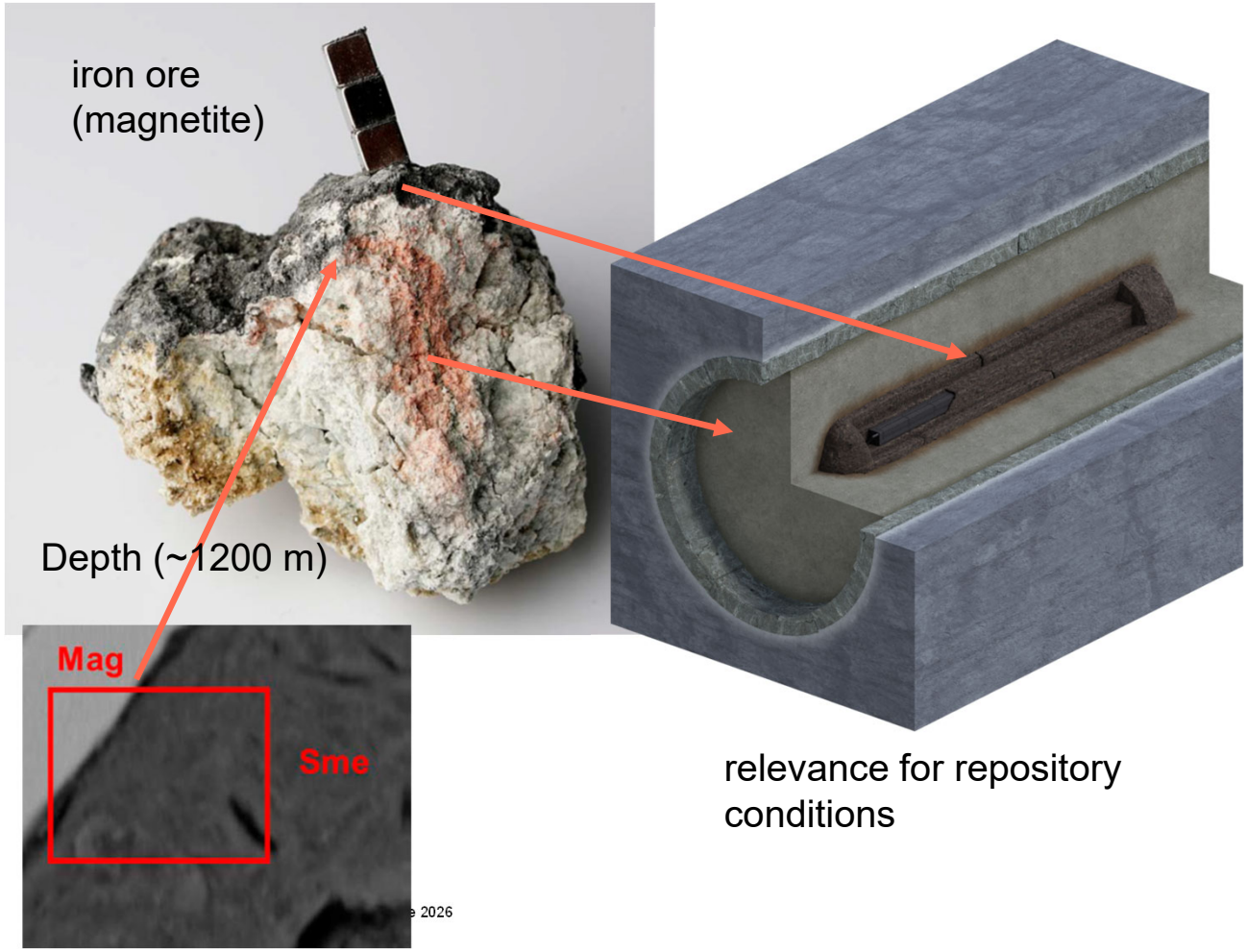
Natural analogues provide the only evidence at geological timescales

LKAB (SWEDEN'S NORTHERNMOST CITY):

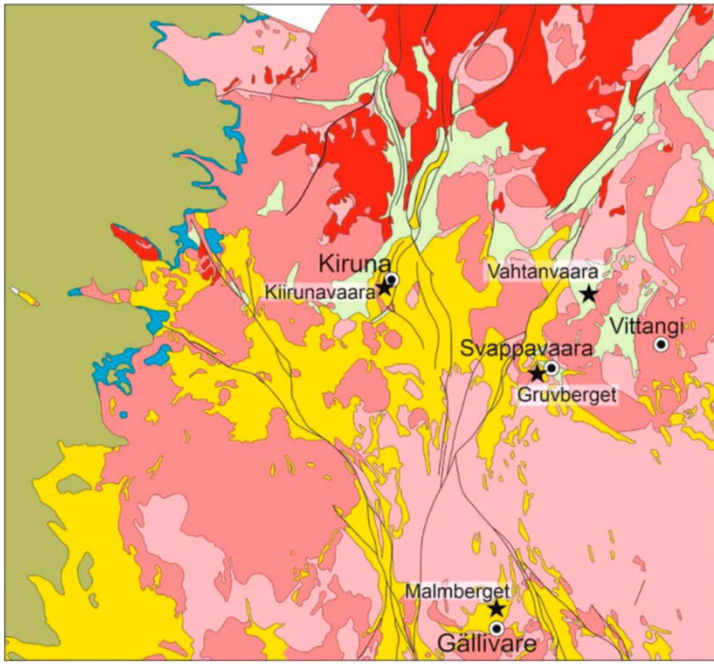


- Mining in Kiirunavaara since beginning of 20th century
- world's largest underground mine for iron ore

LKAB' POINT OF VIEW / MINING COMPANY



relevance for repository conditions



- massive magnetite deposit & some hematite associated with felsic volcanic rocks
- formed in a submarine volcanic setting with hydrothermal alterations

CLAY ALTERATION

- Hydrothermal origin
- Smectite-rich deposits along alteration halos of the ore bodies
- *Dioctahedral Fe-poor, Mg-montmorillonite (*44-81 wt-%).

Kiruna clays compositionally comparable to engineered repository bentonite

XRD-pattern

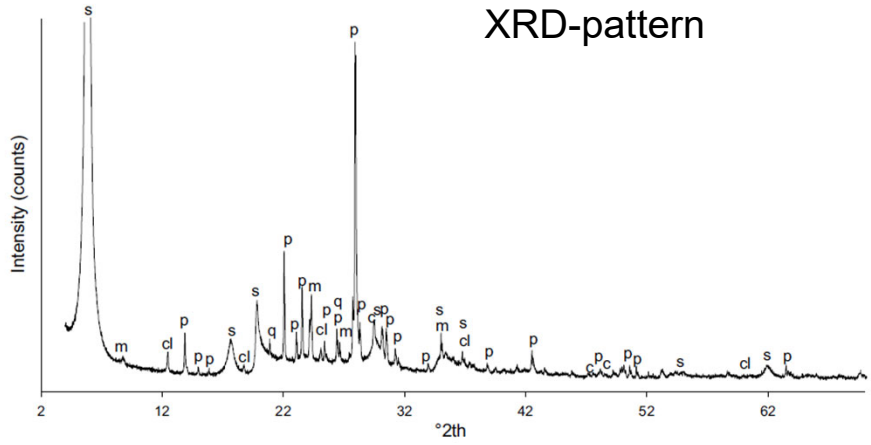
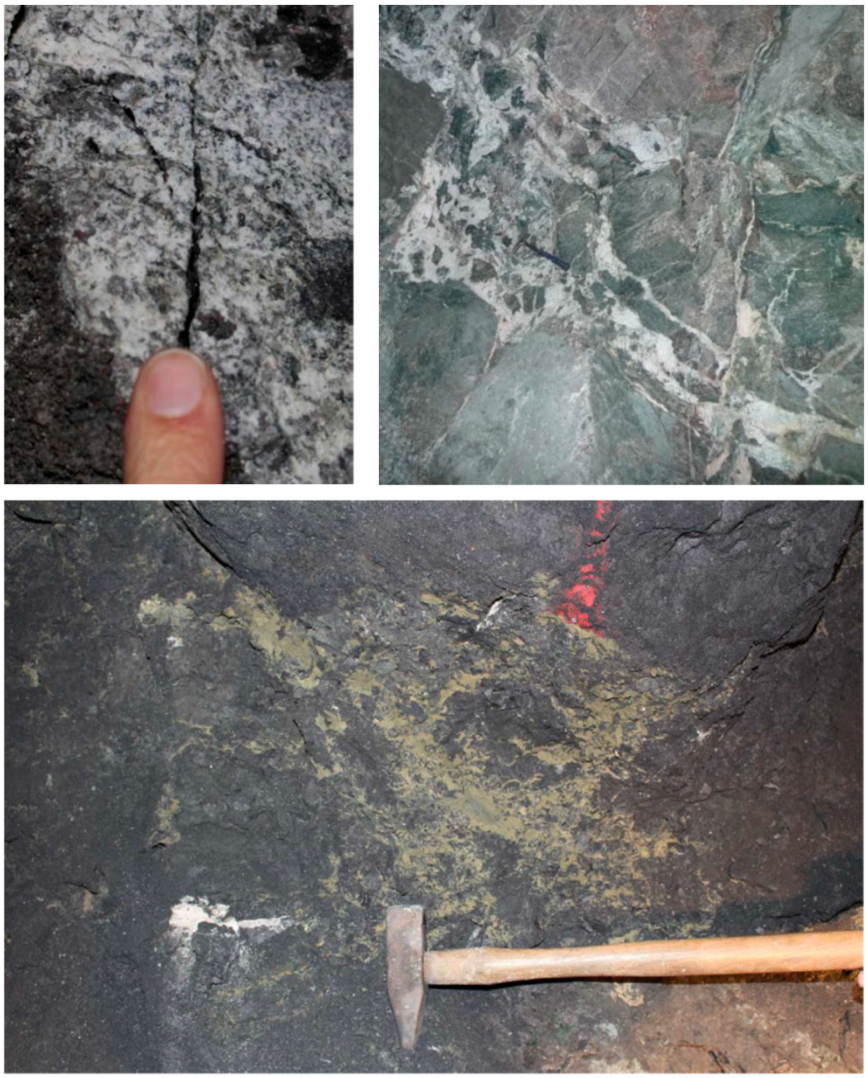


Figure 3-3. X-ray diffraction pattern of c65f8c bulk sample and identified minerals. Abbreviations: s=smectite, m=mica/illite, c=calcite, cl=chlorite, p=plagioclase and q=quartz.



HOW OLD IS THE CLAY?

Clay stable for >66 million years under relevant conditions

Proterozoic: Origin and initial host rock deposition until the Mesozoic (ca. 250–66 Ma) (Rb-Sr age dating)

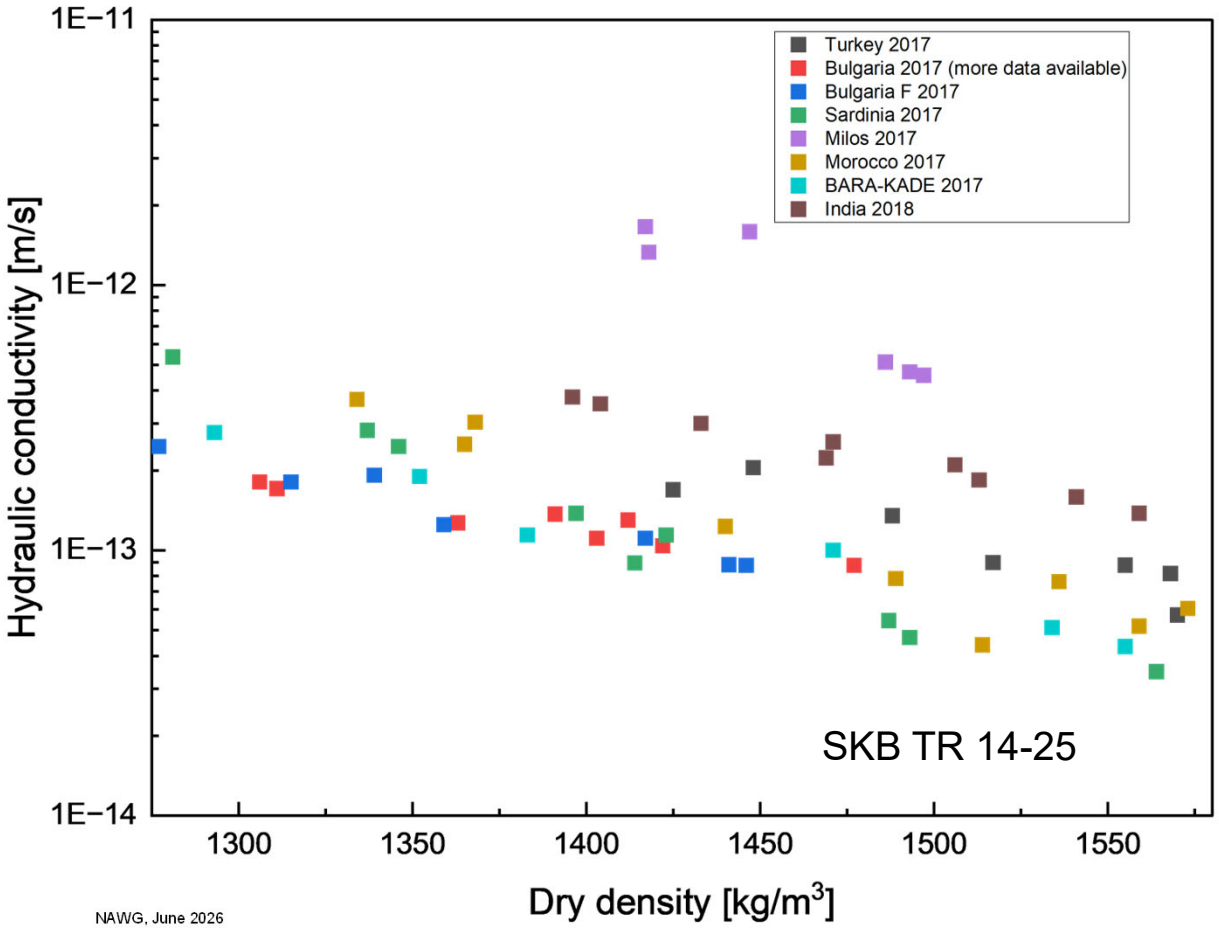
Mesozoic: alteration and formation of the smectite clay deposits (66-100 Ma)

> δ2H and δ18O isotopes & low B content of the smectites = meteoric fluids led to clay-formation (i.e. low **T <50 °C**!). Formation Temperatures confirmed by absence of stilbite and significant illitic components in the smectites. The isotope compositions of the fluids that formed the clays at Kiruna are similar to those forming the Mesozoic kaolins in Southern Sweden (Gilg et al. 2013)

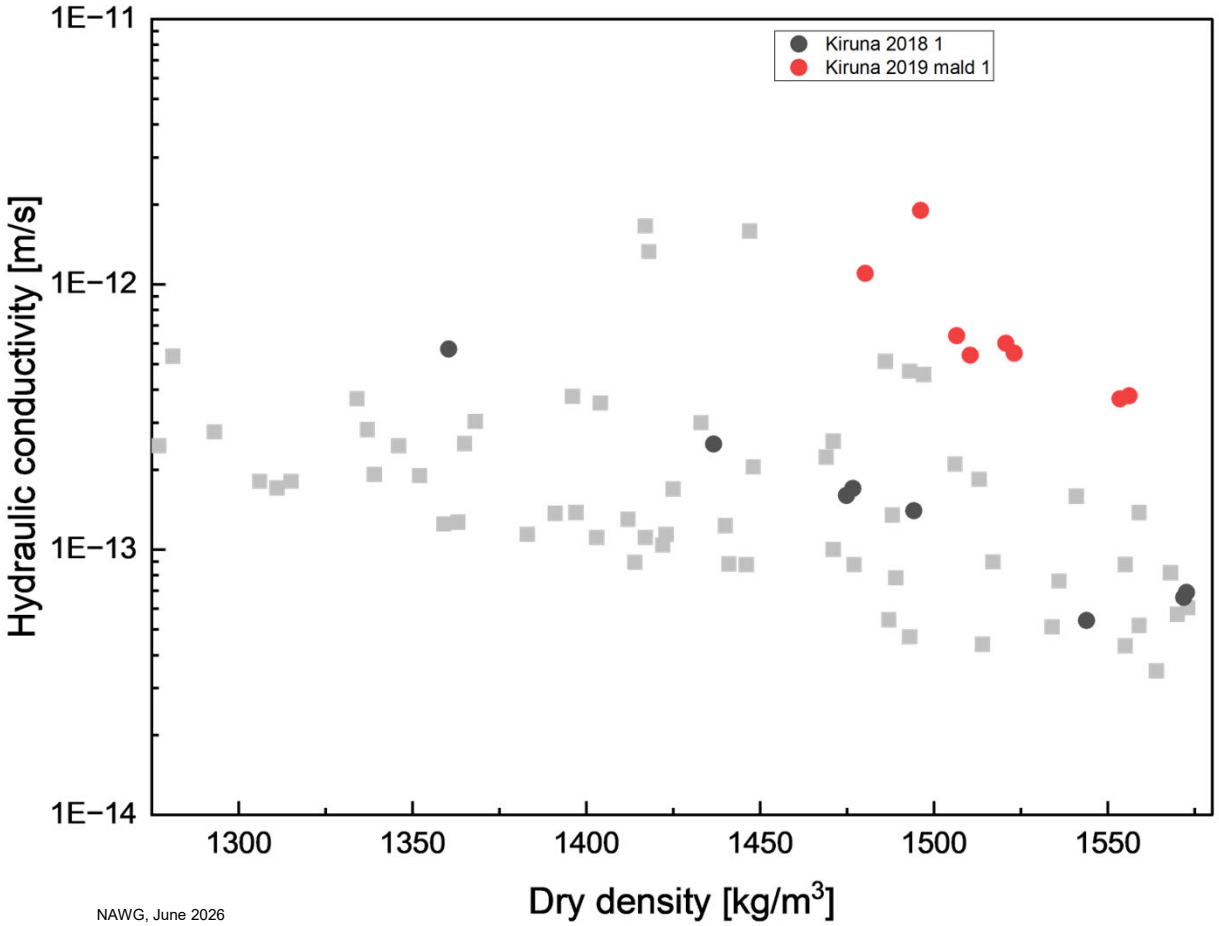
Post-Mesozoic: no further water circulation event recorded for the Kiruna clays

→ Clay system significantly older than repository timescales

HYDRAULIC CONDUCTIVITY AS PERFORMANCE MEASURE

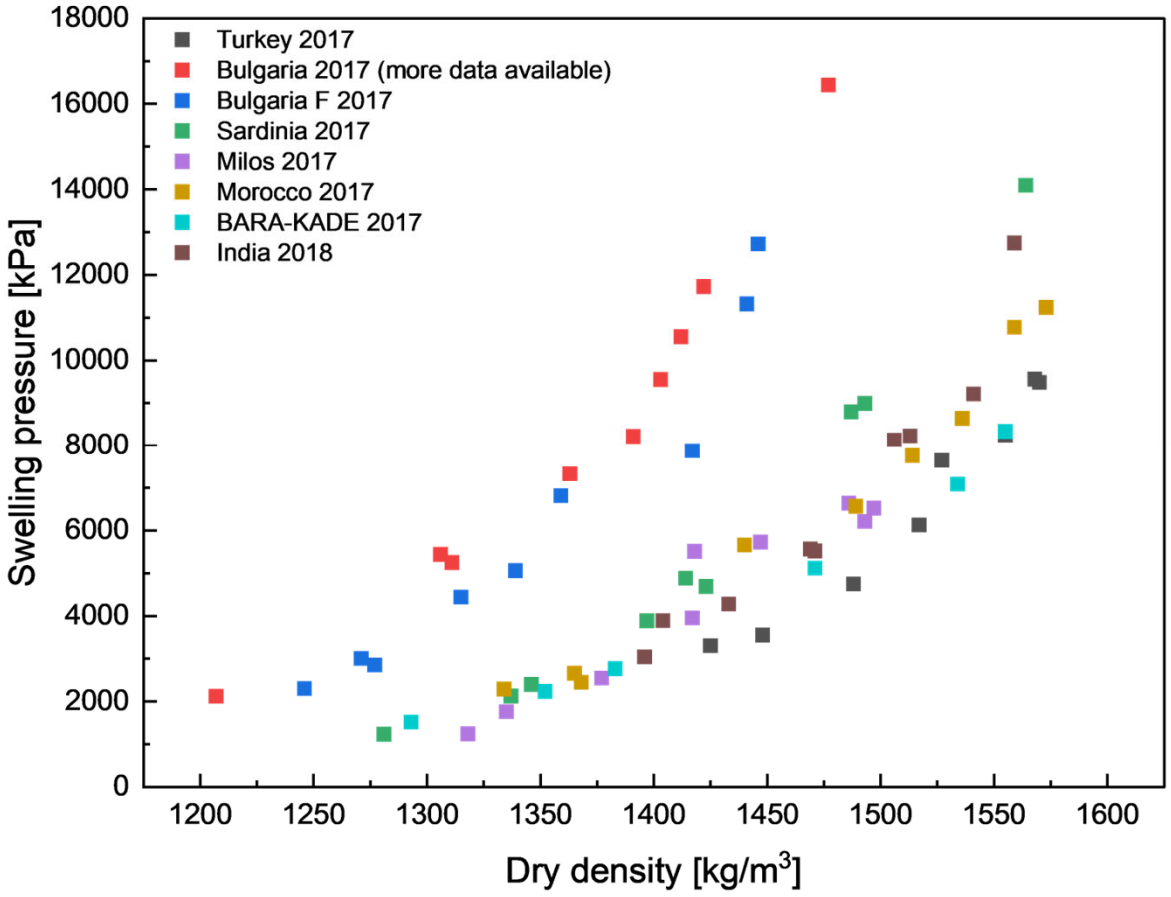


HYDRAULIC CONDUCTIVITY AS PERFORMANCE MEASURE



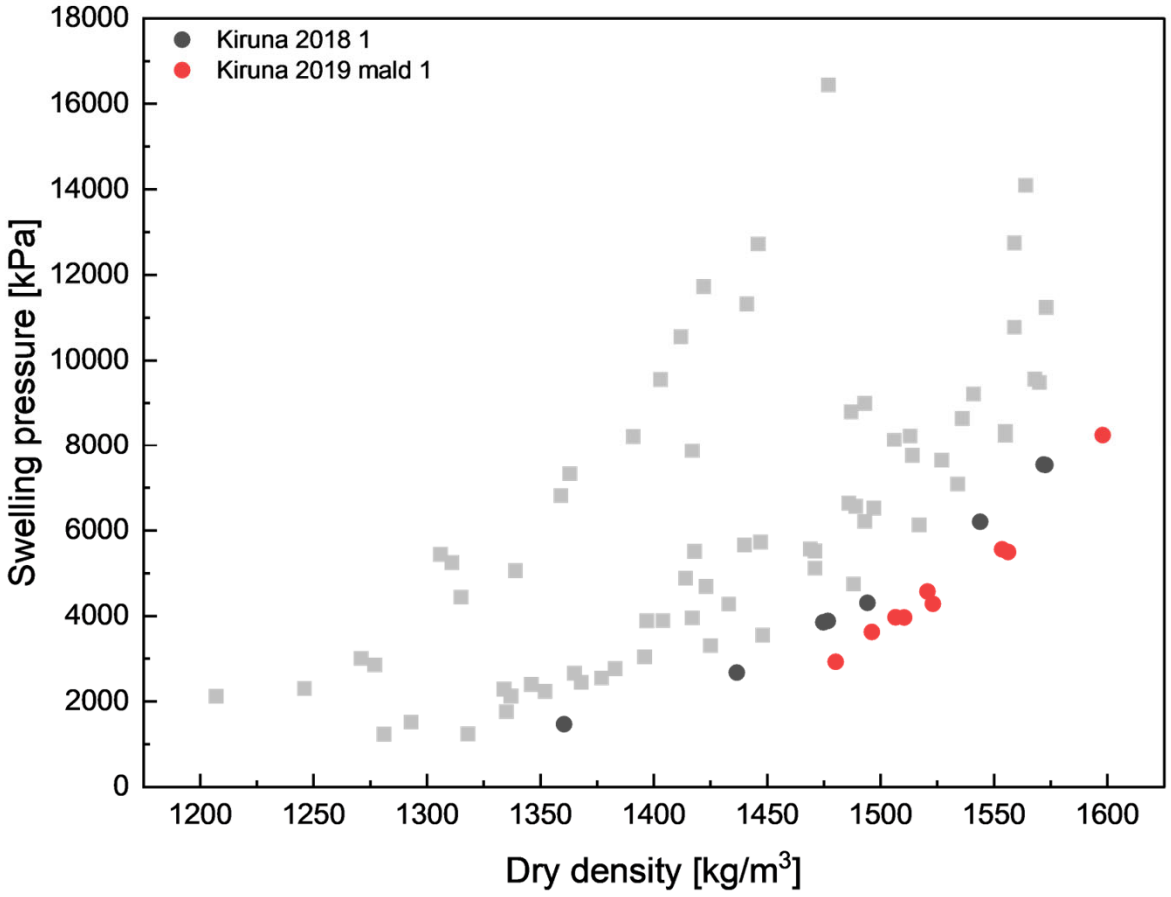
Hydraulic conductivity is comparable to engineered bentonite buffers

SWELLING PRESSURE OF KIRUNA CLAY



SKB TR 14-25

SWELLING PRESSURE OF KIRUNA CLAY



- Hydraulic performance is comparable to other bentonite types
- Swelling pressures in range of engineered materials

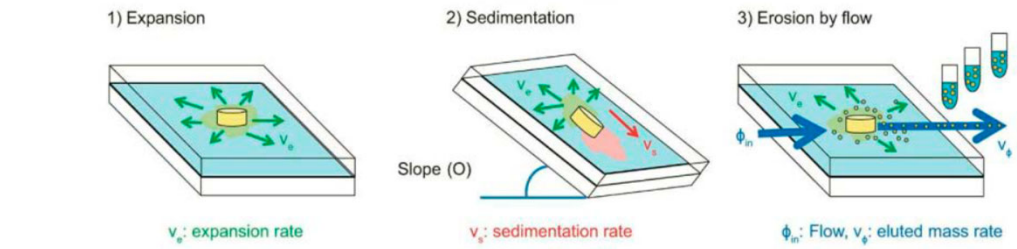
LIMITED LONG-TERM IRON-CLAY INTERACTION OBSERVED

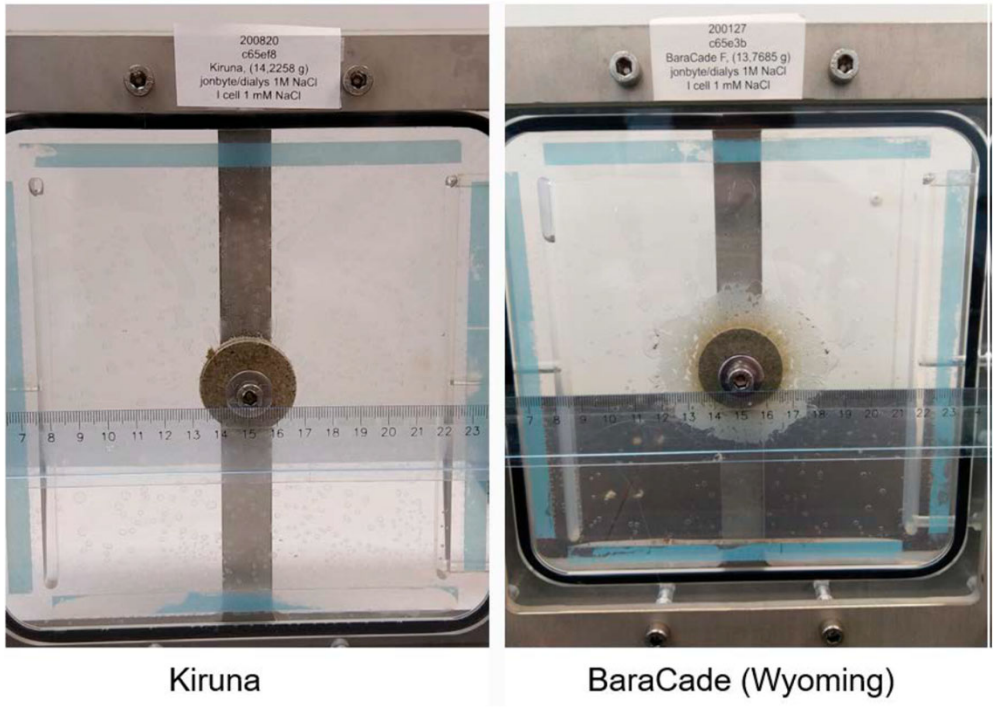
- *Mineral stability*
  - Kiruna clay appear stable since at least Mesozoic times (>66 Ma)
  - Elemental composition of smectite shows low Fe content → little magnetite / clay interaction at Kiruna even after long contact time
    - Saturation, Eh/pH conditions at magnetite interface are unknown but chemical environment may have inhibited magnetite dissolution and thus Fe-enrichment in fluids (environment should be low pH, high Eh)

STABILITY AGAINST EROSION

Kiruna clays show limited erosional potential

- no expansion into artificial fractures
- No erosion / sedimentation behaviour
- No colloid formation detected (Na-smectite) (possibly due to $CaCO_3$ in clays)
- Role of calcite within the clays towards stability is unclear – but may influence geochemistry of fluids



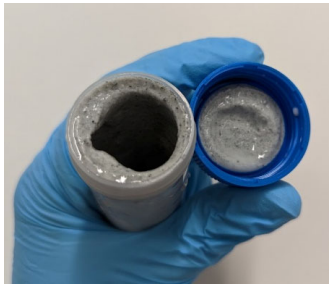


Kiruna BaraCade (Wyoming)

ACTIVE MICROBIAL PROCESSES CONFIRMED (Fe, NITRATE, SULFATE)

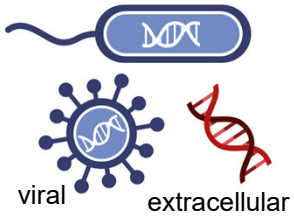
- Microbial presence identified in the clays
- DNA extraction confirms presence of life in clay matrix

Samples from 1200 m depth

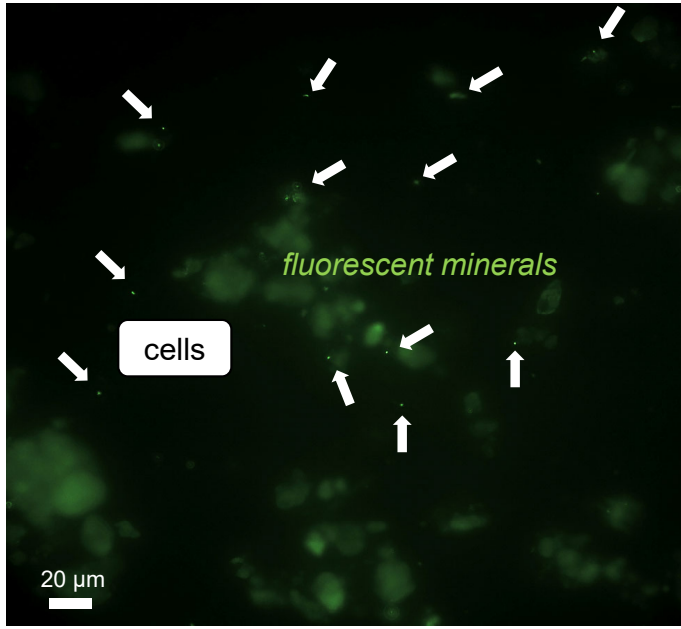


Decalcification and protein denaturation

DNA isolation and clean-up



Collection of DNA/RNA/protein fragments ≥ 30 kDa



KIRUNA NATURAL ANALOGUE – DEMONSTRATES THAT

- Long-term stability of Kiirunavaara natural smectites over geological time-scales (> 66 Ma)
- Preservation of key barrier (buffer) properties
- Limited interactions with iron ore (magnetite) or iron corrosion products (i.e. minimal clay interactions)
- Key properties, such as hydraulic conductivity, swelling pressure behaviour, erodability, etc. are comparable to other bentonites
- Microbes are present within the clay masses

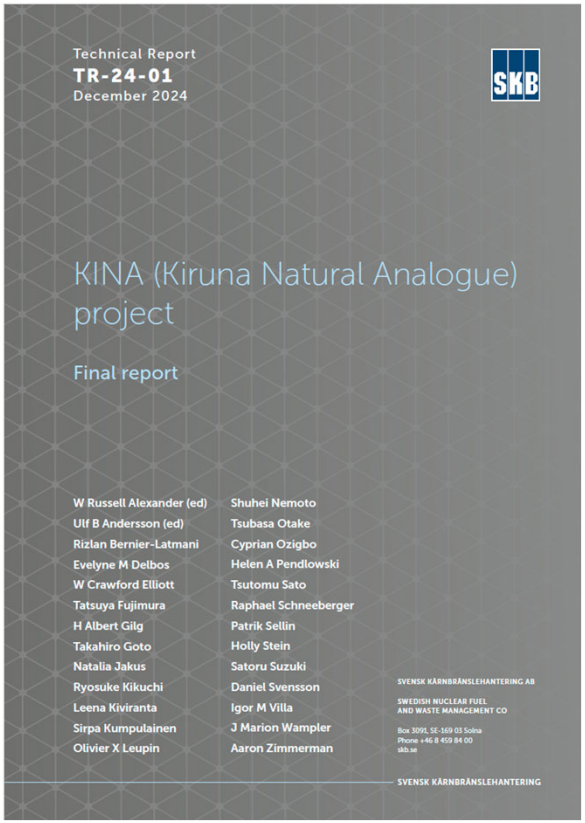
- Strong confidence in long-term bentonite performance in repositories
- Natural analogue demonstrates long-term barrier robustness

RELEVANCE FOR THE SAFETY CASE?

Bentonite buffer maintains its sealing capacity over the assessment time frame

- KINA project reinforces the **barrier robustness claims** – and confirms core safety function of bentonite buffer material
- Confirms long-term barrier stability
- Confirms and supports assumptions on low permeability performance over geological time-scales
- Provides evidence that iron-bentonite interaction is limited under repository-relevant conditions, reducing uncertainty in near-field evolution
- Provides natural evidence that far exceed experimental time-scales

THANK YOU!


Technical Report
TR-24-01
December 2024
SKB
KINA (Kiruna Natural Analogue) project
Final report
W Russell Alexander (ed)
Ulf B Andersson (ed)
Rizlan Bernier-Latmani
Evelyne M Delbos
W Crawford Elliott
Tatsuya Fujimura
H Albert Gilg
Takahiro Goto
Natalia Jakus
Ryosuke Kikuchi
Leena Kiviranta
Sirpa Kumpulainen
Olivier X Leupin
Shuhei Nemoto
Tsubasa Otake
Cyprian Ozigbo
Helen A Pendlowski
Tsutomu Sato
Raphael Schneeberger
Patrik Sellin
Holly Stein
Satoru Suzuki
Daniel Svensson
Igor M Villa
J Marion Wampler
Aaron Zimmerman
SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO
Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se
SVENSK KÄRNBRÄNSLEHANTERING