Use of Natural Analogues to support Safety Case development

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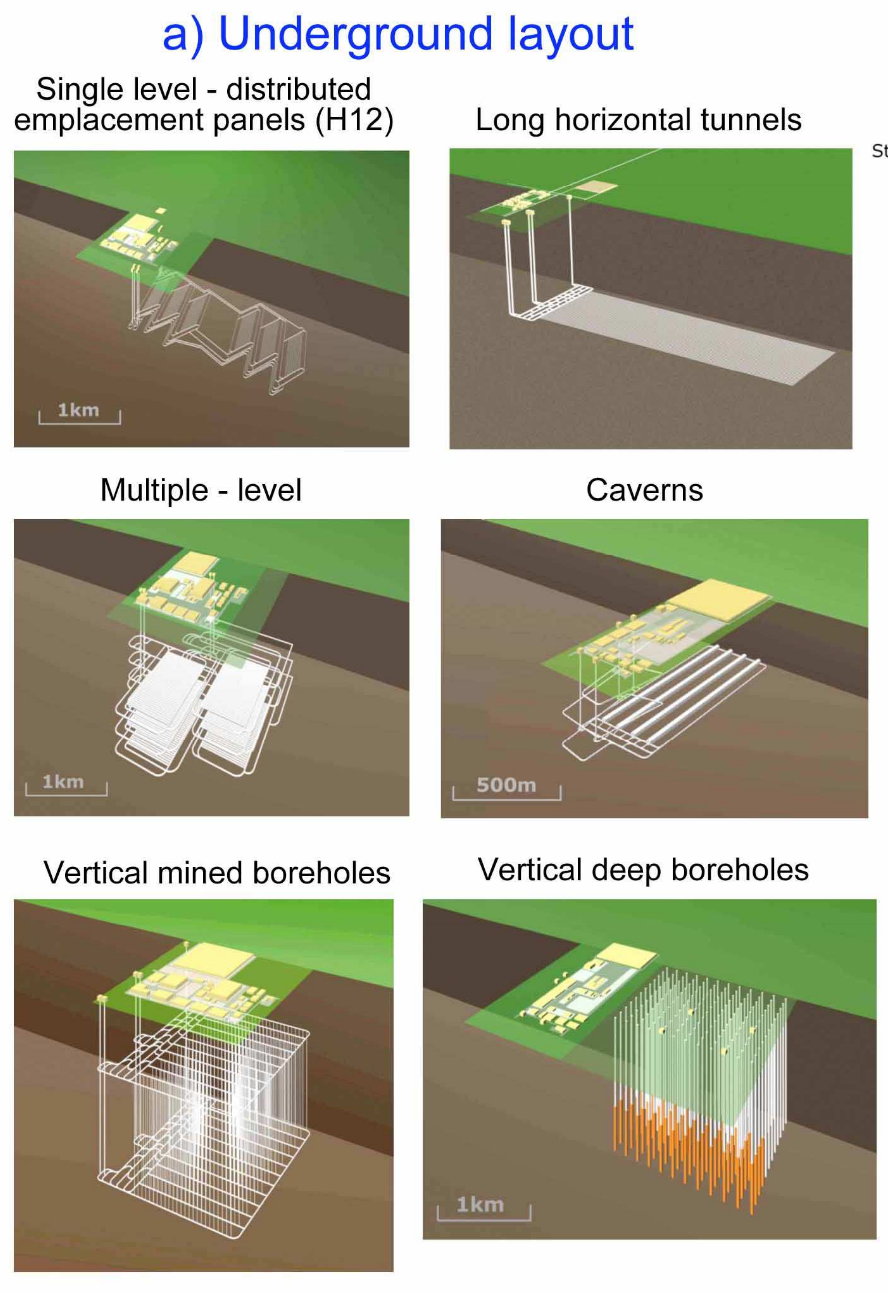
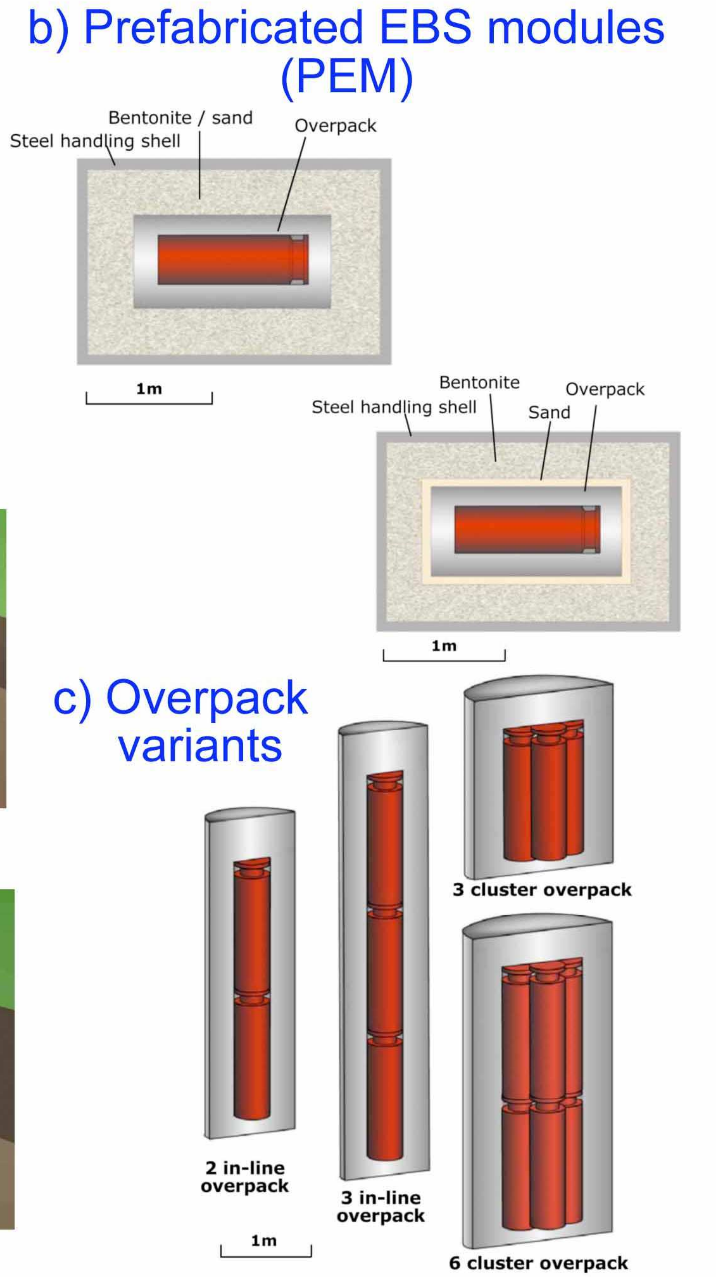
Overview

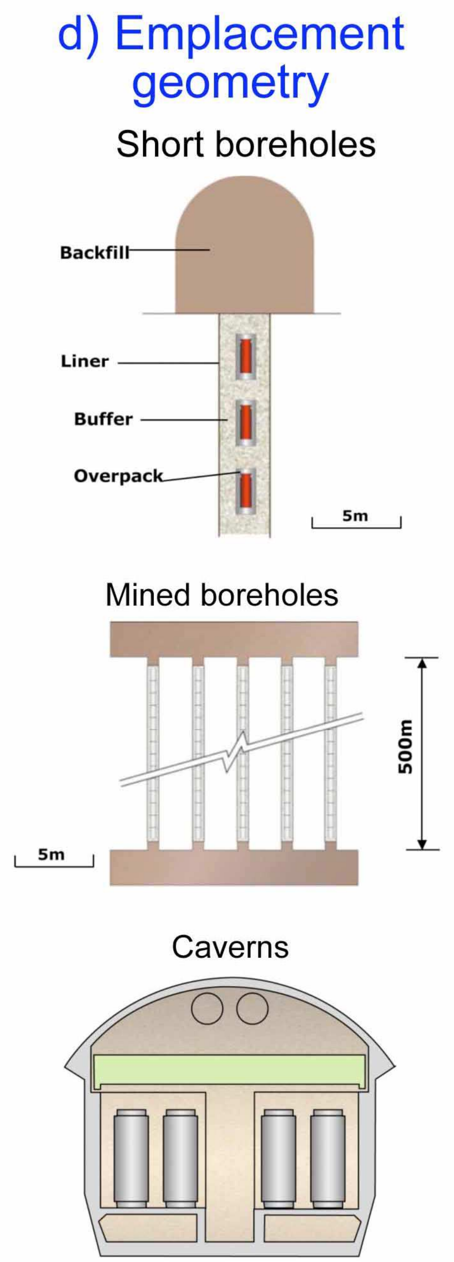
- Introduction
  - Components of an integrated safety assessment
- Potential use of analogues to support a safety assessment
  - Summary of applicability of major NAs
- Actual use of analogues
  - Overview of some recent major safety assessment
- Recent developments - the “Safety Case”
  - Implications for use of analogues
- A look to the future
  - Requirements for new analogue studies
- Summary & Conclusions

Safety assessment

There are many different designs that can result in safe disposal - but a fairly standard approach for demonstrating their safety



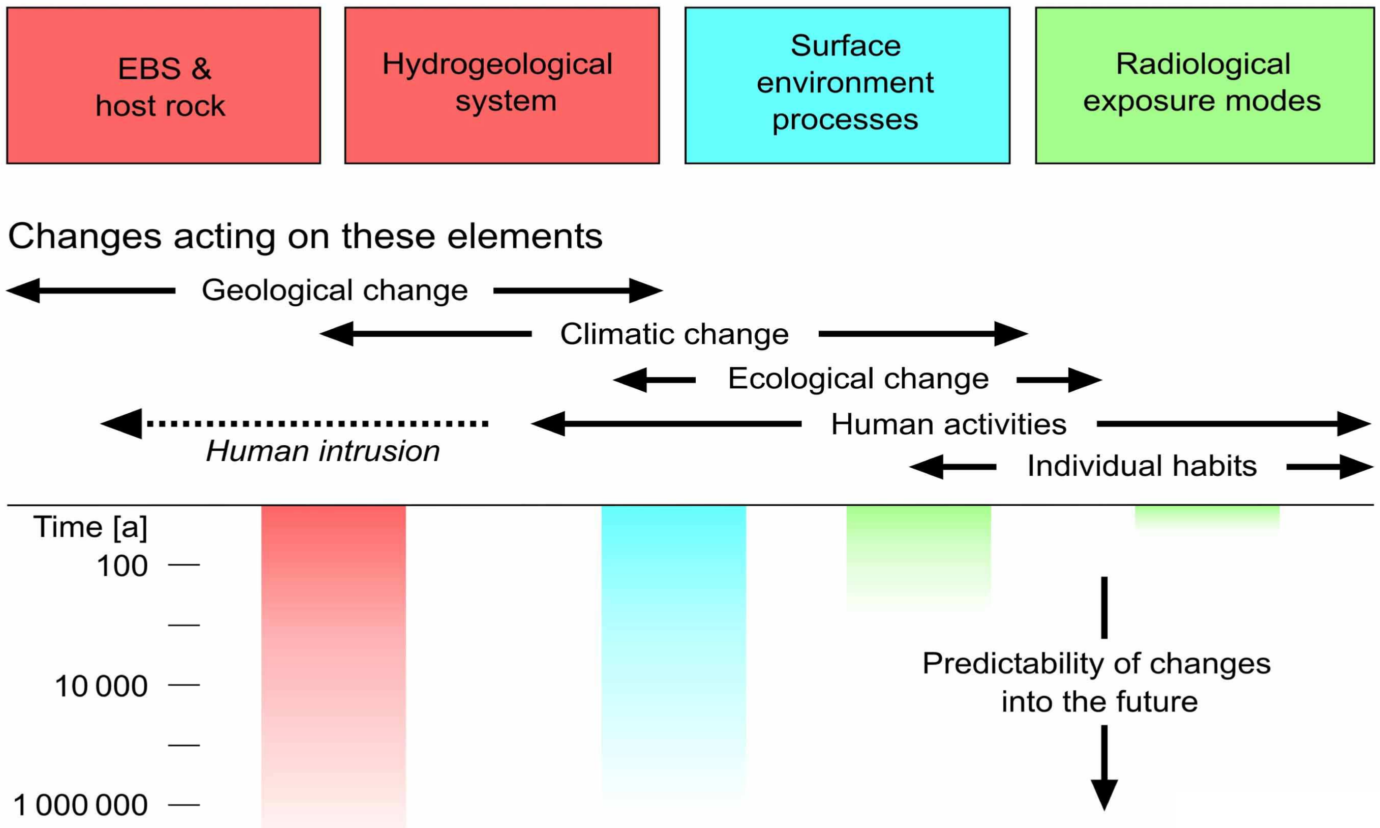




Quantitative Performance Assessment (PA)

The level of sophistication of a PA depends on the type of waste and the disposal concept

The key process involves establishing an approach to examine the future evolution of the repository system

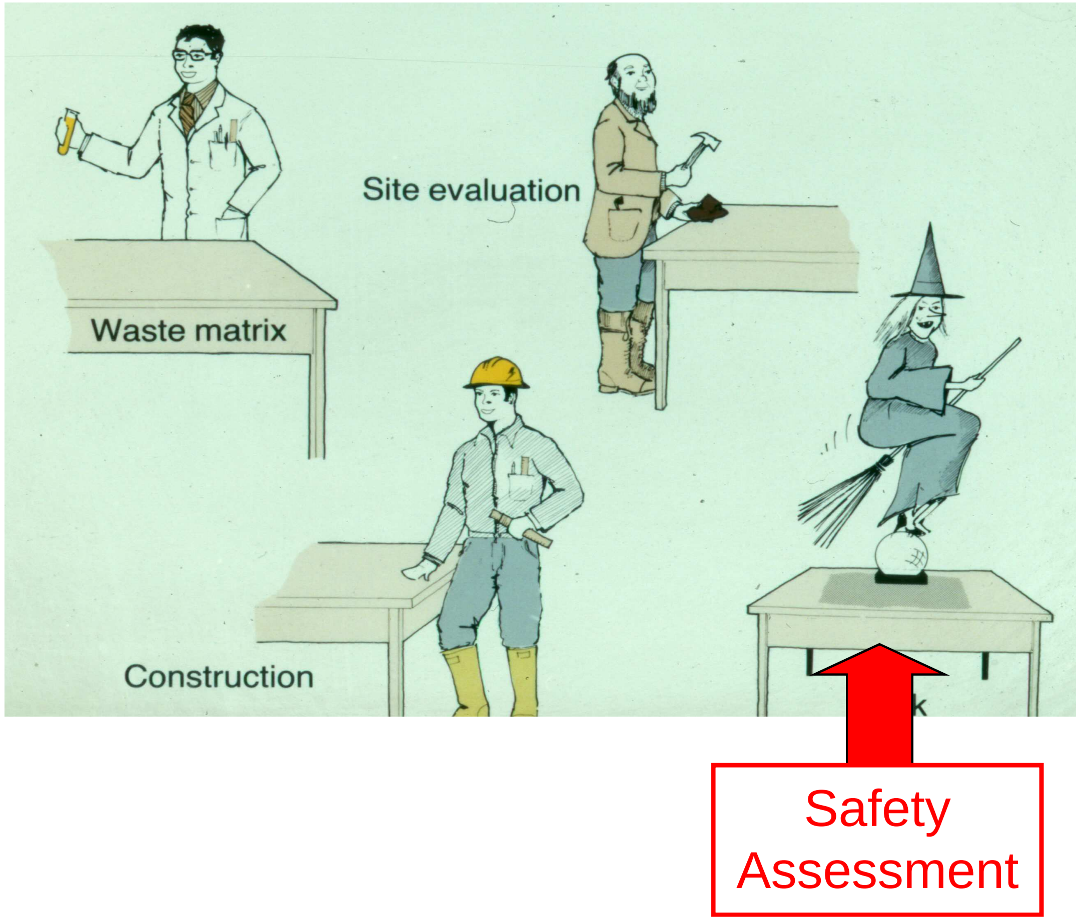


The Safety Case concept

The hard question – Is it even possible to show high levels of safety on such long timescales?

- **Requires a well-constructed repository in a suitable geological setting**
- **Future behaviour can be assessed using mathematical models**
- **Uncertainty can be bounded / covered by conservatism**
- **Confidence in conclusions can be supported by multiple lines of evidence**

➔ This together comprises a Safety Case



Scenario analysis

It is not possible to predict the future, but, for well buffered systems like repositories, possible future evolution of the disposal system can be bounded by a range of representative scenarios. A scenario is a description of the main phenomena governing system evolution and radionuclide release.

Scenarios considered in PA

Groundwater Scenarios

Base Scenario

- Stable geological environment
- The EBS performs as designed
- The current surface environmental conditions

Perturbation Scenarios

External events and processes :
- Natural perturbations
- Future human activities
- Early barrier degradation

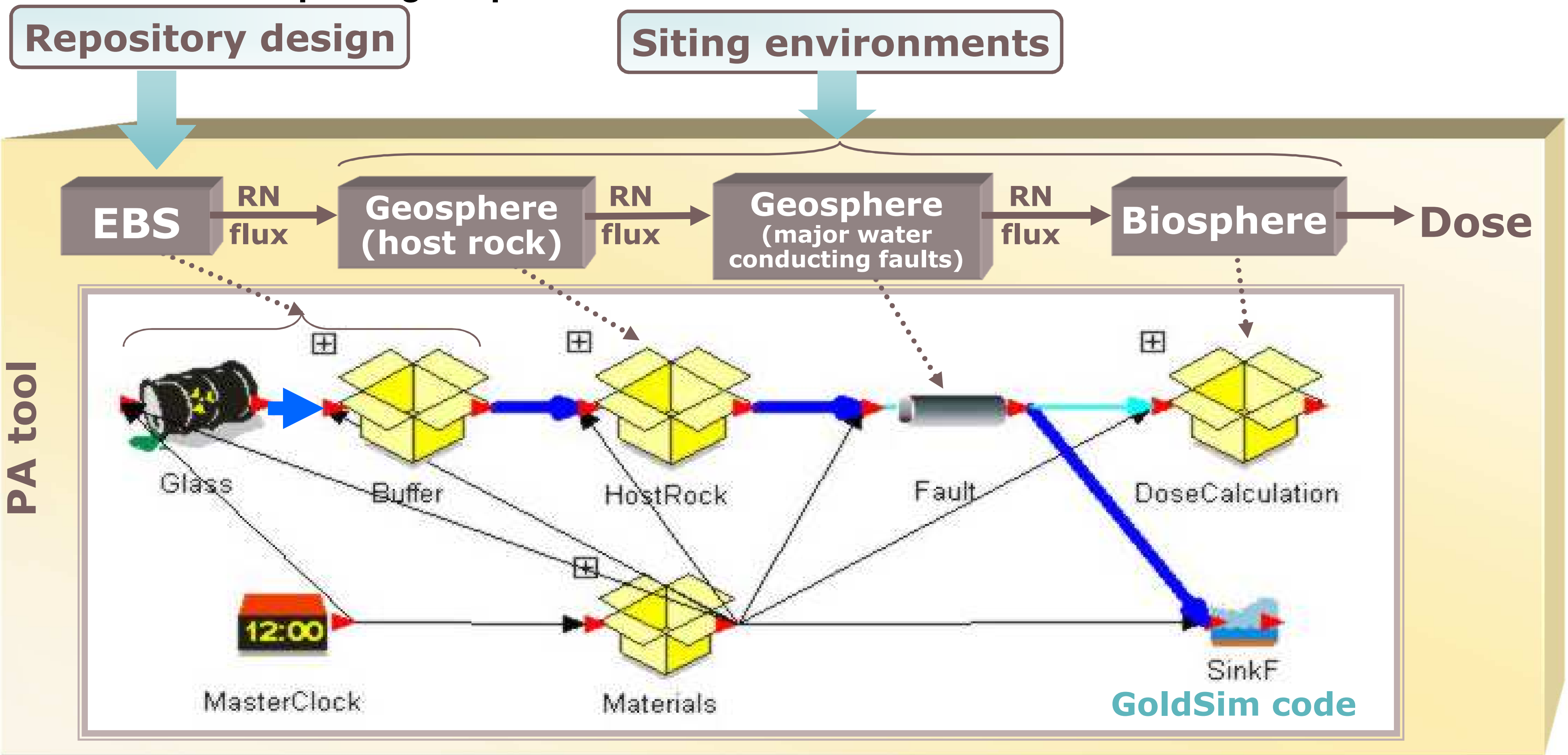
Isolation Failure Scenarios

Physical isolation is compromised :
- Direct magma intrusion
- Direct human intrusion
- Meteorite impact, etc.

Scenario modelling

For any scenario, the system is defined and can be quantitatively analysed

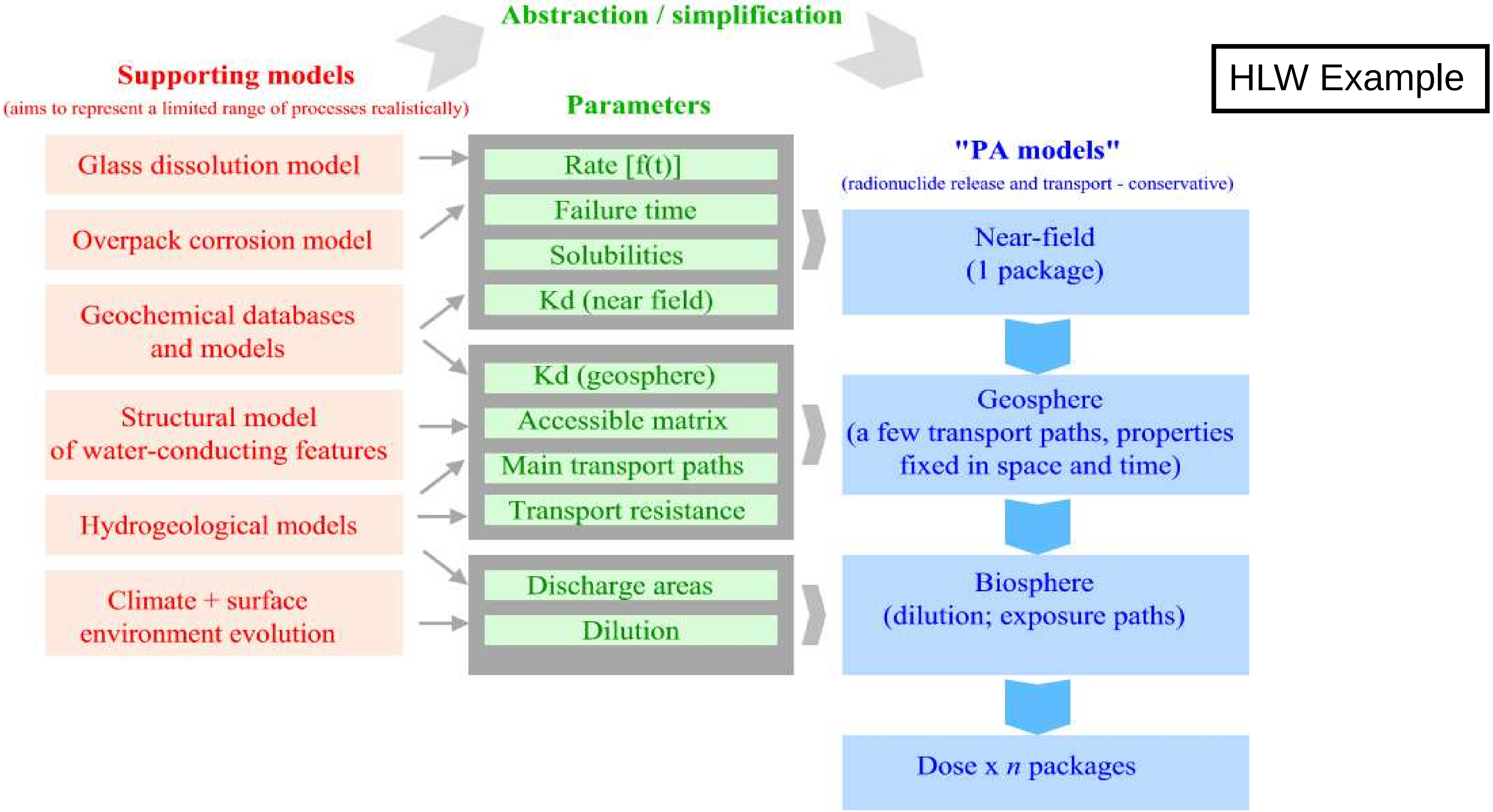
- **The scenario is reduced to component Features, Events and Processes (FEPs)**
- **Consequence analysis of each scenario**
  - **PA model chains**
  - **Interpreting output**



RN: Radionuclides

Development of a model chain

A series of models of components of the repository system are combined to evaluate consequences for any particular scenario (approach may be deterministic or probabilistic)



Modelling constraints

- Any model is an inherent simplification of a real system; the consequences of the simplification process must be understood, particularly when it is represented in a computer code
  - Assuming processes are constant with time or undergo stepwise changes
  - Averaging or nesting models to allow spatial scales from sub-cm to many km to be represented
- Even if sub-models are well understood, combining models into chains must be done with care
- Even if some models are reasonably realistic, some must be idealised (e.g. biosphere)
- An important area is taking into account inevitable uncertainties

Total System Performance Assessment (TSPA)

Integrated assessment of barrier performance and system safety, with an evaluation of the effects of uncertainties via sensitivity analysis.

Evaluation of Barrier Performance

Reference Case

Construct/compile appropriate

- Conceptual model
- Mathematical models/codes
- Data

Provide a baseline for the derivation and assessment of alternative cases

Sensitivity analysis

- Variations in the geological environment and design
- Uncertainties in scenarios, models and data

Key factors

Evaluation of System Safety

TSPA

Combination of uncertainties and variations

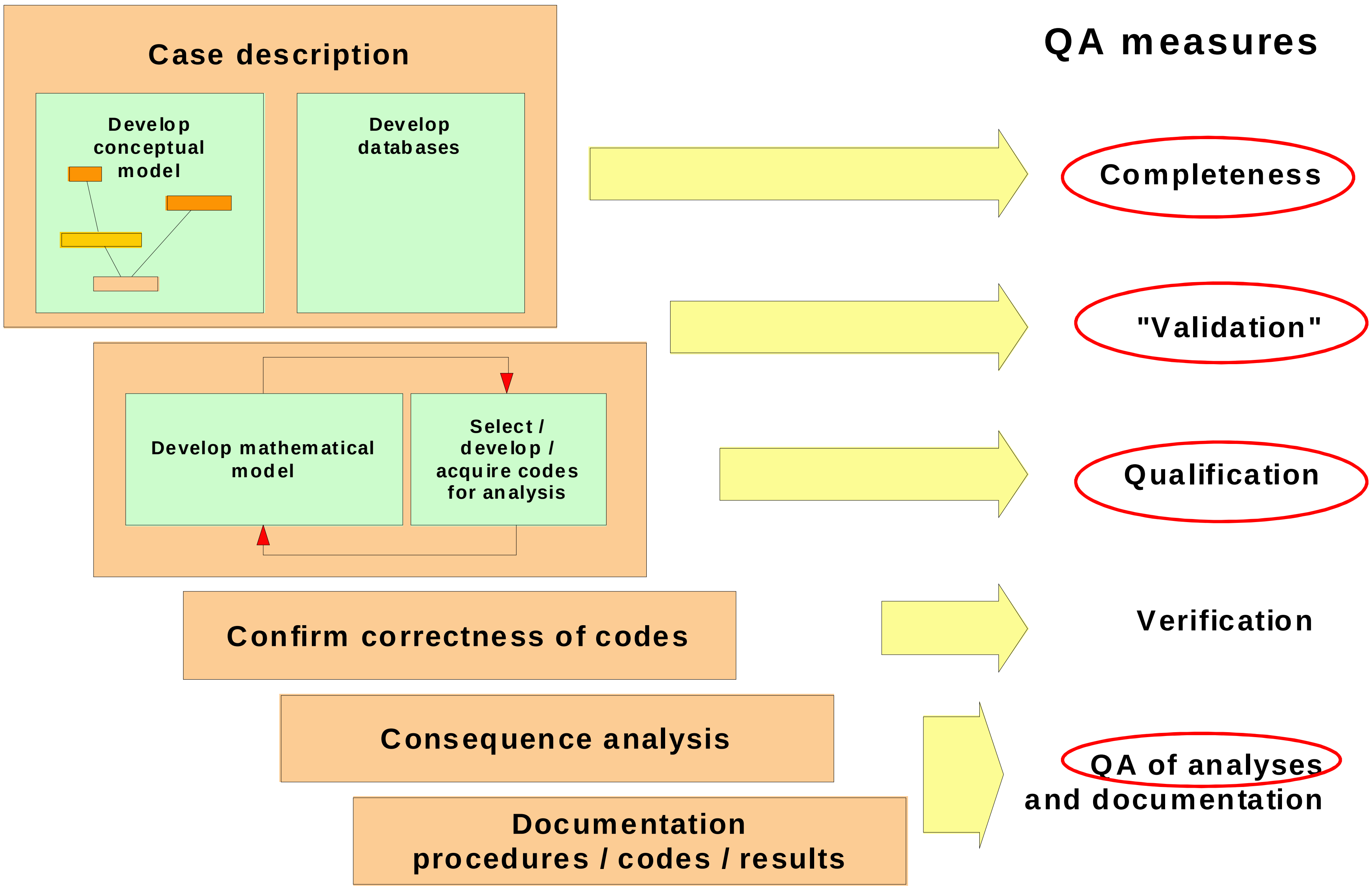
Evaluation of confidence

- Supplementary analysis
- Qualitative assessment
- Comparison with other SAs

Safety standards

Model QA and testing

Model quality assurance & testing plays an important part in building a Safety Case:
this can be a key role for natural analogues



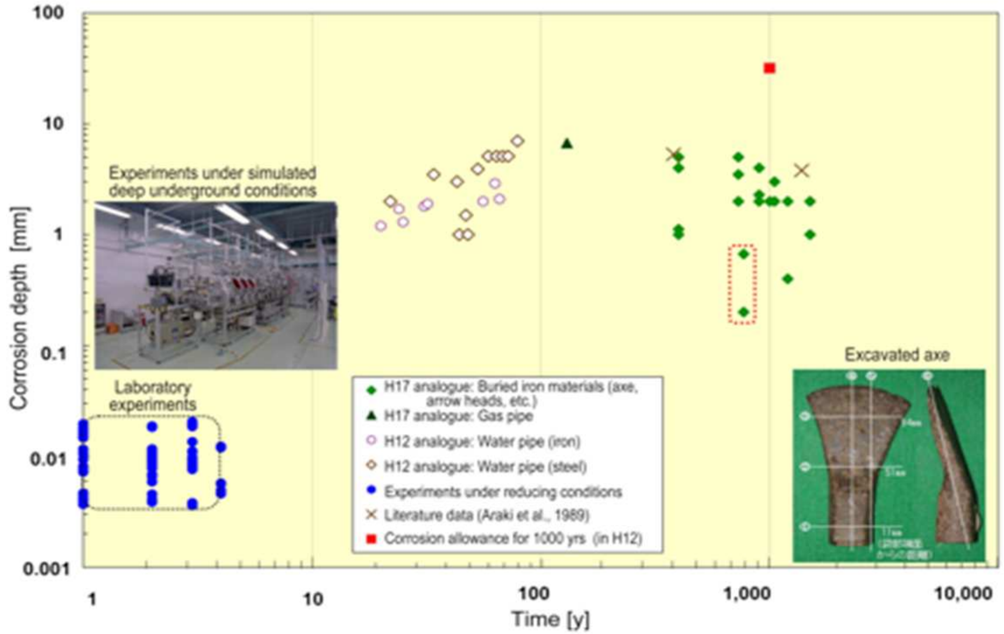
Overview of NA applications and limitations

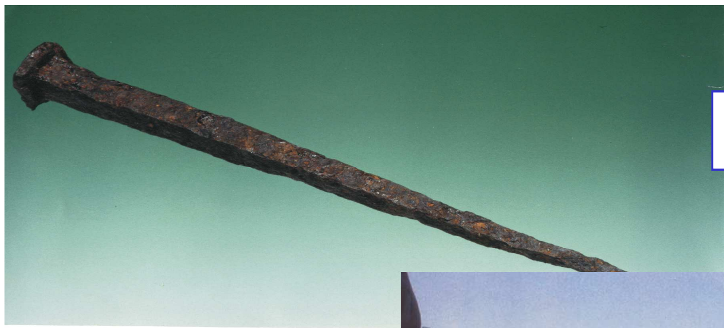
- **Archaeological analogues**
  - **Main focus on materials performance**
  - **A few process analogues or repository-specific applications**
- **Geological analogues**
  - **Total system analogues**
    - **Oklo**
    - **Cigar Lake**
  - **Model testing**
    - **Poços de Caldas**
    - **Loch Lomond**
    - **Maqarin**

Archaeological analogues - materials

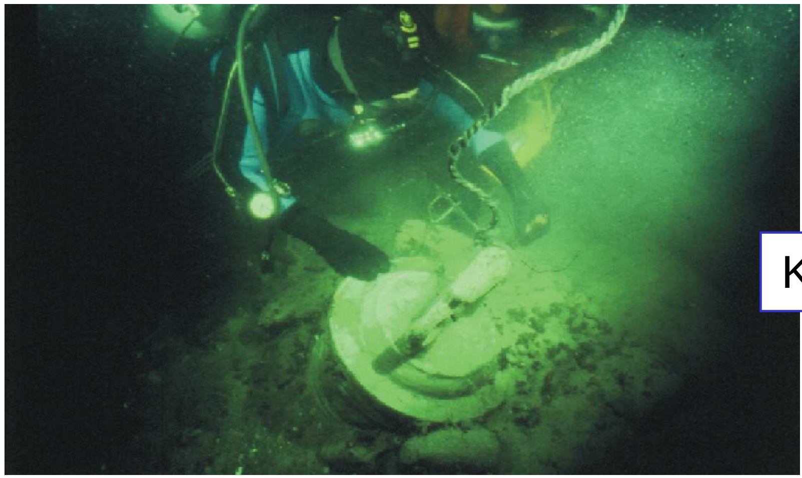
Artefacts which have been recovered from relevant settings can provide evidence for the longevity of materials used in repositories

- **in some cases measured corrosion rates can be compared with PA model predictions**
- **limitation - analogy constrained by extent of similarity of material and burial conditions**





Inchtuthil nail

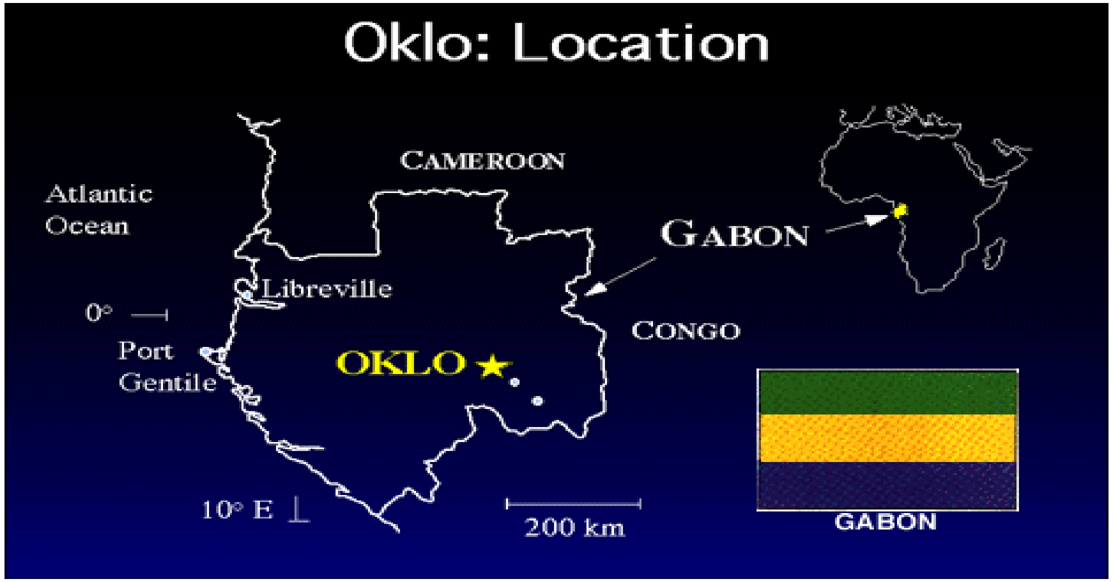


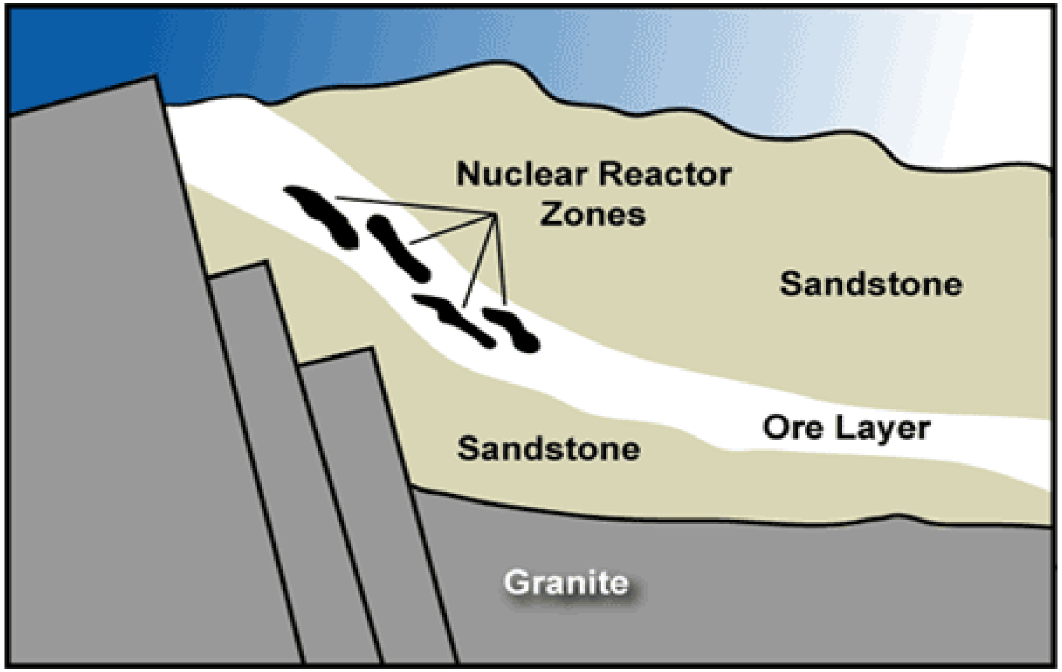
Kronan Bronze cannon

Total system geological analogues - Oklo

Natural chain reaction occurred in several ore bodies at this location around 2000 Ma ago: only cases ever found

Ore bodies remained effectively stable during long periods of chain reaction (~100 ka) and were still intact when discovered during mining

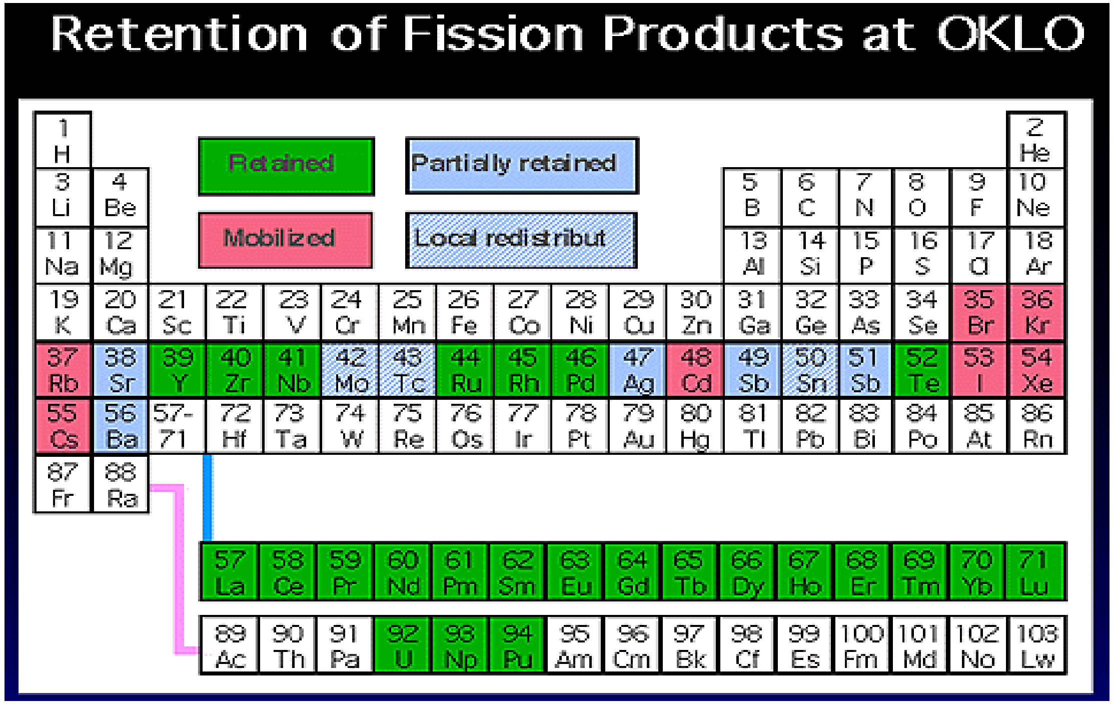


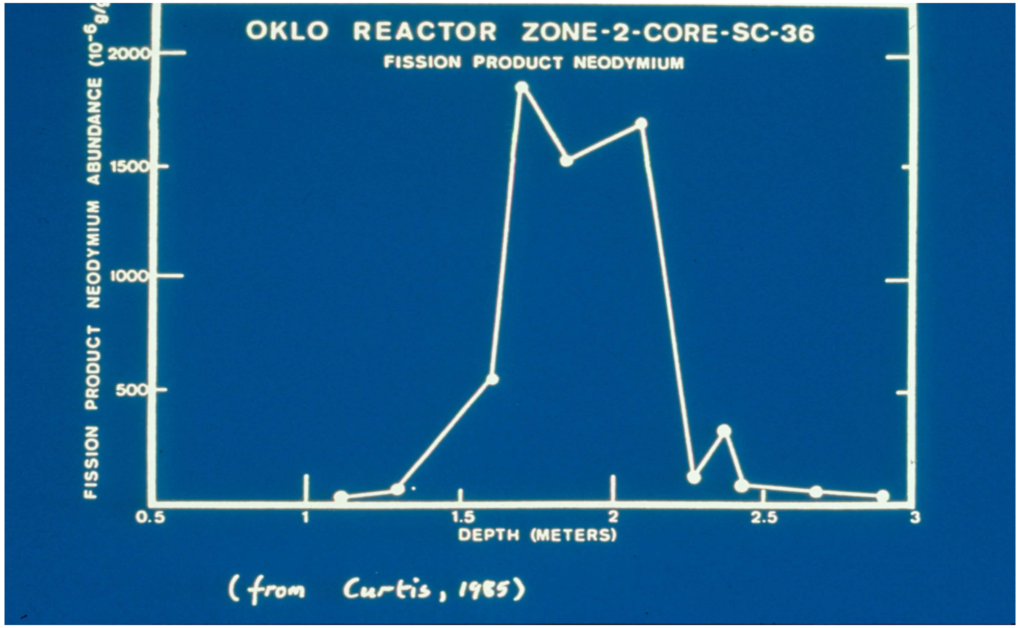


Oklo - synthesis

Conclusions

- Geological disposal is fundamentally feasible - in a suitably stable setting
- Criticality will not necessarily result in loss of isolation properties
- Pattern of retention / loss of RN broadly compatible with expected chemistry
- No evidence of oxidising conditions due to radiolysis - but availability of water may have been limiting factor





Unambiguous demonstration of deep geological isolation of radioactive wastes *for 2,000 million years*

Confirms our general understanding of the processes which lead to the immobilisation of waste radionuclides (Pu, fission products retarded, ^{135}Cs, ^{129}I mobilised)

Shows that radionuclides such as Pu are not just man-made

Oklo - limitations

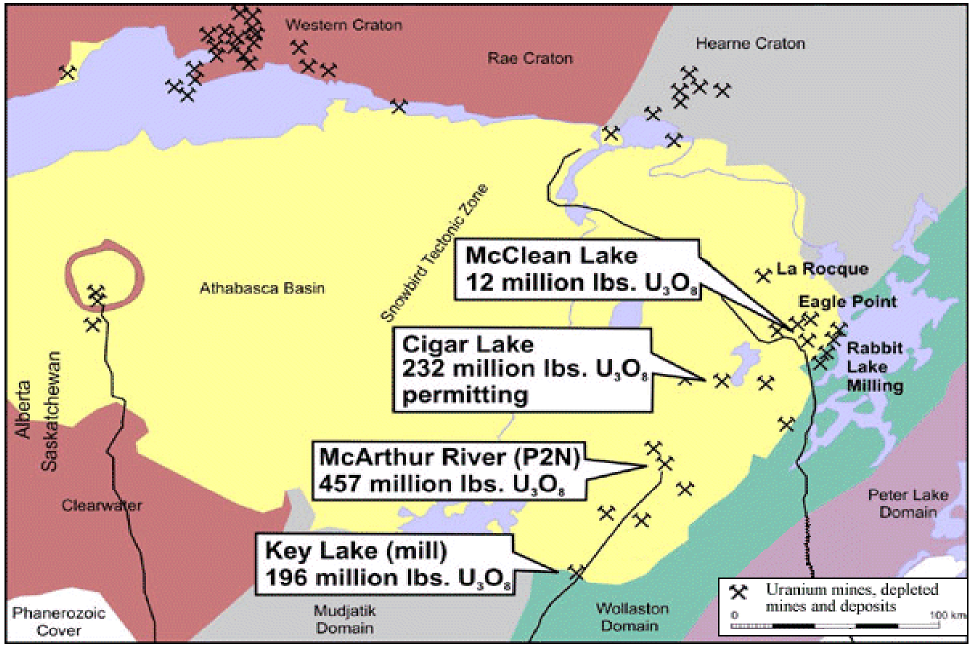
The analogue does NOT

- **Give any indication of feasibility of disposal at a different location**
- **Give any information on the probability or consequences of criticality at a repository site**
- **Allow radiolysis models to be validated**
- **Indicate that bitumen would be a suitable matrix for HLW!!!**
- **Give any support to disposal concepts above the water table!!!**

The Oklo analogue has attracted much attention, but its applicability to radioactive waste management is often greatly exaggerated

Cigar Lake

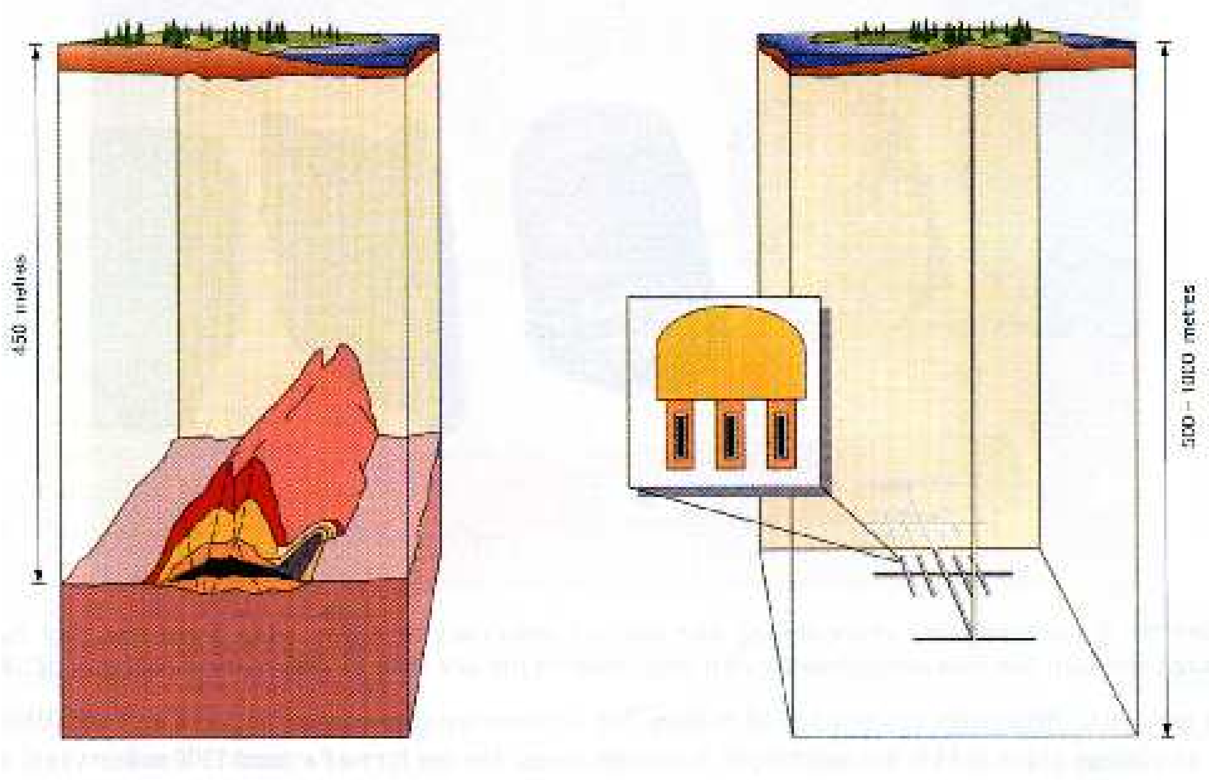
- Very long term (about 1300 Ma) stability of an extremely rich ore body (containing high concentrations of U and a range of other relevant elements including Ni, Co, Mo and Pb)
- Highly effective containment of radionuclides under present conditions with no significant surface radiological signature of the ore, despite the relatively high permeability of the host sandstone formation
- No evidence of criticality, but extensive radiolysis of water would be expected within this rich ore body
- The protective role of the surrounding clay-rich layer appears to function despite the presence of microbes, dissolved organics and colloids in pore waters



Athabasca Basin
courtesy of JNR Resources Inc.

Cigar Lake - Conclusions

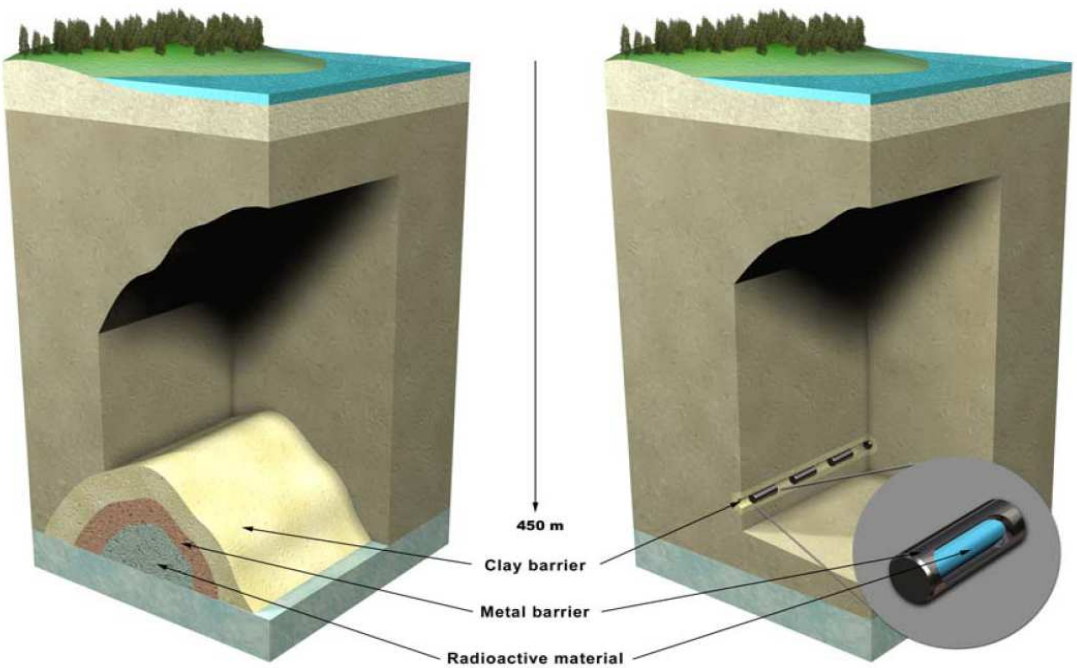
- Geological disposal is fundamentally feasible - in a suitably stable setting
- Clay-rich materials may contribute to preservation of U ore even in a rather permeable host rock
- Concentrations of specific elements in porewater generally compatible with predicted solubilities
- Fault movement will not necessarily disrupt an isolation system (self healing)
- Presence of colloids does not necessarily disrupt an isolation system
- No evidence of oxidising conditions due to radiolysis - but microbial activity may be a contributing factor



Cigar Lake - limitations

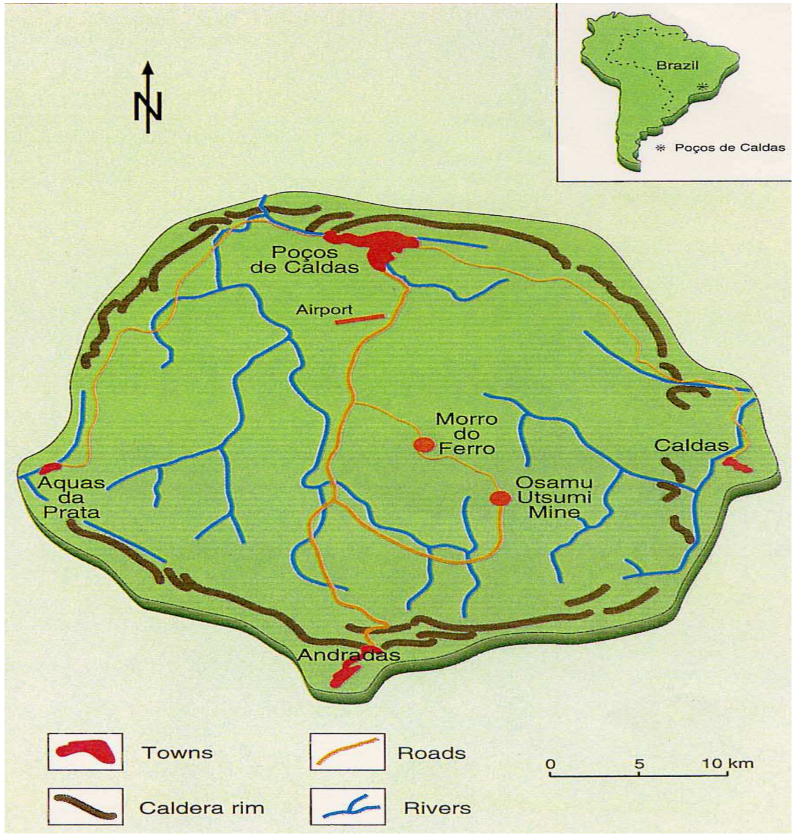
The analogue does NOT

- **Give any indication of feasibility of disposal at a different location**
- **Validate the longevity or performance of bentonite backfills or buffers**
- **Allow radiolysis models to be validated**
- **Validate chemical thermodynamic models or databases (variable agreement can as easily be interpreted as "invalidation")**
- **Provide any relevant information on the behaviour of specific RN based on measurements of ultra-trace concentrations**



Like Oklo, the Cigar Lake analogy to specific repositories is often exaggerated

Poços de Caldas - background



Examination of a range of processes occurring at 2 sites with the volcanic caldera of Poços de Caldas.

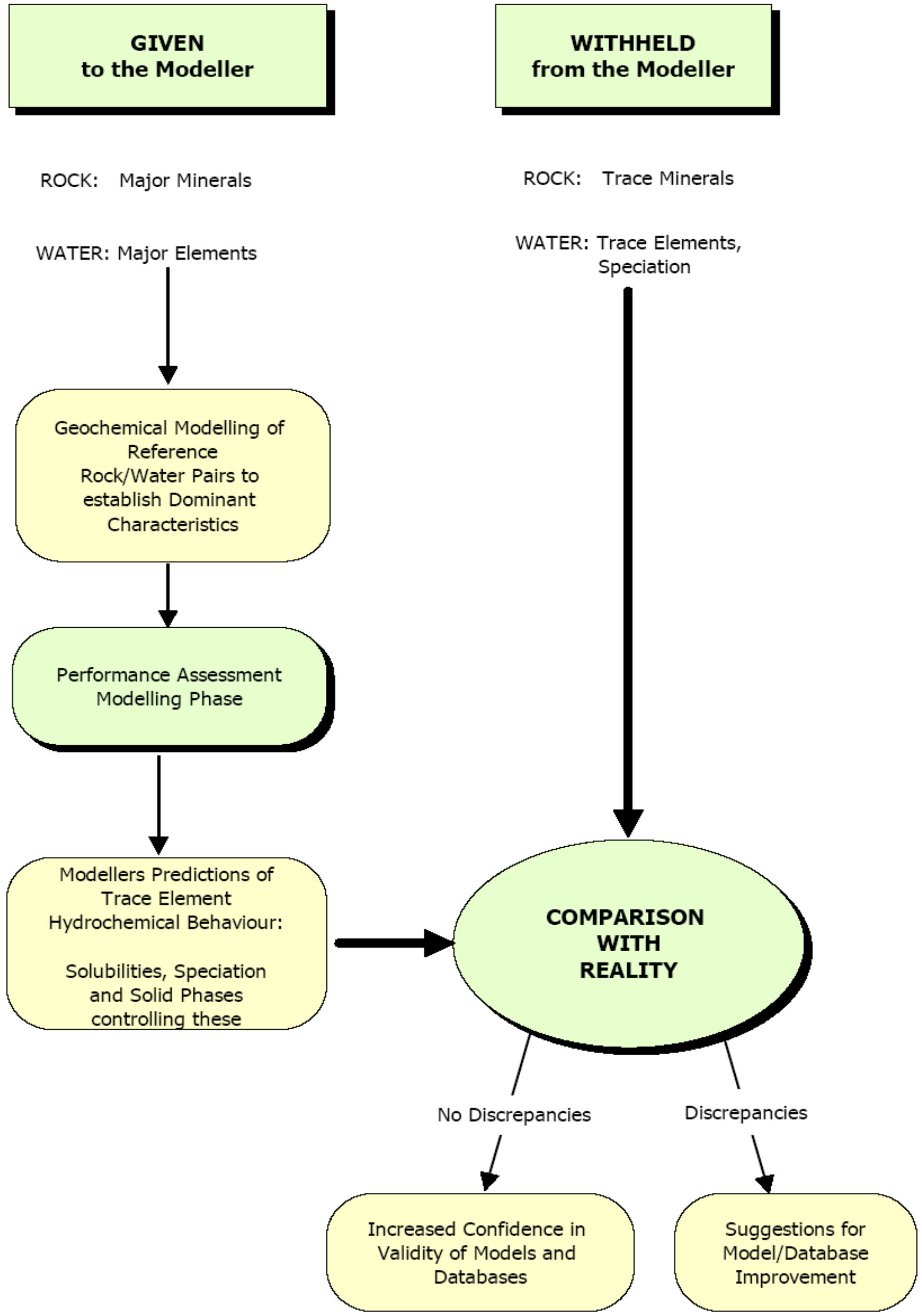
Main importance of the analogue is due to the approach rather than the sites studied:

- **Close technical coordination**
- **Strong support by the funding organisations and the mine operator**
- **Highly qualified international specialist working groups**
- **Comprehensive and timely production of a range of documentation**

Two sites examined:
Morro do Ferro; near surface high Th / REE ore body
Osamu Utsumi; open cast U mine showing distinct redox fronts

Poços de Caldas - Conclusions

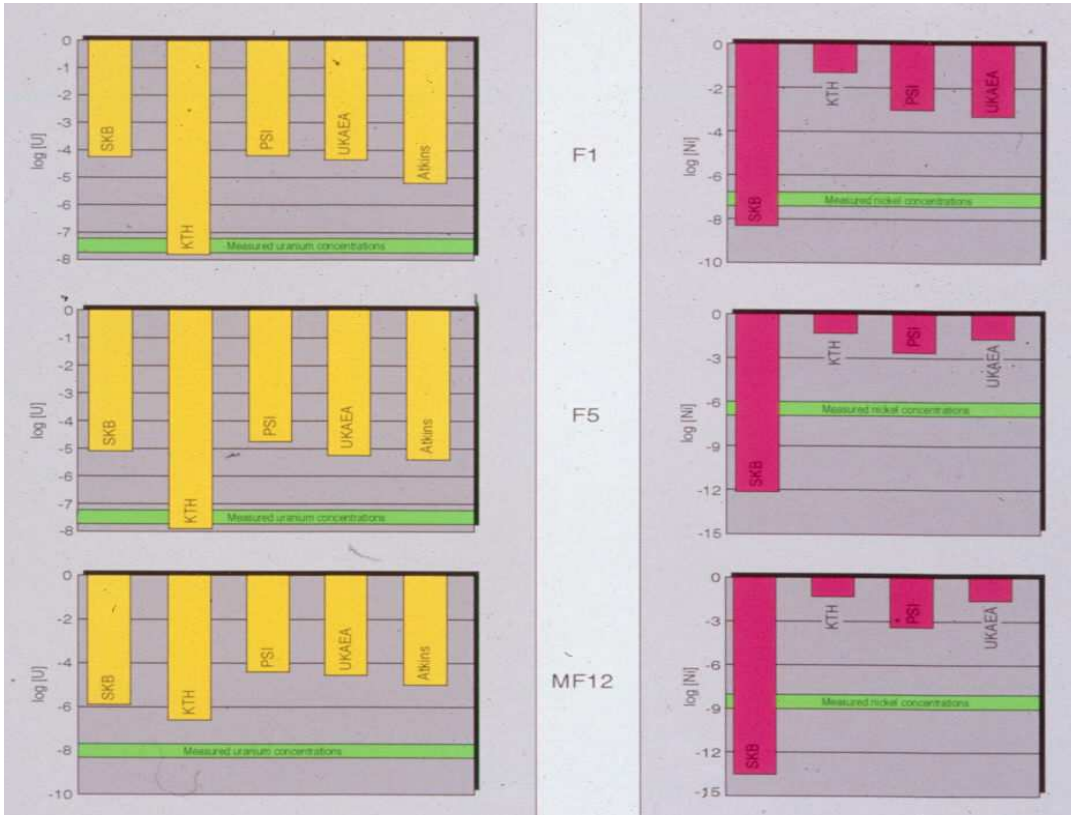
- Qualitative confirmation of RN immobilisation at redox fronts
- Qualitative demonstration of matrix diffusion of oxidants from fractures and the buffering capacity of the rock matrix
- Qualitative demonstration of microbial catalysis of redox processes associated with RN immobilisation
- Quantitative testing of chemical thermodynamic model predictions: clearly demonstrated some major problems
- Despite presence of colloids at Morro do Ferro, no evidence of their role in mobilisation of RN

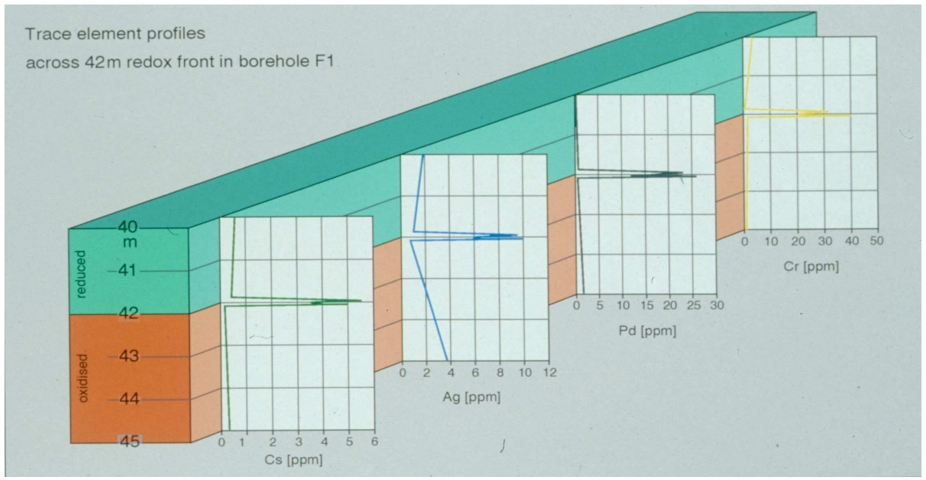


Poços de Caldas - limitations

The analogue does NOT

- **Validate the general use of chemical thermodynamic models**
- **Provide proof that colloids will not act as short circuits at repository sites**
- **Demonstrate conclusively that redox fronts will immobilise key RN in a repository setting**
- **Provide evidence on the role of matrix diffusion in a deep geological setting**
- **Validate redox front migration models**
- **Provide any support for high-temperature disposal concepts**

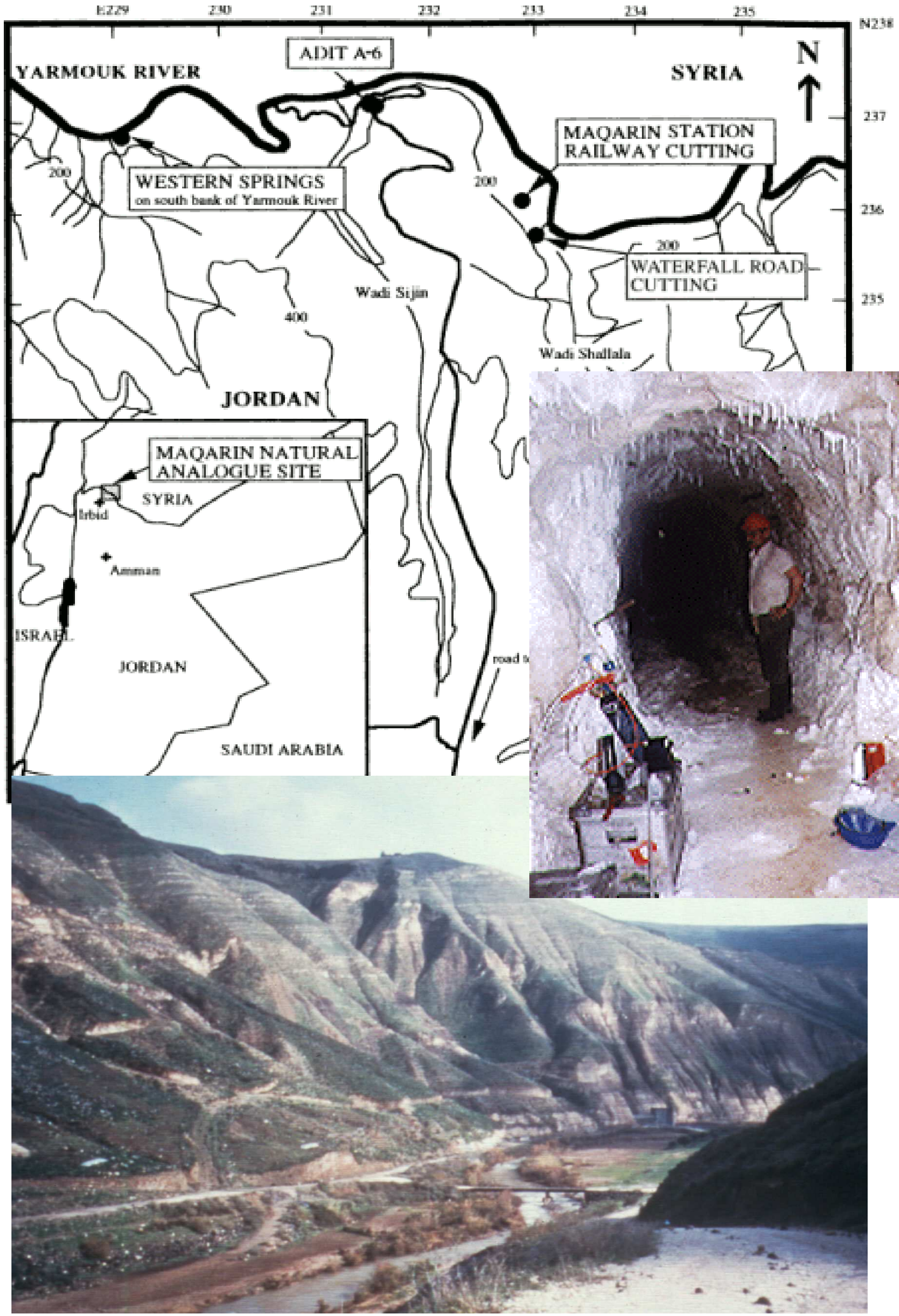




Maqarin

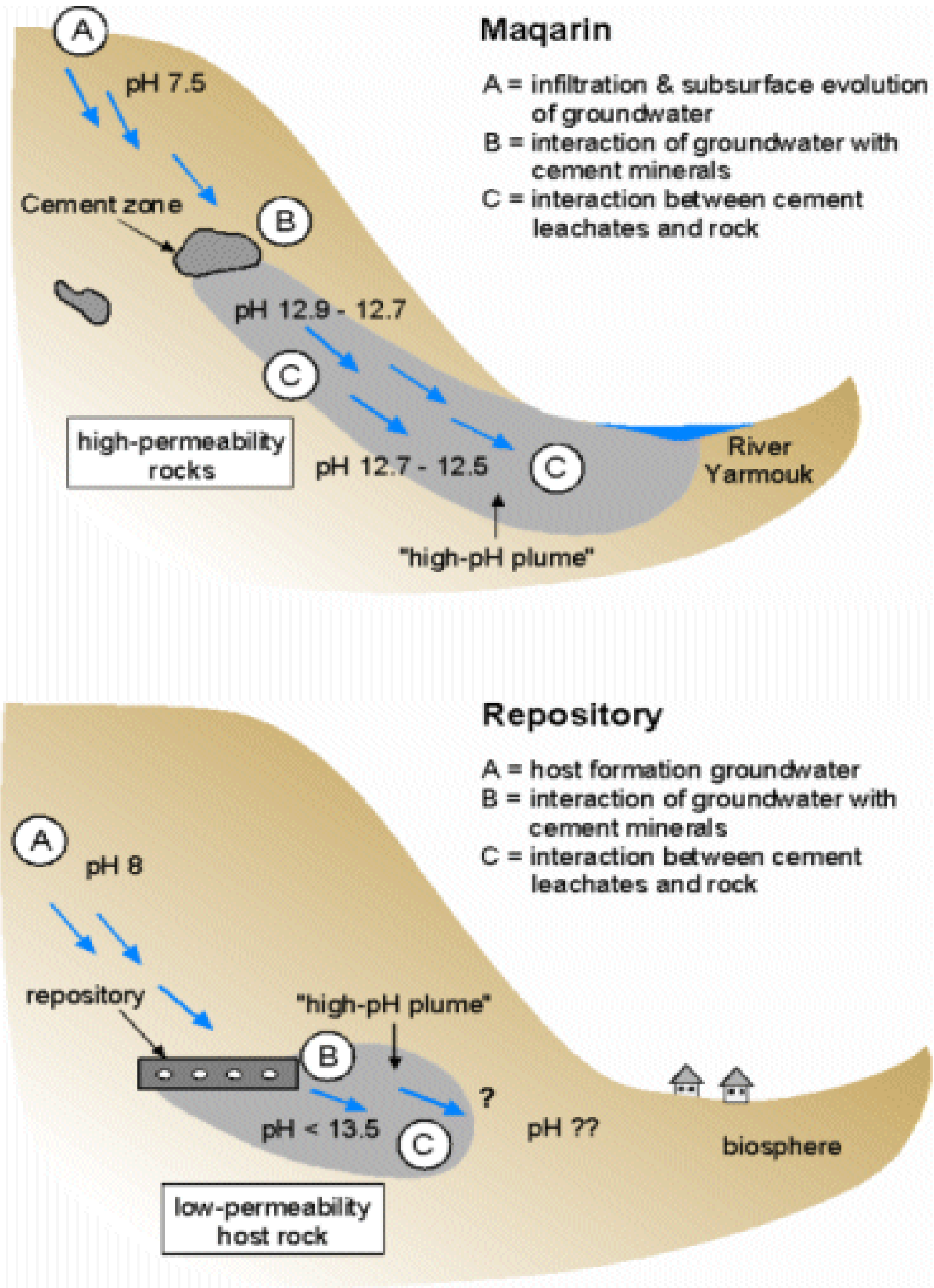
Unique example of ongoing leaching of natural cement produced by spontaneous combustion of a bituminous marl

- **Evidence for extensive penetration (100s of metres) of a high pH front in a fracture flow system**
- **Hyperalkaline waters have chemistry similar to leachates of industrial cements of different ages**
- **Hyperalkaline waters contain both colloids and microbes**
- **Particular focus of repository-relevant goals and relatively good (content / QA) publication record**



Maqarin - Conclusions

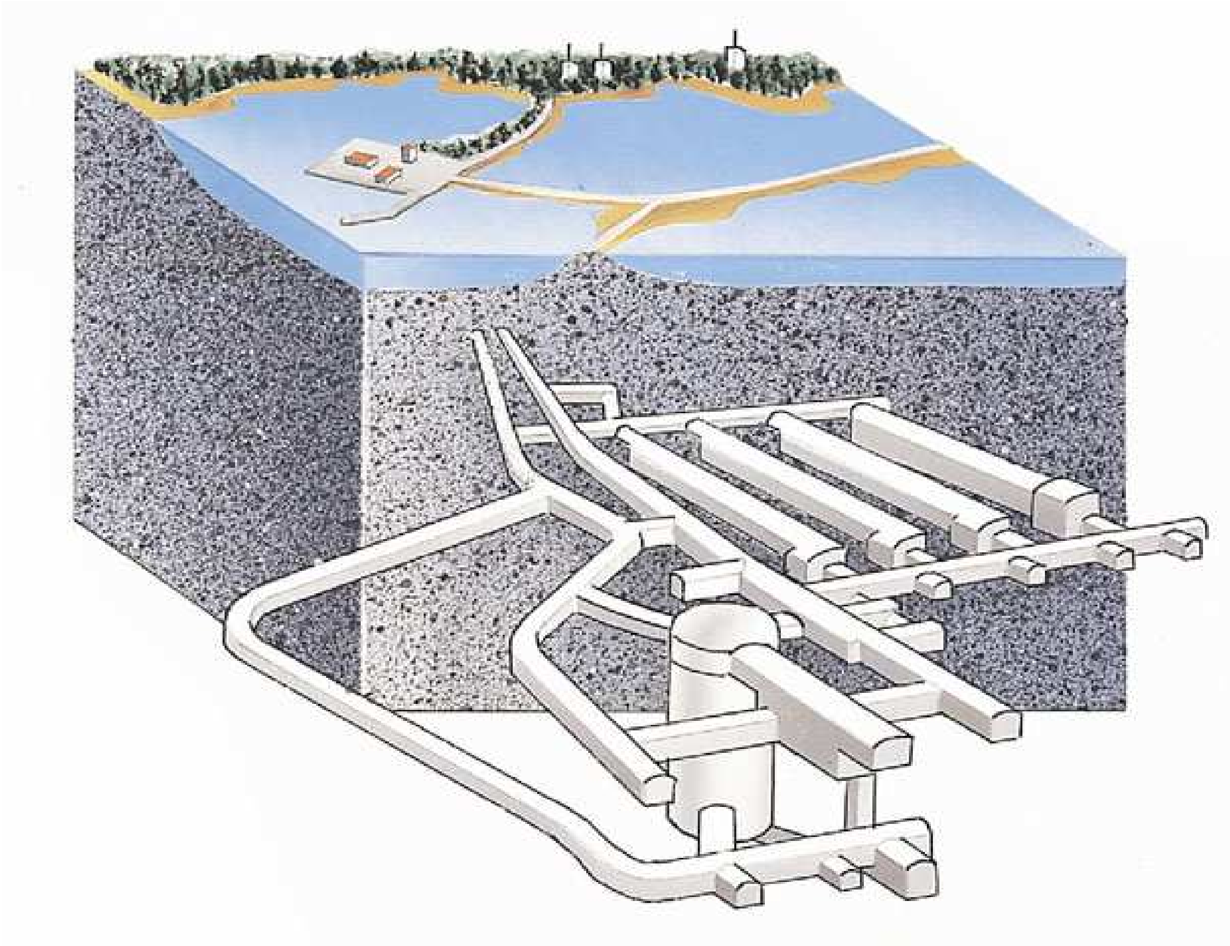
- Observed secondary phases and leachate chemistry are roughly consistent with models of cement leaching / aging
- Processes involved in hyperalkaline plume development also roughly consistent with fracture flow / rock alteration models
- Predicted sealing of flow system not seen - probably due to physical reactivation processes
- BPM of solute concentrations generally consistent with observations, but less agreement in terms of speciation
- Microbes are present in all waters and populations are less than conservative model predictions
- Colloids are present in all waters although predicted to be unstable at very high pH



Maqarin - limitations

The analogue does NOT

- **Validate cement leaching models**
- **Validate high pH plume migration models**
- **Validate chemical thermodynamic models of solubility / speciation**
- **Prove bitumen stability under hyperalkaline conditions**
- **Allow any testing of colloid migration models**

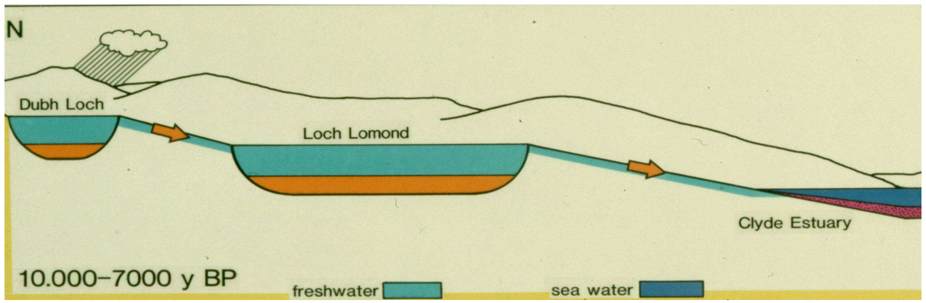


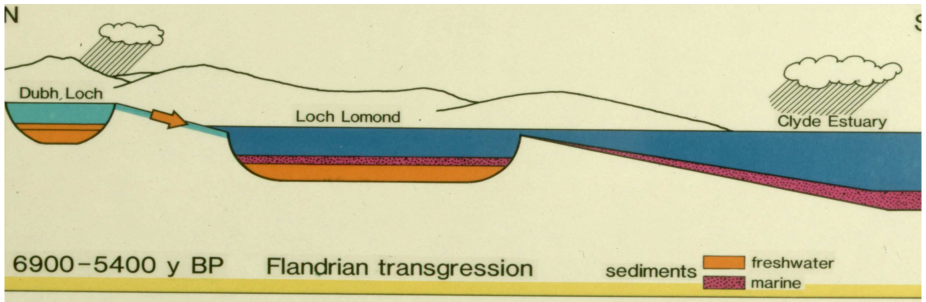
SFR repository: crystalline rock, salt water, many materials in addition to concrete, …

Loch Lomond

Well-dated geochemical anomaly resulting from marine transgression (sea-level changes as a consequence of deglaciation)

- Many elements concentrated in marine sediments or in the marine - fresh transition zones
- Profiles of some elements suggest diffusion from the marine layer
- Laboratory sorption experiments of safety-relevant elements show differences in behaviour in fresh & marine systems

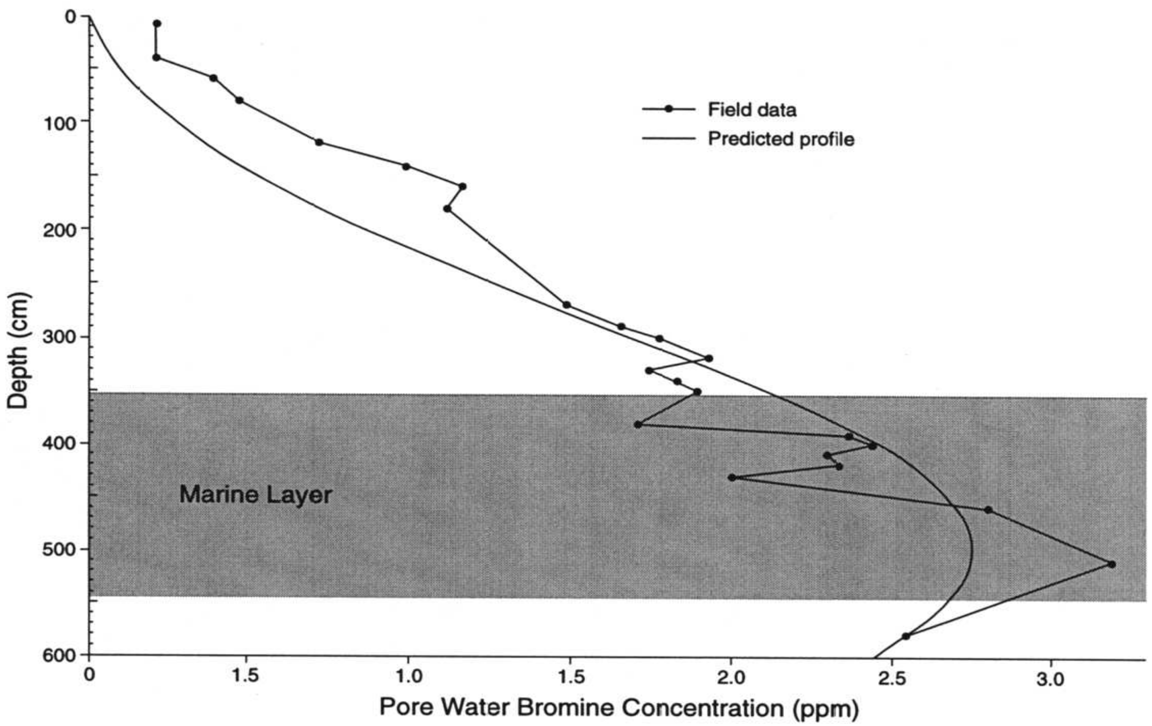




Loch Lomond

Conclusions

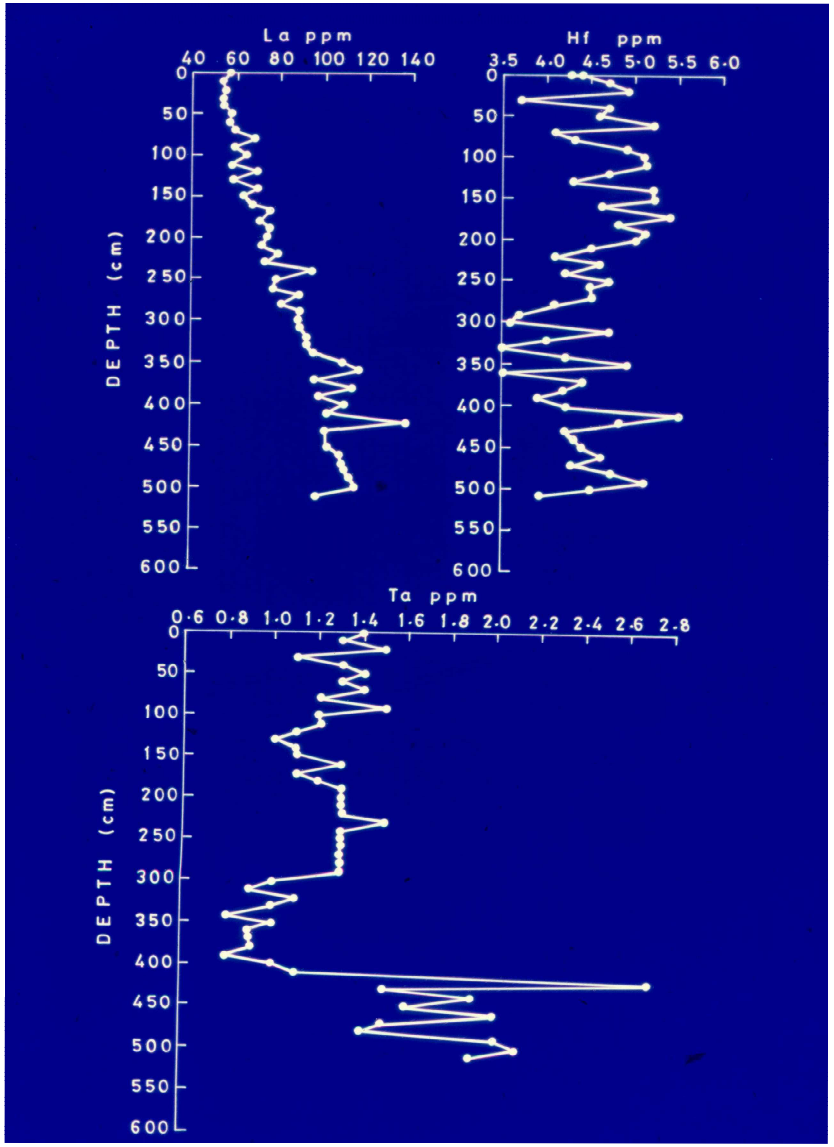
- Patterns of elemental redistribution generally consistent with expectations / laboratory sorption data
- Some safety-relevant elements (especially I) are much less mobile than expected - probably due to incorporation in immobile organic material
- Fresh-marine and marine-fresh transitions are distinctive with unexpected concentration of some safety-relevant natural series RN



Loch Lomond

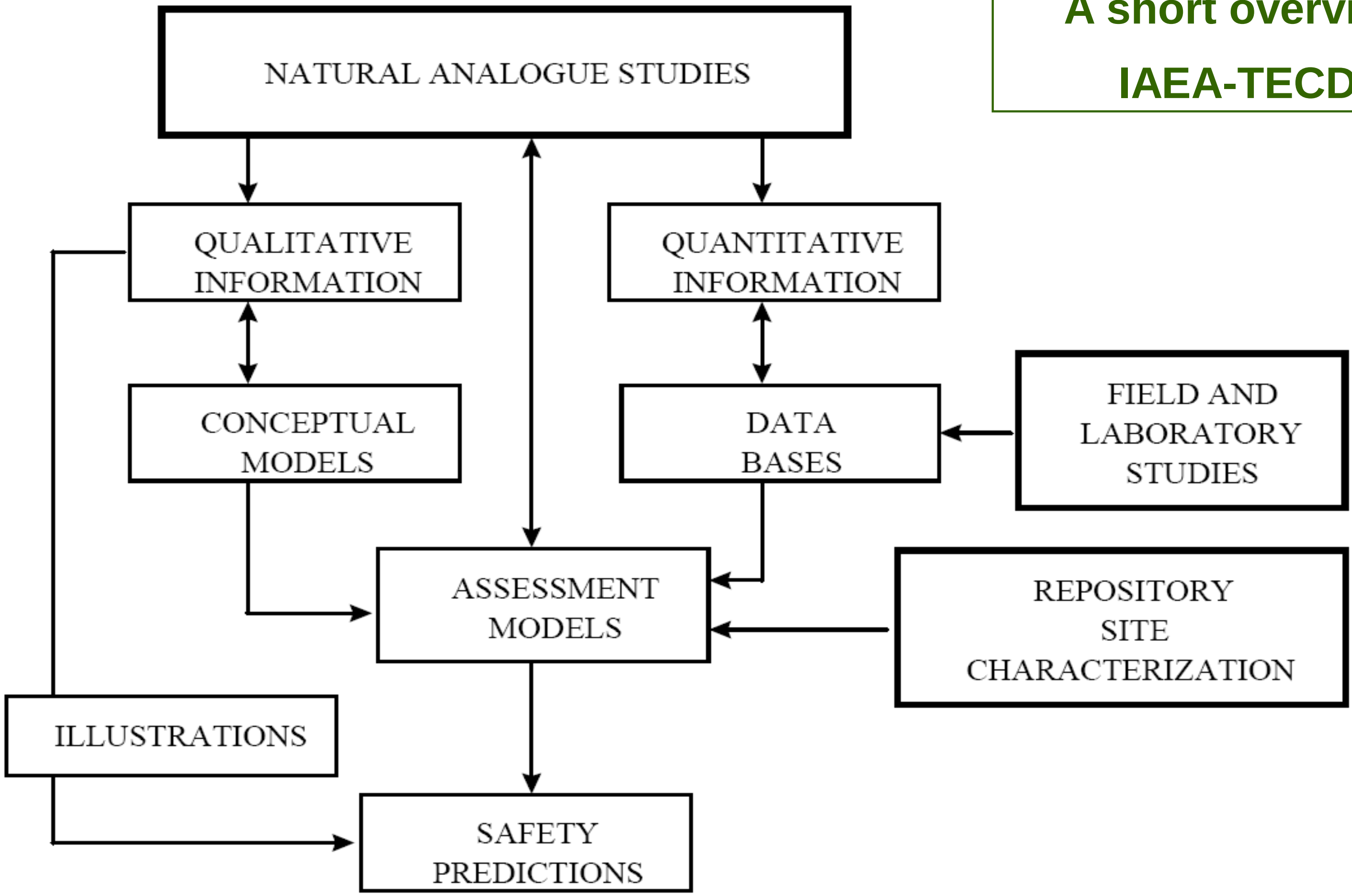
The analogue does NOT

- **Demonstrate the dominance of diffusion as a solute transport mechanism in deep argillaceous rocks**
- **Validate the performance of bentonite backfills or buffers**
- **Allow solute transport models or applicability of laboratory sorption measurements to be validated**
- **Provide any hard information on the behaviour of specific RN during fresh - salt water transitions in deep geological systems; qualitative information applicable only to near-surface / biosphere**



How have NA been used in Performance Assessment?

- To aid or support conceptual model development
- To provide data
- To assist in model validation



A short overview is provided by IAEA-TECDOC-1109 (1999)

Actual use of analogues

Safety Case	Conceptual model development	Data provision	Model validation
KBS-3 (Sweden, 1983)	Radiolytic oxidation of spent fuel against observations from Oklo	Maximum pitting corrosion factor for Cu Bentonite stability at T<100^{oC}	
Projekt Gewähr (Switzerland, 1985)	Stability of borosilicate glasses Stability and instability of concretes and mortars Stability of bitumen Radionuclide release concepts against Oklo observations	Long-term steel corrosion rates Constrain illitisation of bentonite	
SKB-91 (Sweden, 1991)	Support of bentonite stability from observations at Gotland Redox front model supported by Poços de Caldas observations Inclusion of matrix diffusion	Limit relevance of colloid transport by using data from Poços de Caldas Demonstrate conservatism in estimating radiolytic oxidation by using information from Cigar Lake	Radionuclide solubility model testing and comparison with observed solubilities at Poços de Caldas and Cigar Lake
TVO (Finland, 1991)	Use of palaeohydro-geological data in the development of Ice-age scenarios Observations from Cu-deposits and Kronan canon to support corrosion estimates Use of colloidal and microbial information from Poços de Caldas and Palmottu to develop models	Matrix diffusion profiles surveyed from various natural analogues	Testing of UO_2 spent fuel dissolution models using information from Cigar Lake

Actual use of analogues

Safety Case	Conceptual model development	Data provision	Model validation
Kristallin-I (Switzerland, 1993)	Back-up in scenario development	Bounding conditions on redox front development using information from Poços de Caldas Depths of matrix diffusion penetration	Radionuclide solubility model testing and comparison with observed solubilities at Poços de Caldas, Oman and Maqarin Testing models for redox front development
PNC 1st Progress Report (H3) (Japan, 1993)		Bounding values for metal corrosion (archaeological analogues) and bentonite longevity)	
AECL EIS (Canada, 1994)	Support development of conceptual models for fuel dissolution, Cu corrosion, clay buffer behaviour and radionuclide retardation, particularly the role of colloids and organics	Geochemical processes and parameter values for redox control on UO_2 stability (incl. radiolysis bounding values), Cu corrosion, bentonite-to-illite conversion, and radionuclide retardation (incl. matrix diffusion bounding values)	Testing of models and databases for radionuclide solubility, colloid formation and organic complexation, and Cu corrosion, using observations from Cigar Lake, the Canadian Shield and Kronan cannon
NRC IPA (USA, 1995)	Disruptive scenario development (volcanism) Back-up source term conceptual model from Peña Blanca Relative importance of meso-microfracture and matrix transport at Peña Blanca Back-up for vapour phase transport from Valles Caldera Back-up conceptual model for transport in fractures	Identification of secondary phases for long-term release at Peña Blanca	Model testing for elemental transport in unsaturated media at Akrotiri

Actual use of analogues

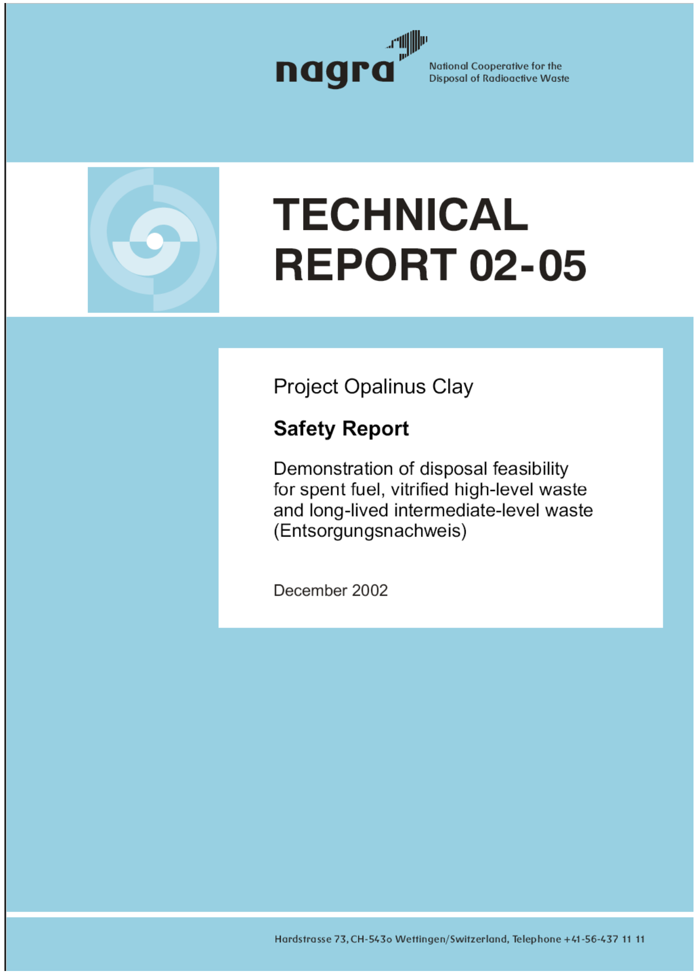
Safety Case	Conceptual model development	Data provision	Model validation
TILA-99 (Finland, 1999)		Support for conservatism in assumptions regarding spent fuel dissolution rate using observations from Cigar Lake; occurrence of matrix diffusion; and canister life time with reference to the Hyrkkölä native copper occurrence	
SR-97 (Sweden, 1999)	Use of permafrost data in development of Ice-age scenarios Use of post-glacial tectonic data in development of Ice-age scenarios	Bentonite stability related to temperature effects; availability of potassium. Clay as a barrier to microbial activity (i.e. Dunarobba) Gas transport in shales Insignificant colloid concentrations at repository depths Bounding calculations supporting reducing conditions at repository depths Incursion of oxidising meteoric waters Lack of mineralogical evidence for Fe(II) oxidation	Justification of model for radiolytic oxidation of UO_2 Reference to matrix diffusion data for model testing (Palmottu and Cigar Lake) Testing models of redox front propagation using observations from Poços de Caldas Development and testing of groundwater mixing model (Palmottu and Oklo)
SFR (Sweden, 1999)	Support for long-term durability of concrete barrier system using observations from Scawt Hill, N. Ireland, Maqarin and ancient/aging concrete structures Hyperalkaline plume scenario using observations from Maqarin	Hydrogeochemical processes and parameter values for released hydroxides due to leaching; CSH and CASH phases; zeolite phases; pH reduction due to reaction with silicate minerals; and colloids/microbes/organics	'Blind Modelling': (Sweden, 1999) Testing of thermodynamic databases at Oman and Maqarin

Actual use of analogues

Safety Case	Conceptual model development	Data provision	Model validation
1st TRU Progress Report (Japan, 2000)	Maqarin used for high pH plume concept development	Matrix diffusion depths (from H12 database)	Longevity of concrete with archaeological analogues
JNC 2nd Progress Report (H12) (Japan, 2000)	Range of archaeological analogues to support iron corrosion model / mechanisms Natural bentonite to support longevity assumptions	Matrix diffusion depths from Kamaishi natural series profiles Volcanic glass studies to support corrosion model	Analogue evidence to support solubility data

Entsorgungsnachweis

- **The most recent integrated SA from Nagra (deep disposal of SF / HLW / TRU in a sedimentary host rock)**
- **Safety report (NTB 02-05) contains 12 mentions of natural analogues in 472 pages.**
- **Definition not included, but comparisons with natural fluxes to put doses in perspective is considered separately (Appendix 3). Use of natural elemental and isotope profiles and palaeohydrogeology to characterise host rock properties also not considered as analogues.**
- **Applications include:**
  - **natural bentonite analogue to argue for slow rates of illitisation**
  - **slow bentonite alteration at temperatures up to 130°C**
  - **retention of bentonite swelling / plasticity even after alteration**
  - **low permeability and sorption properties of bentonite**
  - **low corrosion rates of glass, copper and steel**
  - **validation of codes and databases, particularly with regard to long timescales**


nagra
National Cooperative for the Disposal of Radioactive Waste

TECHNICAL REPORT 02-05

Project Opalinus Clay

Safety Report

Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis)

December 2002

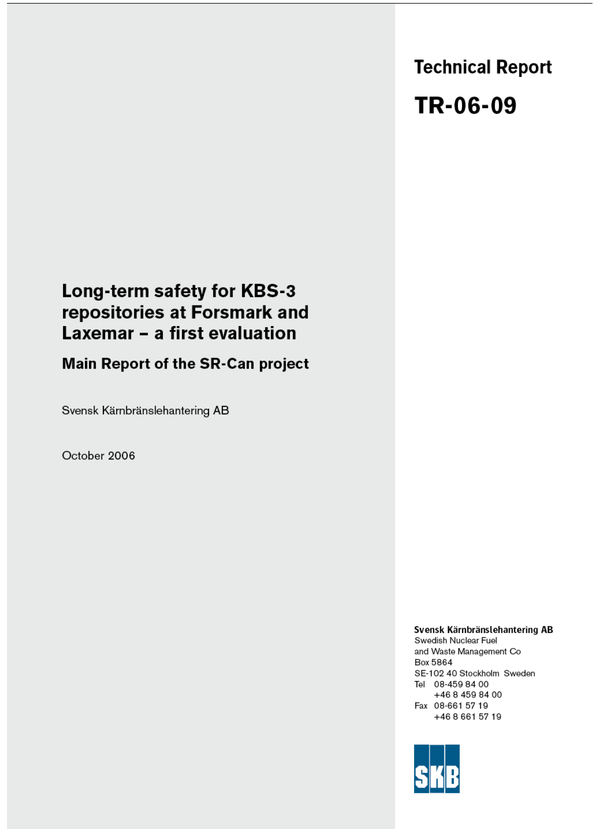
Hardstrasse 73, CH-5430 Wettingen/Switzerland, Telephone +41-56-437 11 11

SR-Can

- **The most recent integrated SA from SKB (deep disposal of SF in a crystalline host rock)**
- **Summary report (TR-06-09) contains 12 mentions of natural analogues in 620 pages.**
- **Definition: rather limited**

Natural analogues	A natural system studied in order to make it possible to investigate processes that have proceeded for a much longer time than can normally be followed by experiments in the laboratory or in the field.

- **Most mentions (5) in a single short section (13.3.7) explaining use of analogues and giving examples of:**
  - **support of Cu corrosion rates**
  - **natural bentonite as a buffer analogue**


Technical Report

TR-06-09

Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation

Main Report of the SR-Can project

Svensk Kärnbränslehantering AB

October 2006

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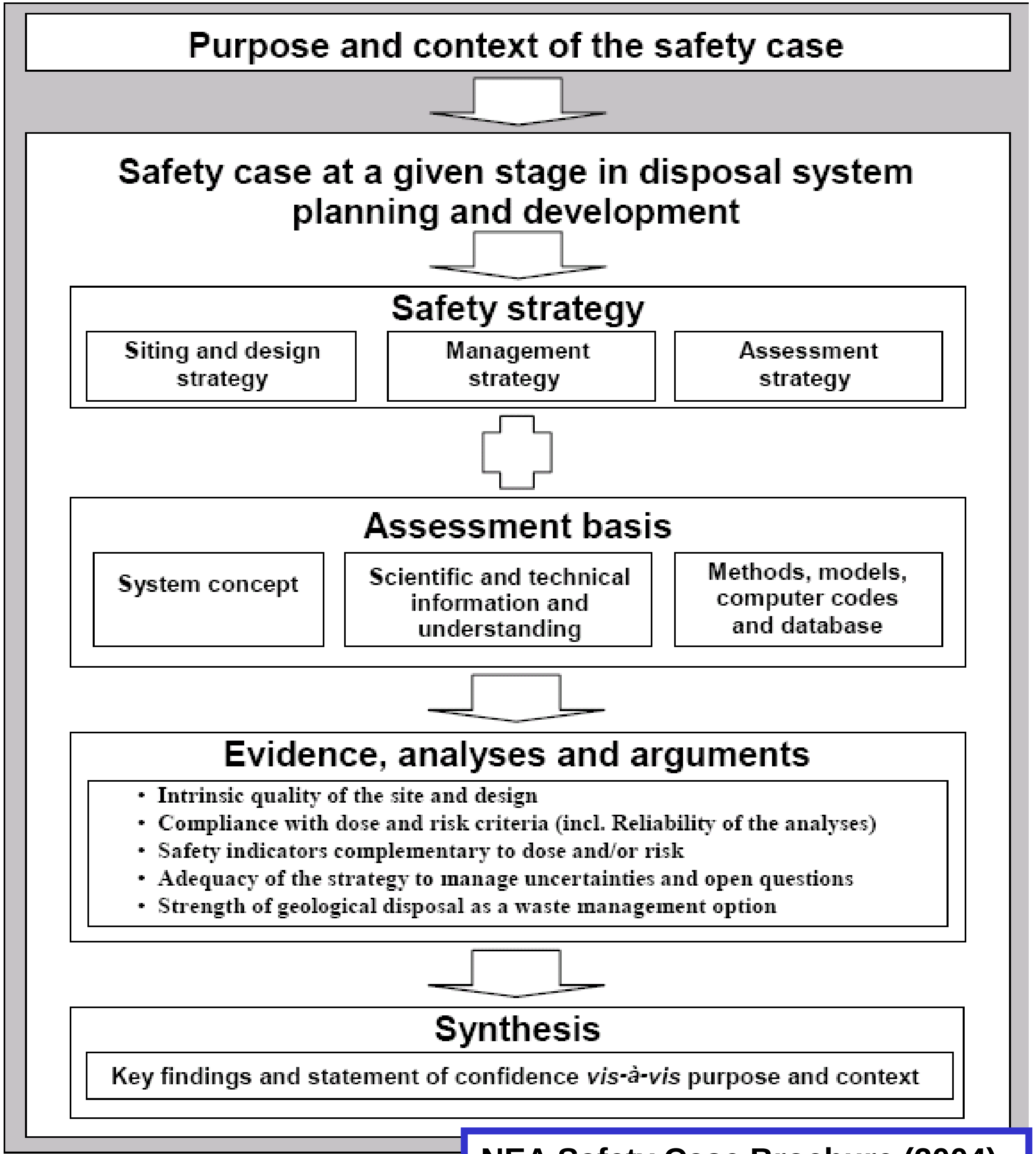
SKB

Future trends

The requirements for preparation and presentation of safety cases are becoming more rigorous:

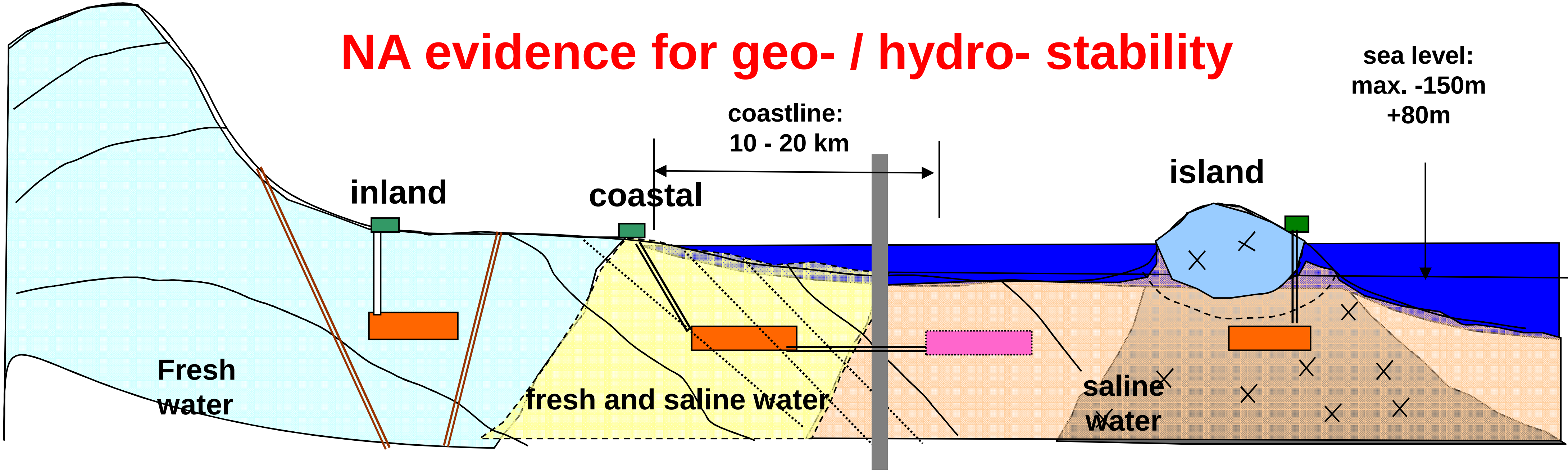
- NA will be expected to play a bigger role in technical support of the assessment - in particular supporting key models
- NA will also be needed to aid communication to a wide range of stakeholders

IAEA: Safety Standards for Geological Disposal
"The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility."

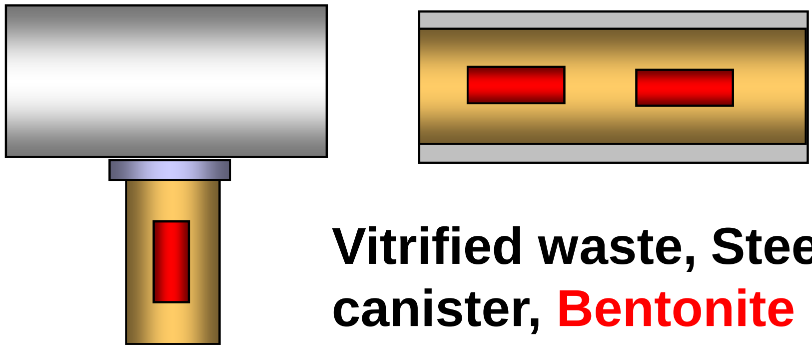


NEA Safety Case Brochure (2004)

Focus NA on project-specific concerns

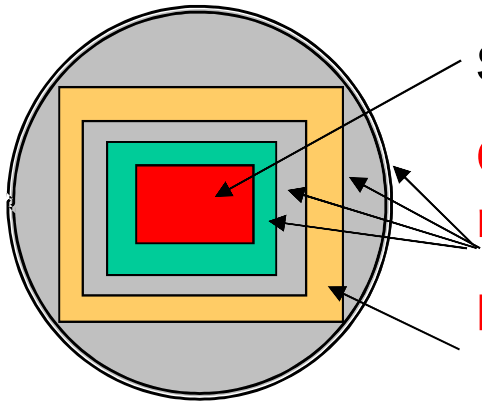


HLW EBS concept



Vitrified waste, Steel canister, Bentonite buffer, Concrete lining

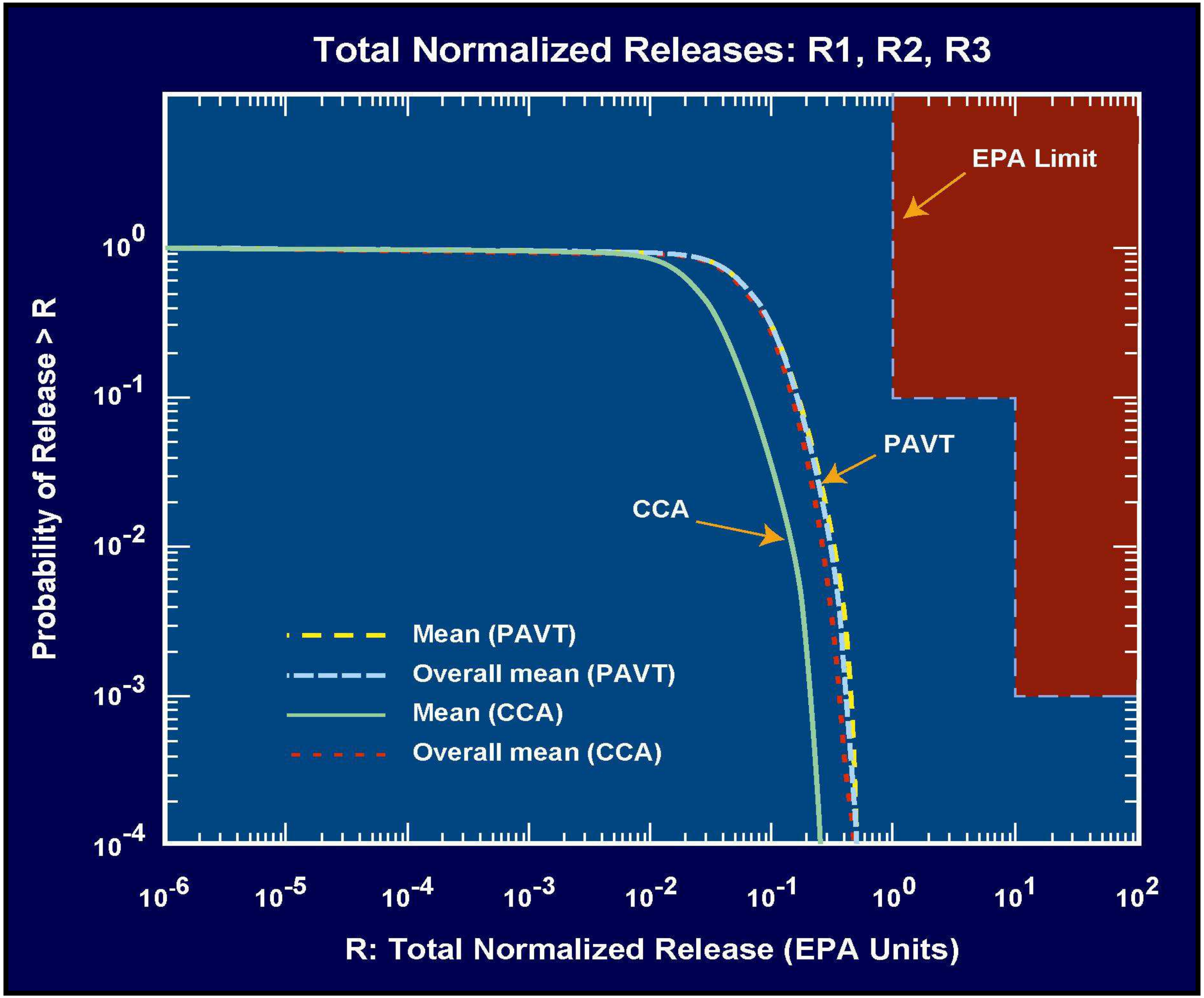
TRU EBS concept



Presenting model results

PA modelling produces complex data

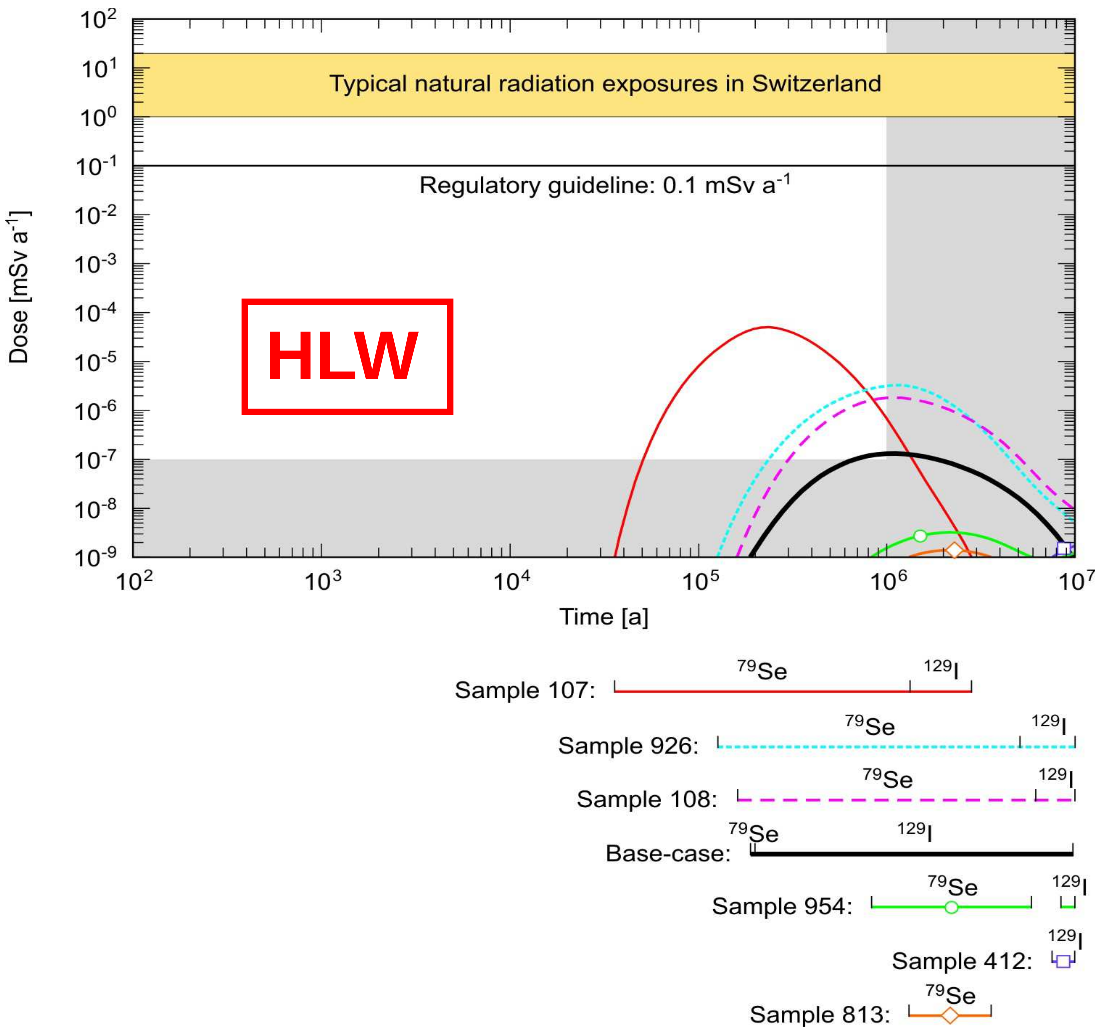
- **Often presented in complex illustrations that need to be carefully interpreted**
- **Most difficult case is probably the CCDF, commonly used in the USA**
- **Such presentation of the results from a fully probabilistic analysis is very controversial and understood by few in the radwaste business**
- **...there has also never been an NA study that rigorously supported probabilistic analysis**

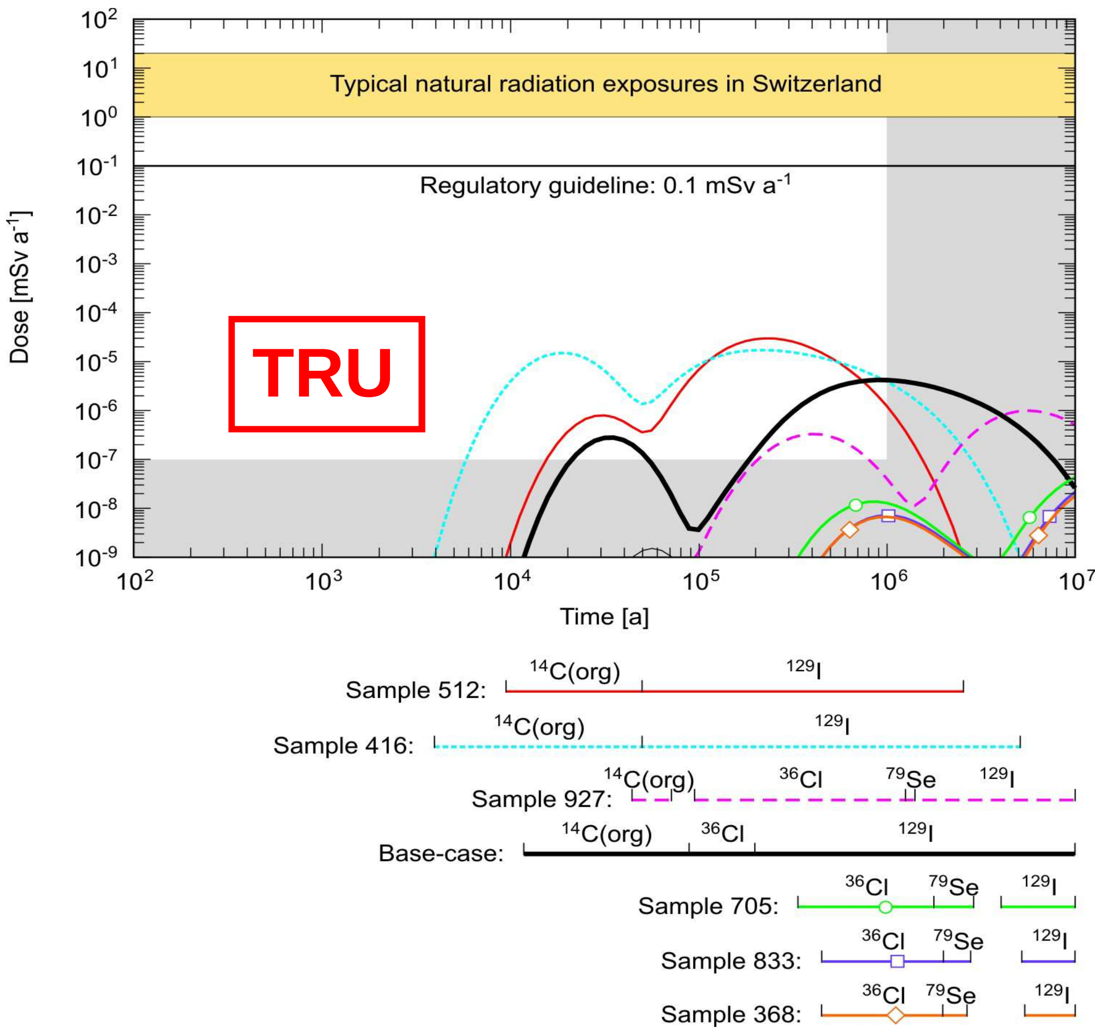


Log – Log plots from deterministic analysis

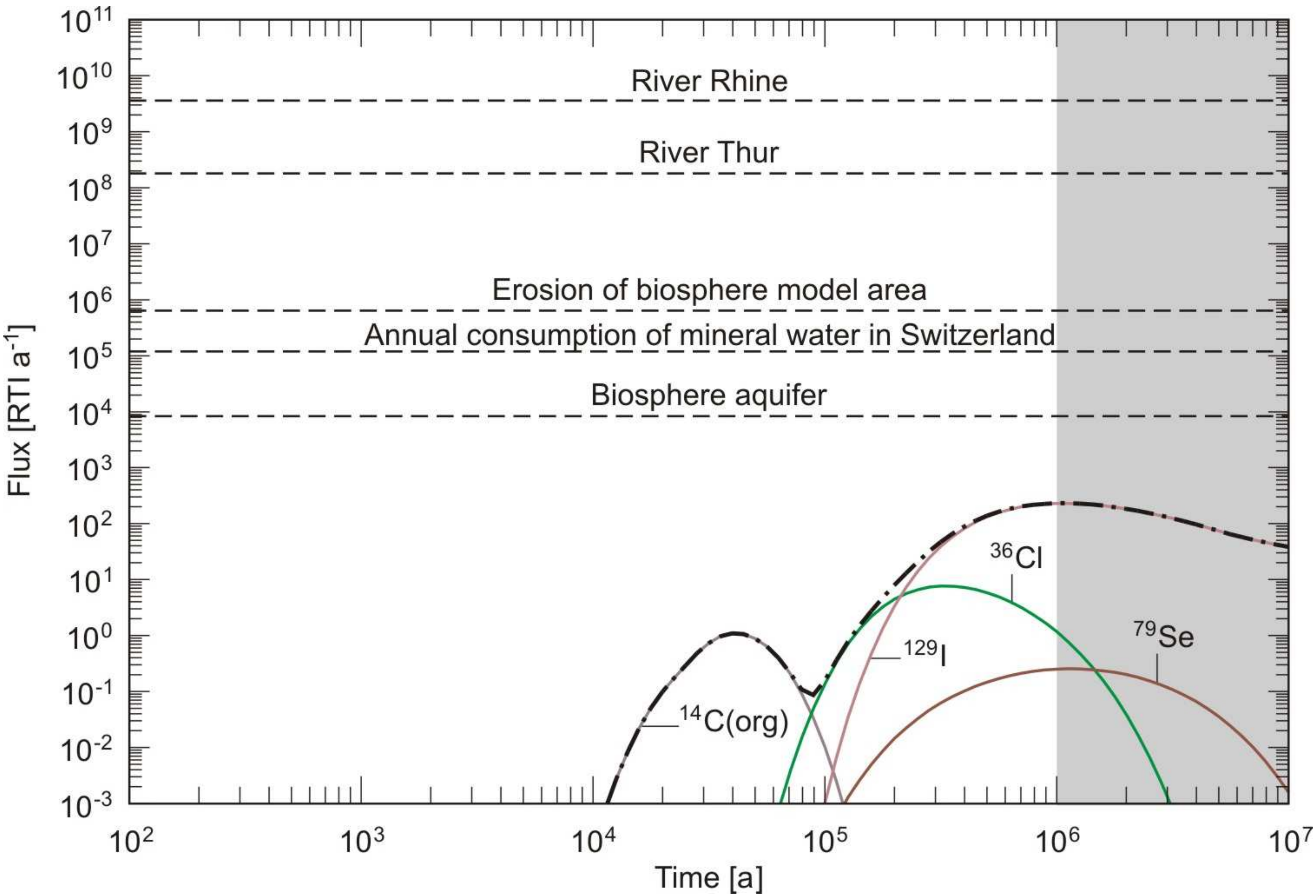
Useful for comparison of performance of different wastes, designs, etc., but

- **interpretation can be tricky (e.g. areas under curves can be misleading)**
- **confusing for general public**



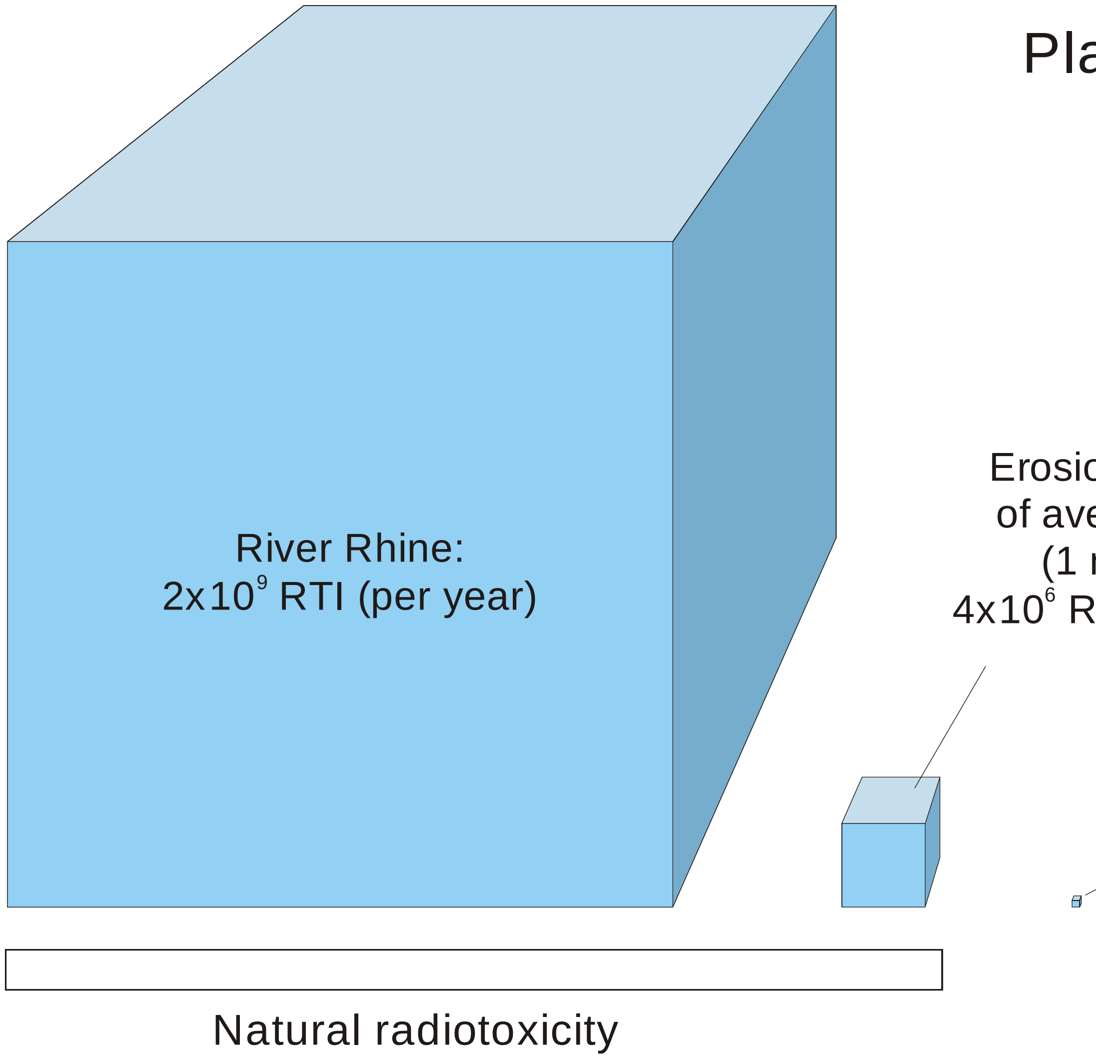


Radiotoxicity flux from the repository vs. Flux due to natural material



Radiotoxicity flux from the repository vs. Flux due to natural material – simpler display

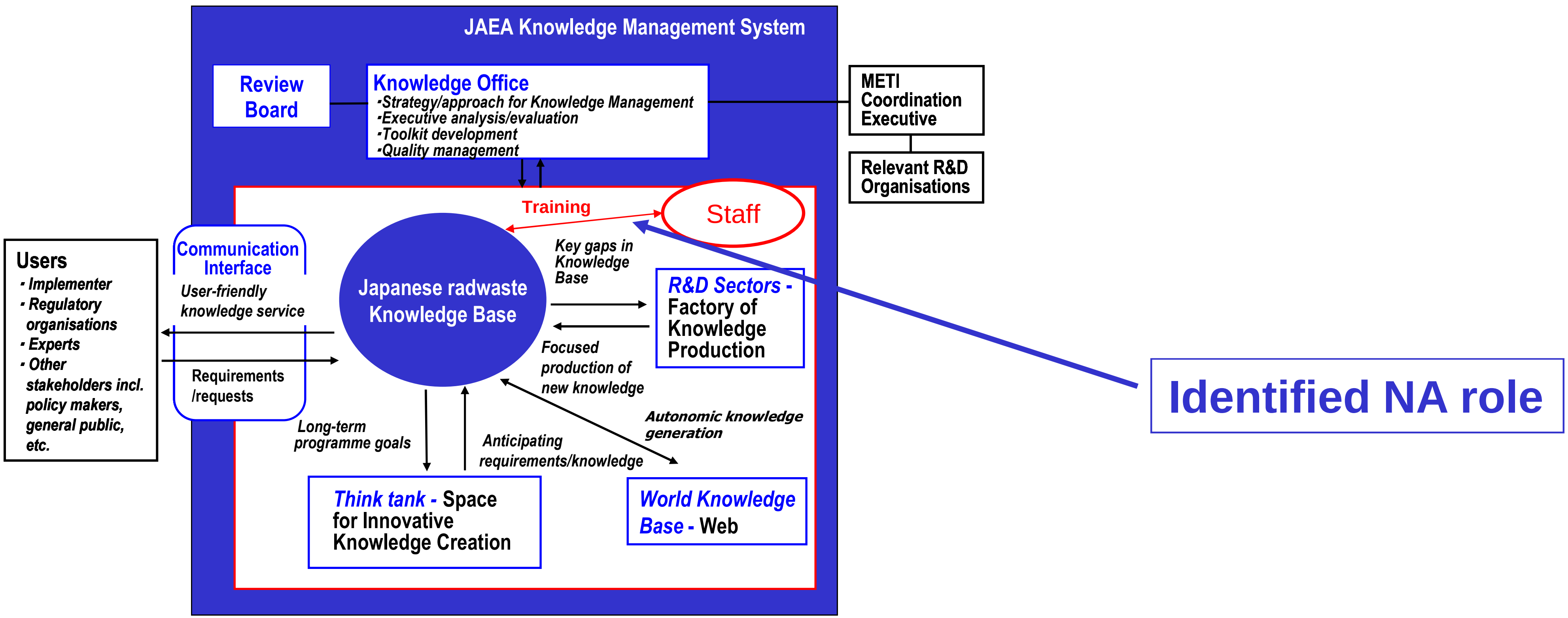
Placing the calculated maximum release rate to the human environment in perspective



A special requirement - training

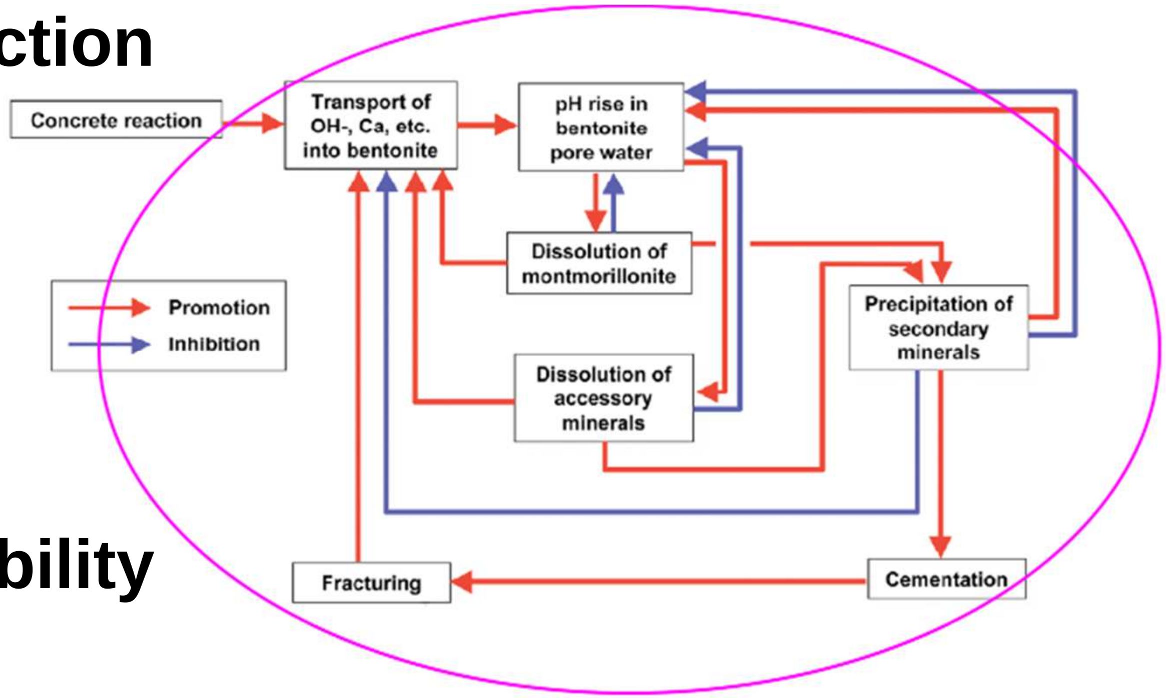
With expanding volumes of information accumulated in national programmes, Knowledge Management is now a critical issue:

- **a particular concern is maintaining the tacit knowledge possessed by expert staff**
- **complex, multi-goal NA project identified as an efficient method of experience transfer**



Possible new NA projects

- **Bentonite - concrete interaction**
  - **Philippines**
  - **Cyprus**
- **New multi-task project**
  - **e.g. Poços**
- **Project focused on site stability**
  - **coastal analogue project**
- **New international video project**
  - **concept developed (US DoE)**



Summary & Conclusions

- NAs play a key role supporting integrated safety assessments
- To date, use in most assessments has been rather limited
- With increased focus on rigorous safety case development and presentation, use of NAs likely to expand significantly
- In addition to purely technical roles, use of NAs for enhancing credibility and, especially, training will probably increase
- Much can be done with data-mining, but new projects are also needed
- NAWG might act as a catalyst to future developments