Deep Borehole Disposal of Spent Fuel and Other Radioactive Wastes
An International Overview

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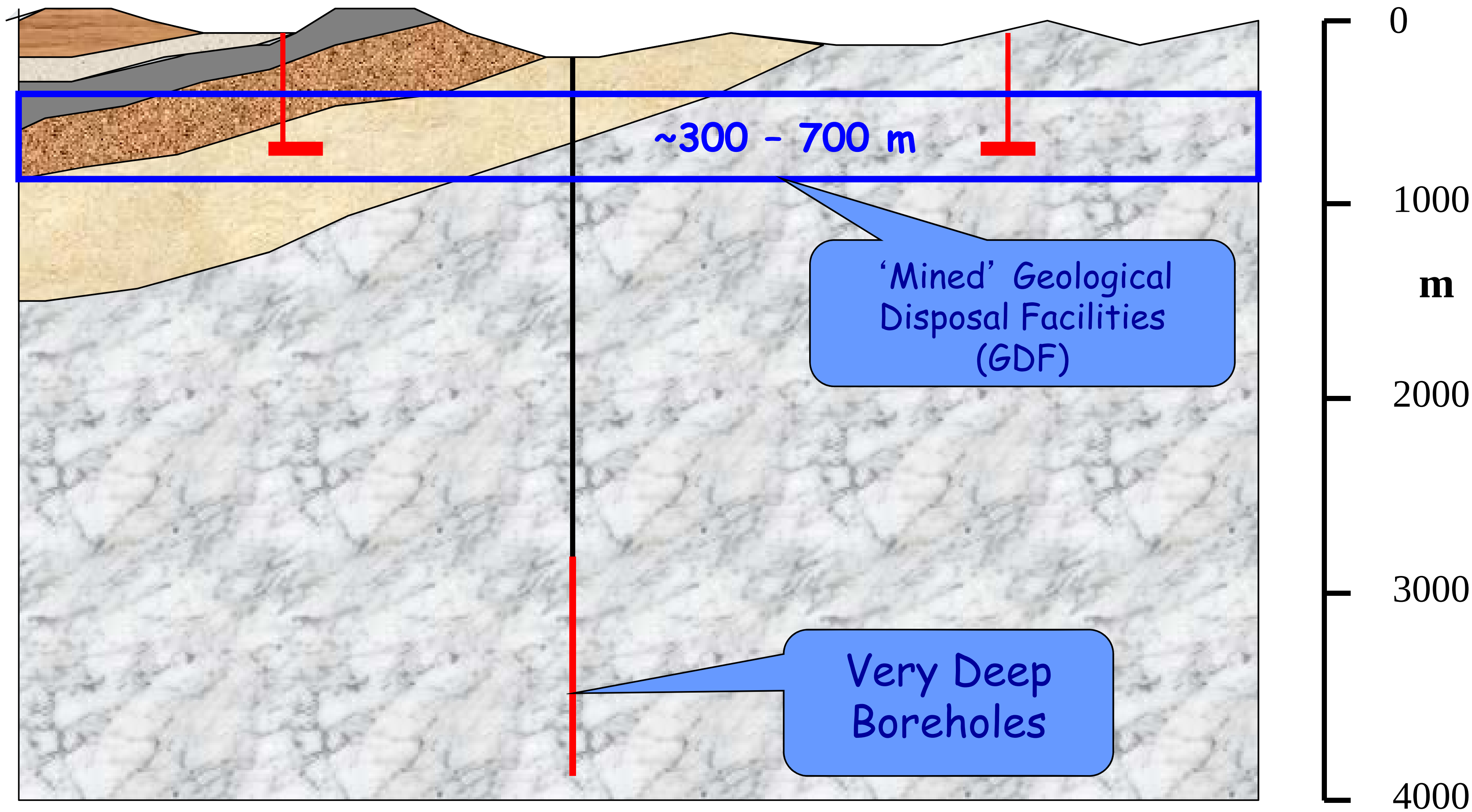
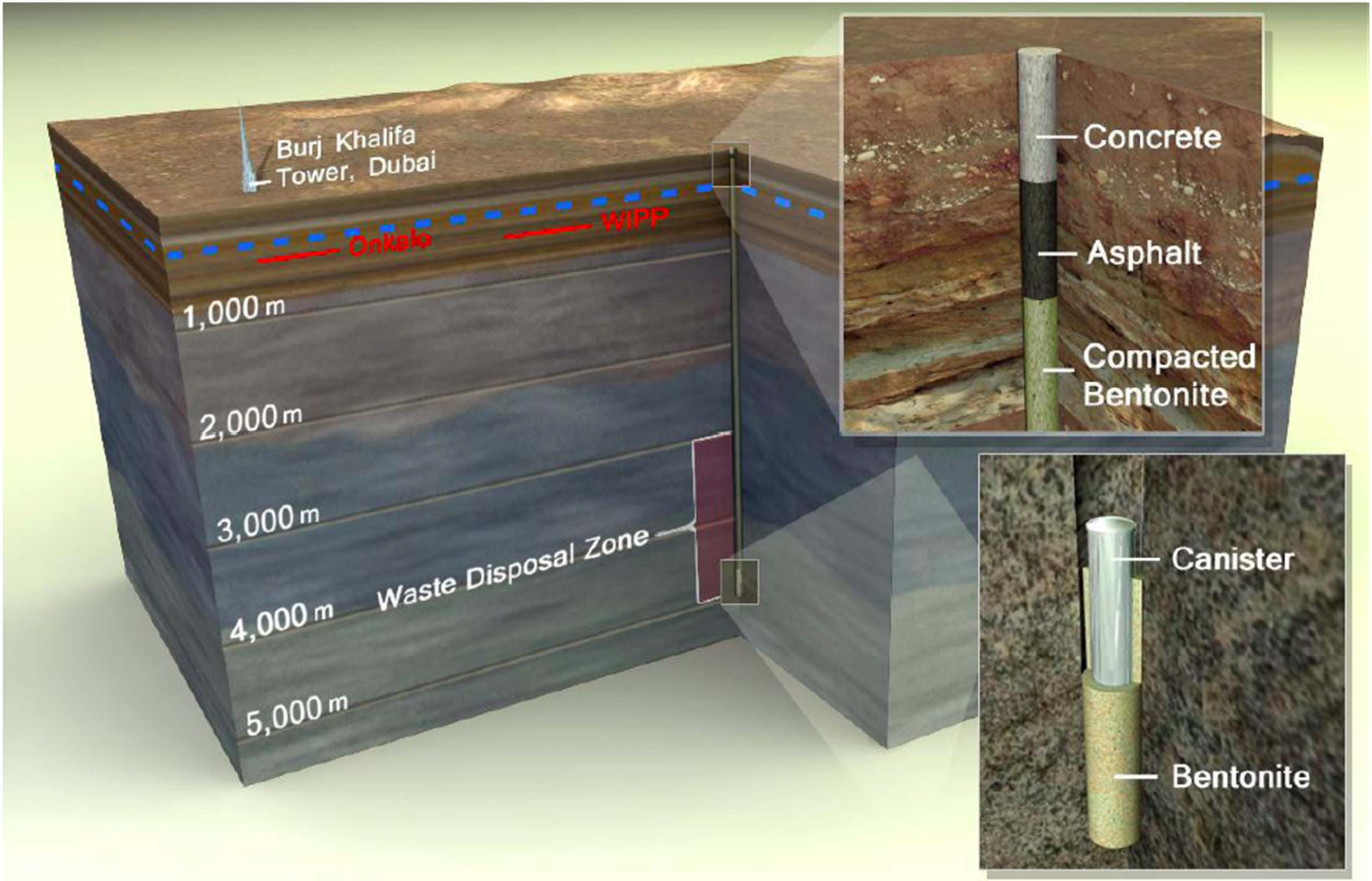
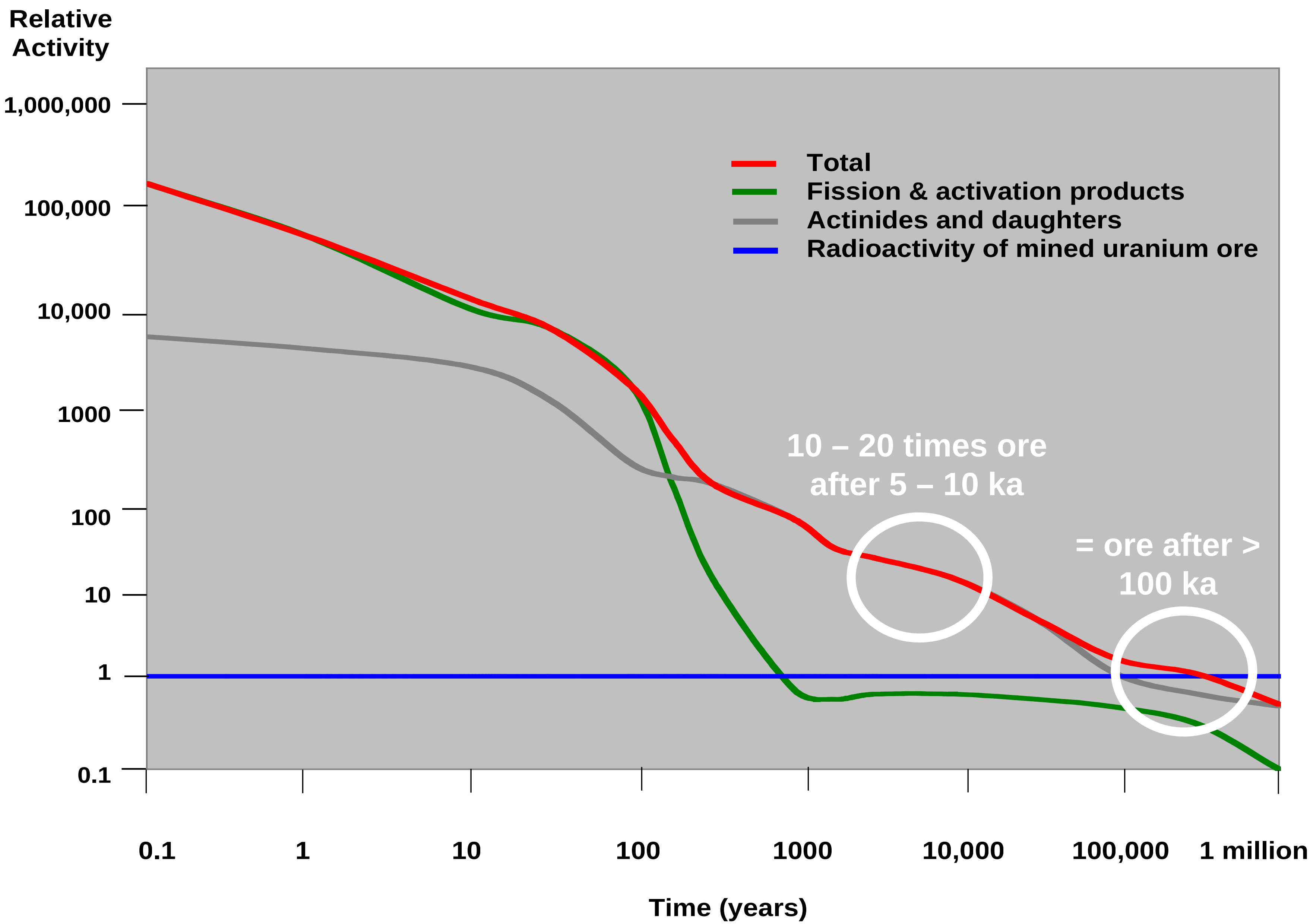
Deep geological repositories





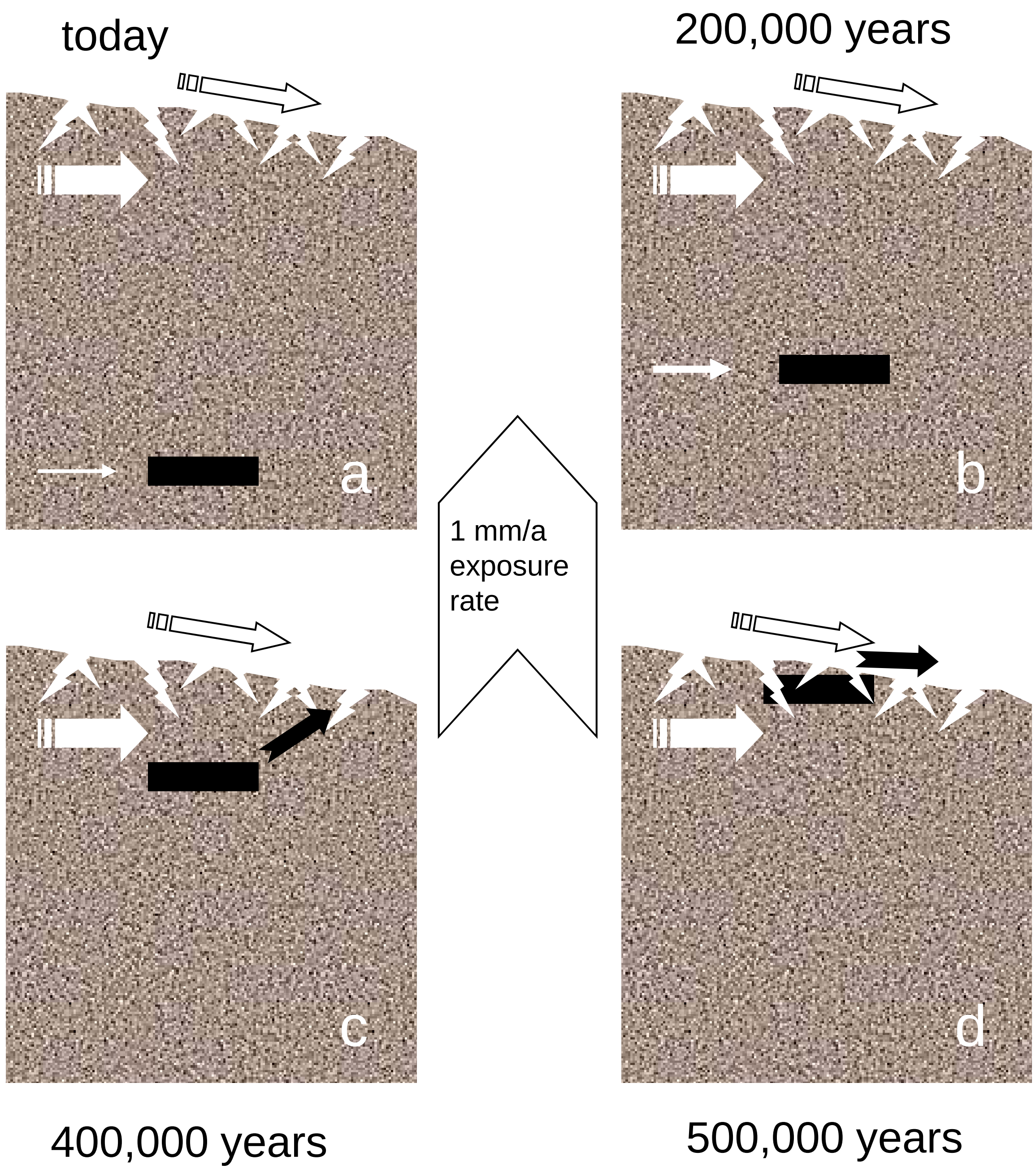
Burj Khalifa
Tower, Dubai
Onkalo
WIPP
1,000 m
2,000 m
3,000 m
4,000 m
5,000 m
Waste Disposal Zone
Concrete
Asphalt
Compacted
Bentonite
Canister
Bentonite

Activity of spent fuel relative to uranium ore (after SKB)



Hazard Potential of SF

- uptake hazard potential
  - low radiotoxicity and U-ore body analogies in stable settings give some confidence that long-term HP is extremely low and within the 'natural envelope'
- external hazard potential
  - exhumation by tectonic processes within next few millions of years is unlikely
  - exhumation by glaciation and neotectonic processes, even in many glacial cycles, seems equally unlikely
  - .....and processes of dispersion in upper region of crust will reduce concentrations in most cases



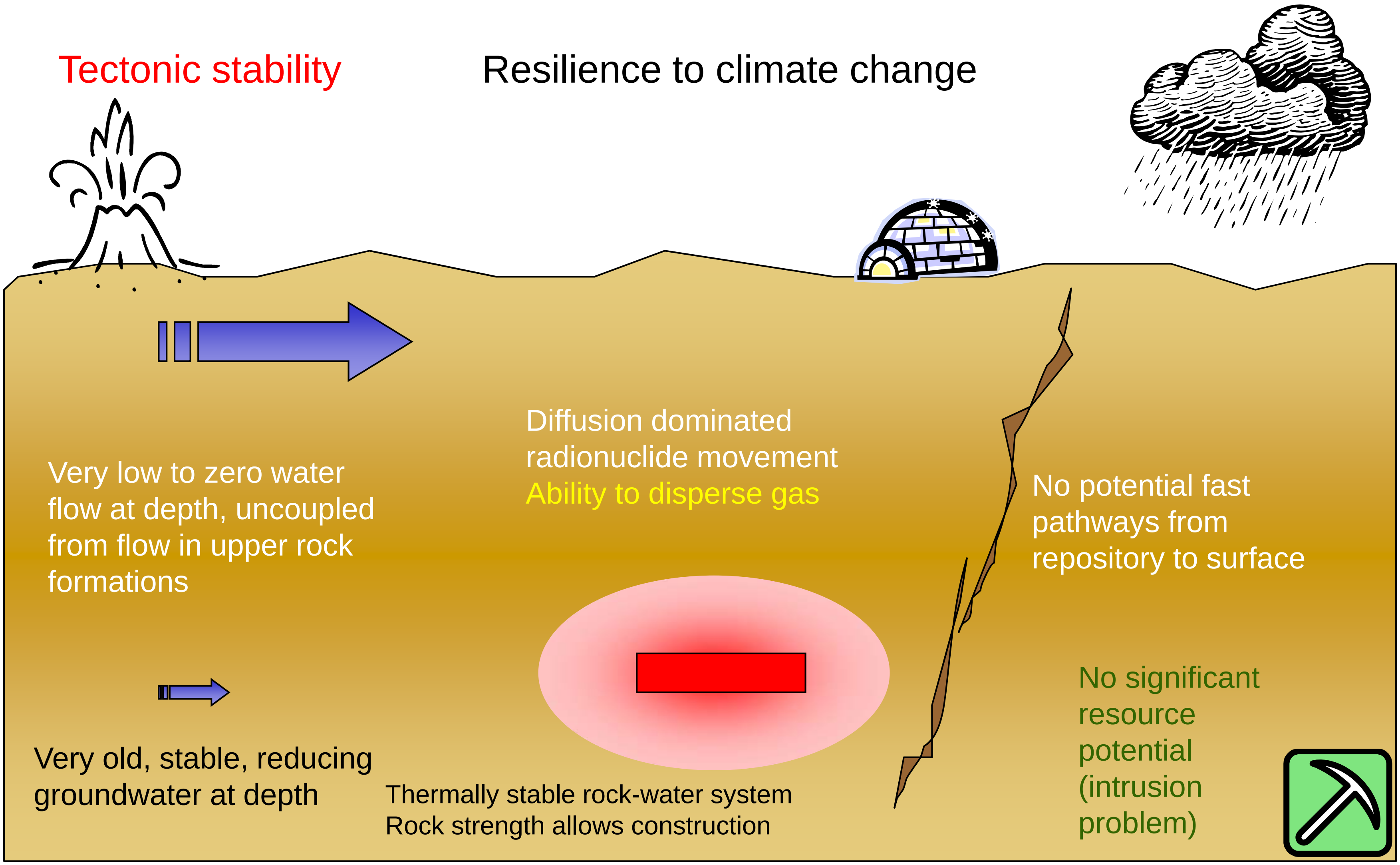
What if it ever got back to the surface so we could walk over it?

.....as a result of uplift and erosion - 'exhumation'

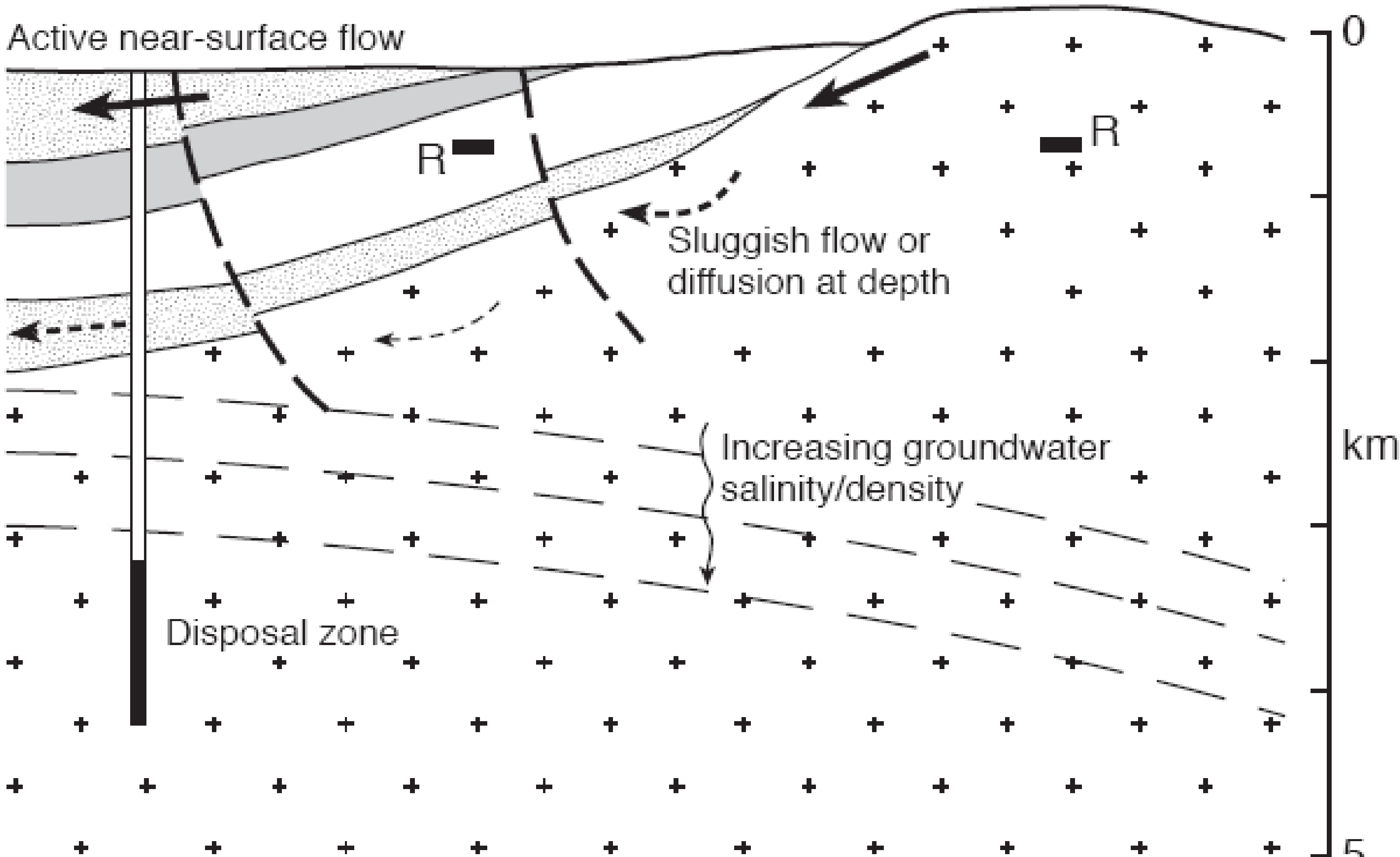
Direct external exposure to 1 tonne of 100,000 year old spent fuel c. 300 times > U ore

This is probably bad news..... could it happen?
Could large masses of undispersed SF reach the surface?

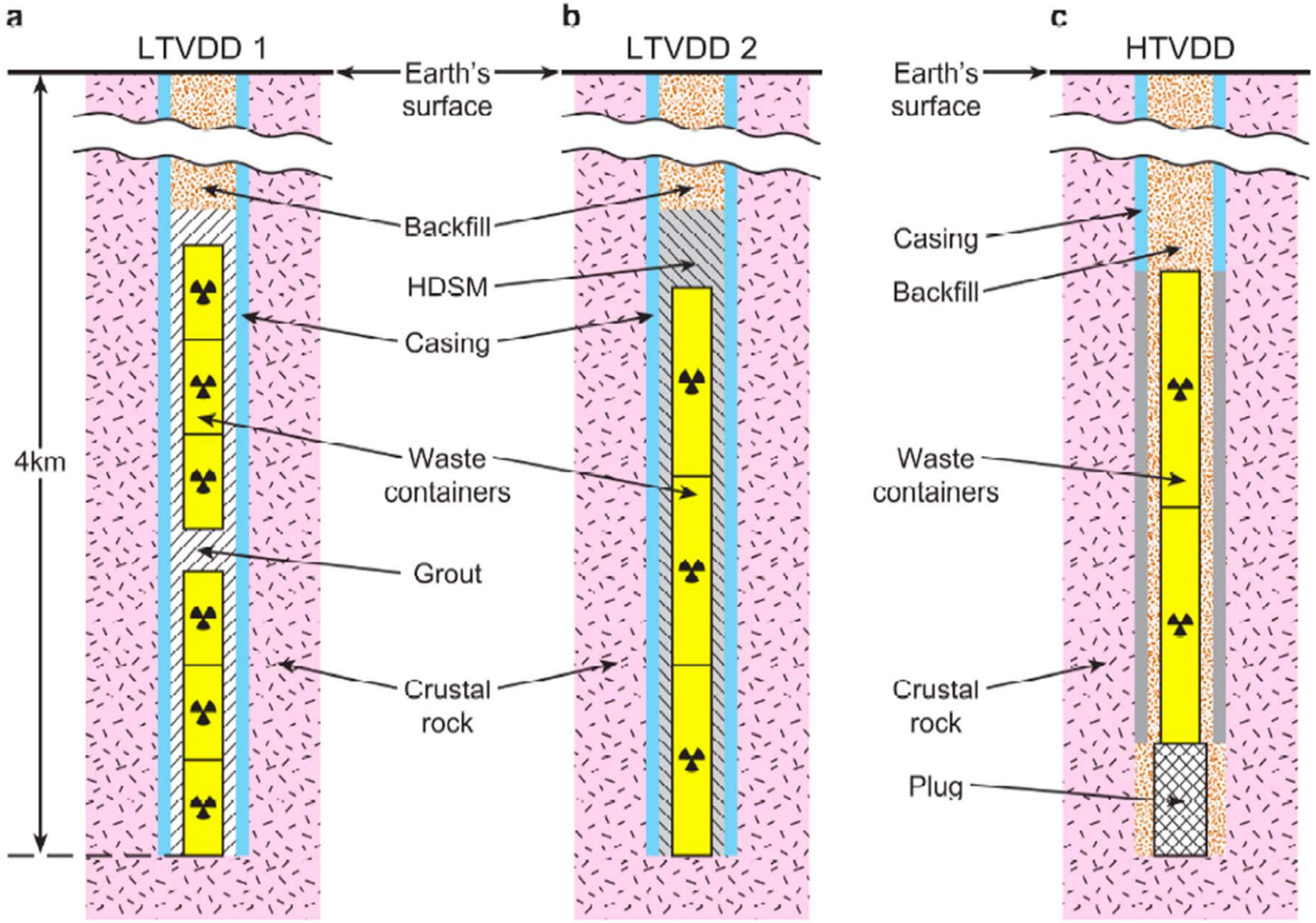
Key Features of Favourable Geological Environments



Deep borehole disposal



Low and high-temperature concepts (Gibb, 2010)



Technology Readiness (some example items only): 4000 m hole, 500 mm diameter at disposal zone (Beswick, 2008)

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Surface location			x		Site selection
Surface borehole facilities	x				Civil engineering
Geology			x		Site selection to optimise conditions
Surface drilling equipment		x			Upgrade existing rig designs with some research into equipment for the large sizes
Tubular handling systems		x			Use existing equipment or designs
Hole sizes and depths		x			Much larger than past experience
Drill string			x		Special strings may be required
Drilling assemblies			x		Use existing designs as a basis
Drilling method (liquid flush)			x		Use existing processes as a basis
Drilling method (air flush)				x	Not practical in these large hole sizes
Drilling bits			x		Use existing oilfield and shaft drilling designs as a basis
Drilling fluid systems			x		Use existing fluids technology as a basis
Solids control		x			Range of equipment available
Verticality control		x			Available, but in small sizes (may need pilot hole)
Borehole surveying		x			Use existing technology adapted for the larger hole sizes
Coring		x			If necessary, but would need to be limited in diameter (;pilot hole)

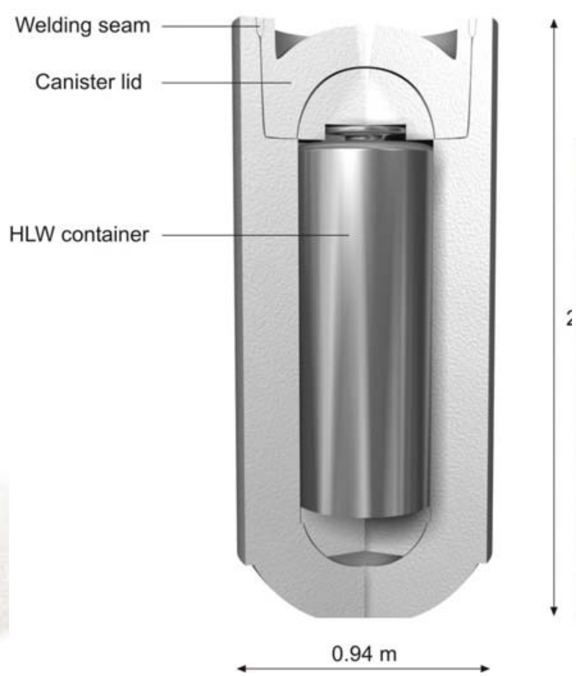
How big a package for SF disposal?

Some waste container types for conventional geological repositories

Spent fuel in cast iron insert inside copper overpack (c.5 metres long)

SKB, Sweden

Vitrified HLW in stainless steel container inside thick cast iron overpack (Nagra, Switzerland)

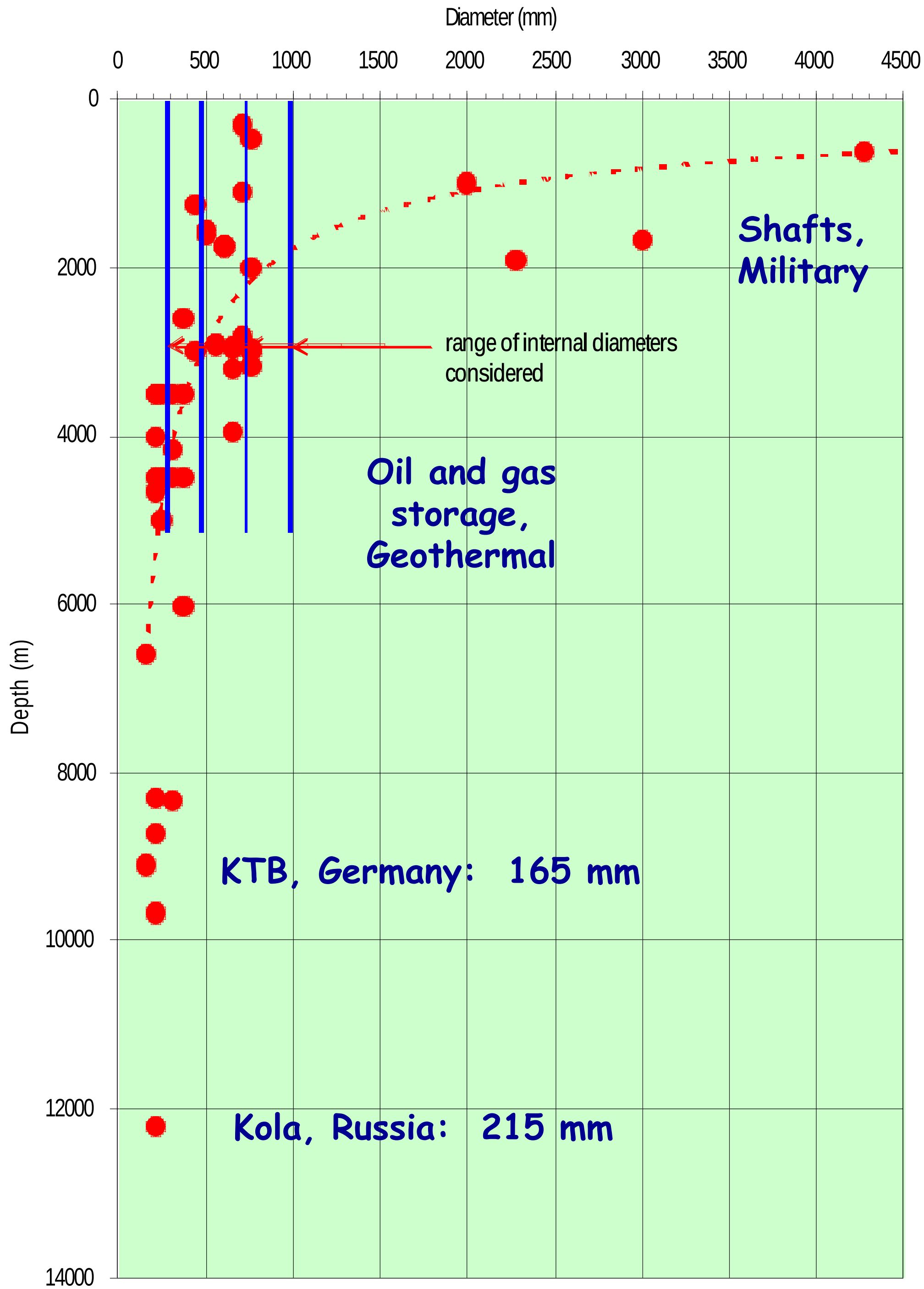


Simplest option for DBD could be to have slim packages for single, or (at a squeeze) 4 unmodified fuel assemblies, depending on reactor type.

The aim is for a package that would fit in a 0.5 m OD hole

about 0.2 - 0.8 tHM / 5 m borehole length

Suggestions also made to disassemble FAs and compact the fuel pins



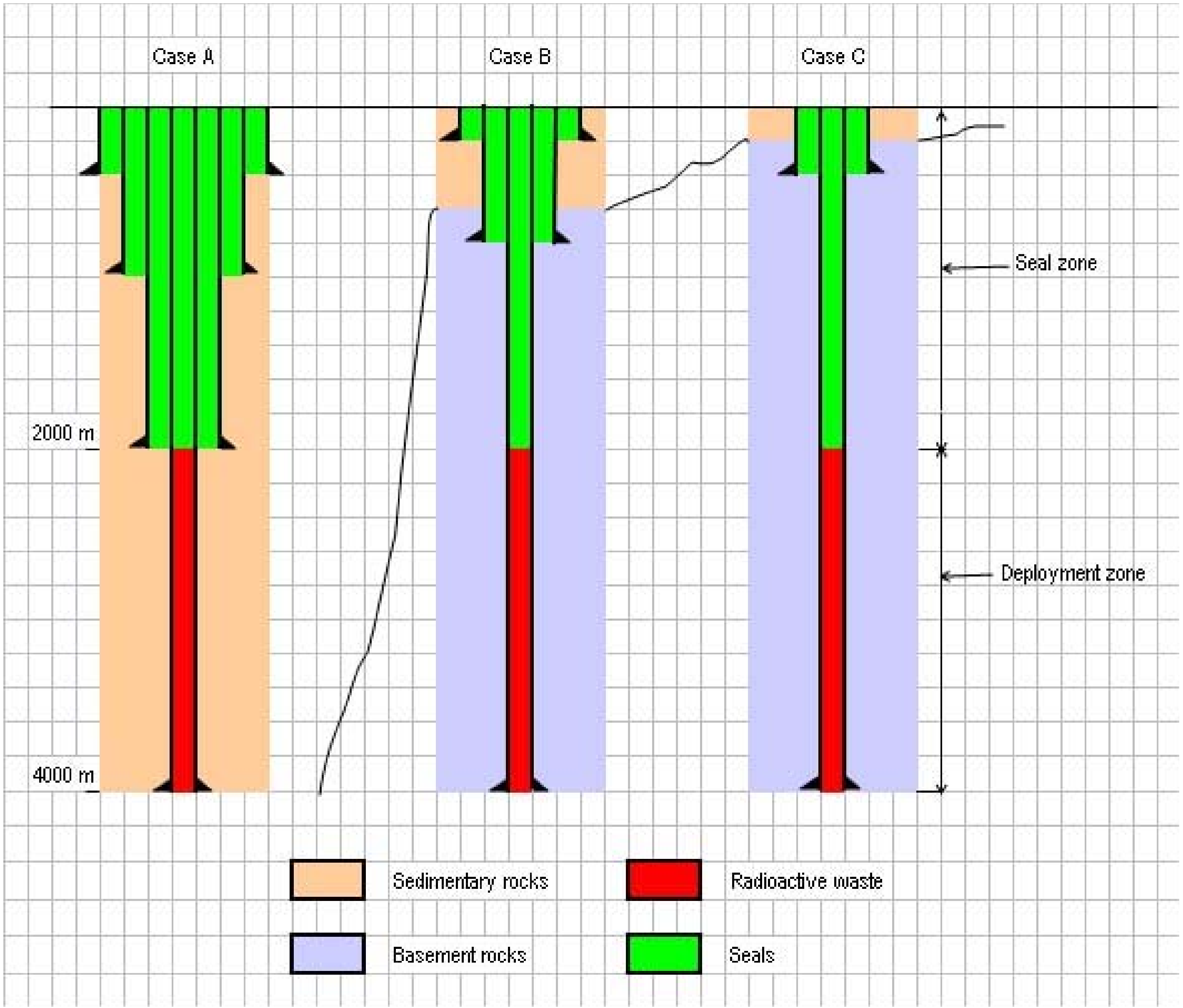
Diameter of drilled holes

Experience internationally and across industries

Beswick, 2008

Lining the borehole

(Beswick, 2008)



Technical Feasibility (Beswick, 2008)

Depth (km)	Completed internal diameter (mm)			
	300	500	750	1000
2				
3				??
4			??	
5				

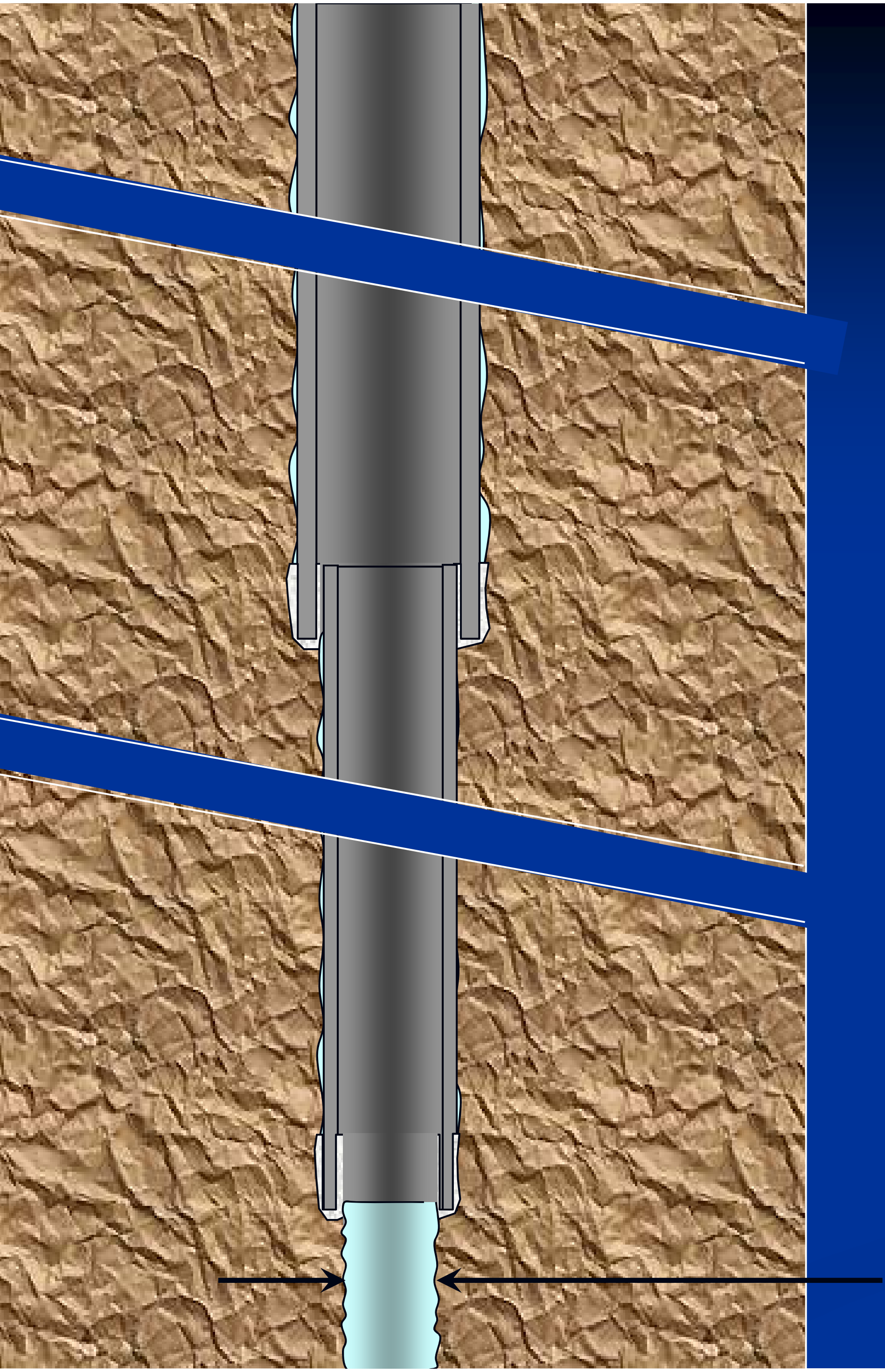
Key : Green = feasible with current technology and favourable geological conditions.
Orange = may be achievable with tool and process development.
Red = considered impractical in the foreseeable future.

Big technology…. (Beswick, 2008)

2009 Beswick Review (UK-NDA)

- 500 - 600 mm diameter borehole to 5000 m in crystalline rock "not far outside current experience envelope of drilling industry" and is achievable with tool and process development
- drilling rigs available and can now assure verticality, even with stress breakout influences
- casing through the full length of the borehole would be essential
- time for drilling, waste emplacement and completion of a single 600 mm diameter DBD borehole could be as little as three years
- development needs:
  - large diameter drilling tools and drill string;
  - casing design and installation procedures for large diameters;
  - casing design for deployment zone;
  - cementation methods for upper large diameter casing;
  - waste deployment procedure and handling tools;
  - annulus sealing in the deployment zone;
  - upper borehole seals and near surface abutment
- cost of constructing 1st borehole: c. 35-40 MGBP

Constructing the borehole

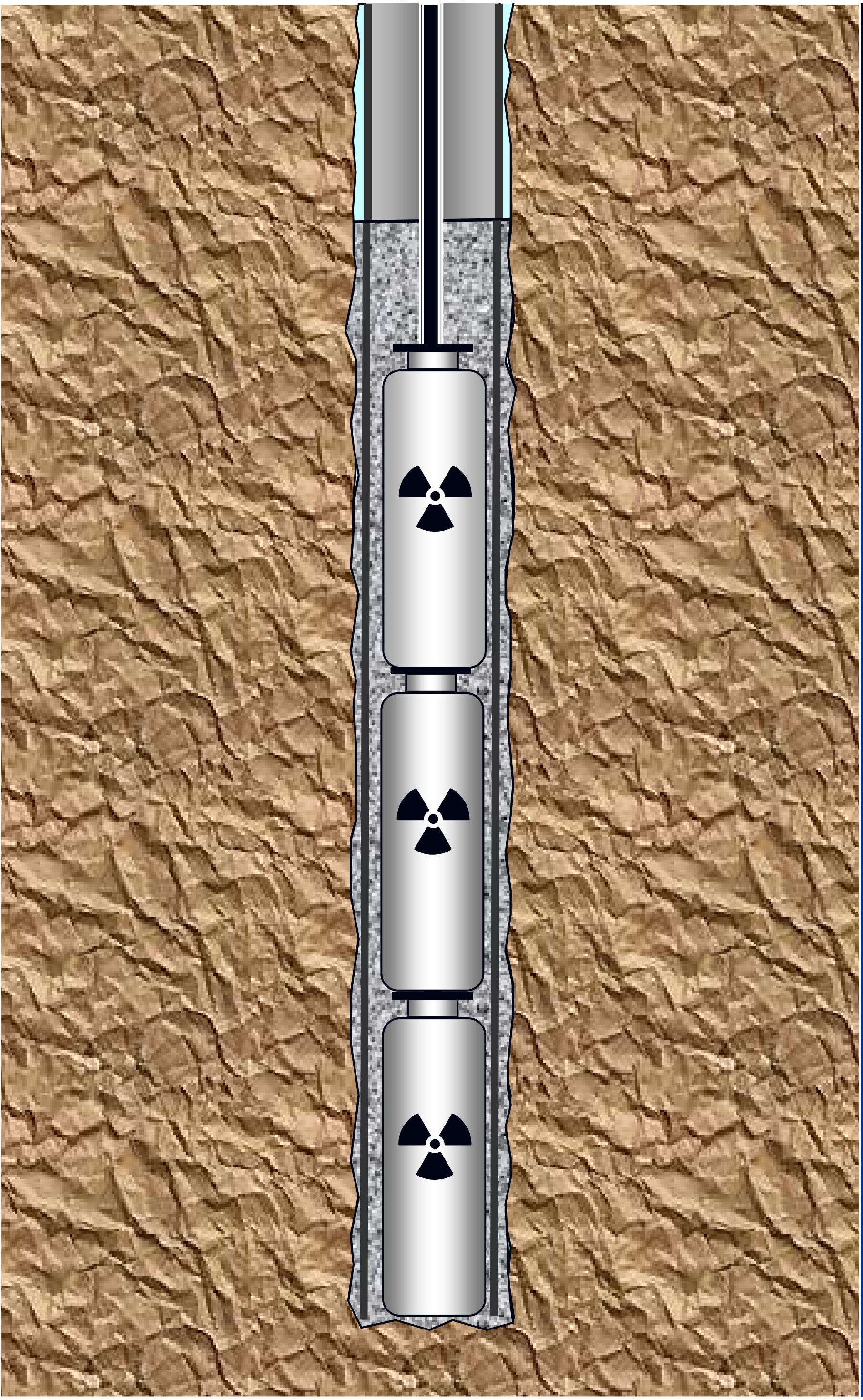


- Drill the first stage of the borehole
- Insert the casing.
- Pour the cement base-plug.
- Drill the next stage of the borehole.
- Insert the casing.
- Pour the cement base-plug
- Drill the next stage of the borehole

And so on, down to > 4 kms

< 0.5 m diameter

Gibb, 2009



Low Temperature Very Deep Disposal

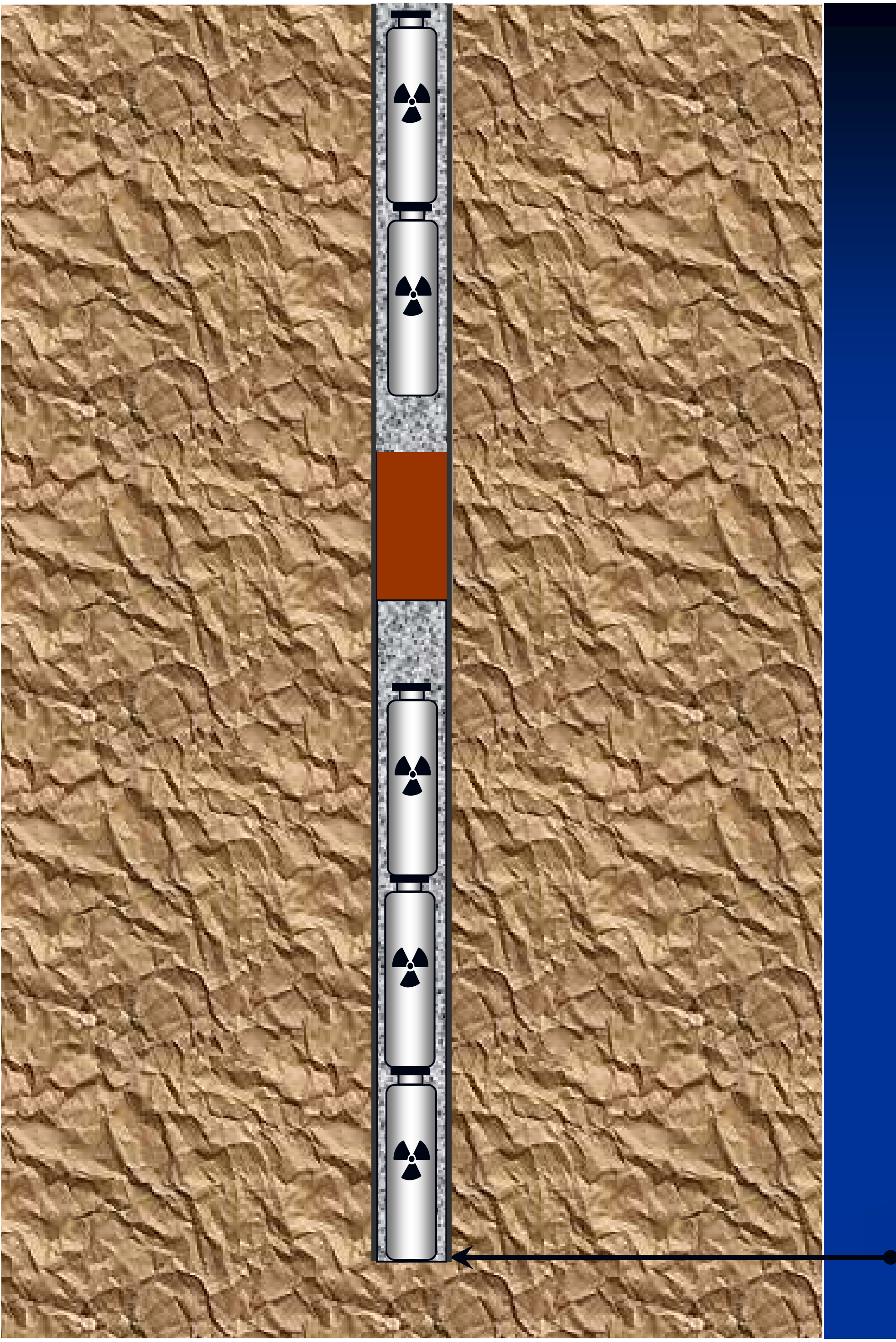
Vitrified waste

- Insert the final run of casing *(continuous to surface; bottom 1 km slotted)*
- Emplace the first batch of HLW canisters
- Pump in the grout and allow it to set

Gibb, 2009

Low Temperature Very Deep Disposal

Vitrified waste (Cont.)

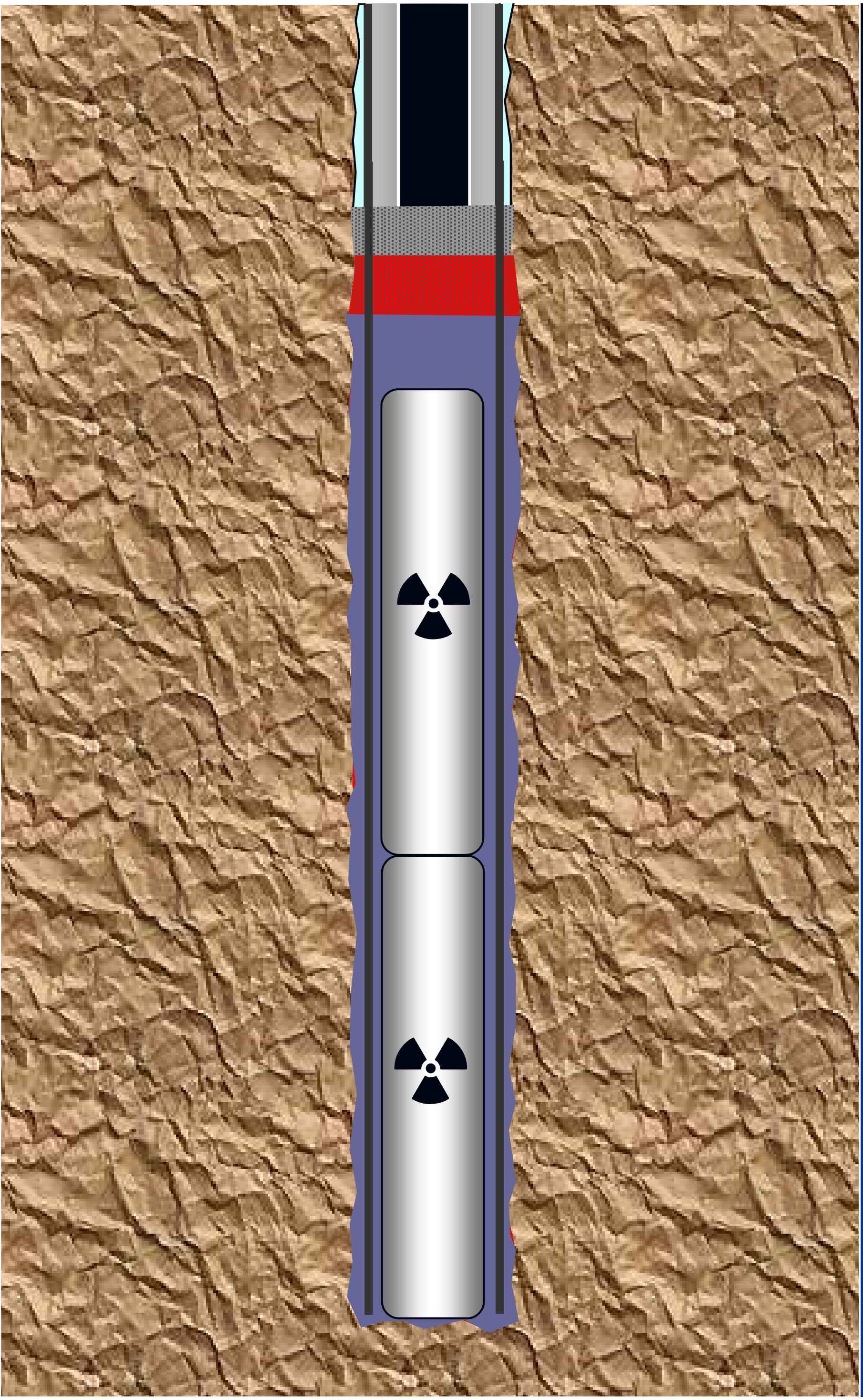


- Insert Bentonite clay (Optional)
- Insert another batch of canisters, pour grout & allow to set

Repeat until the bottom km of the borehole is filled

4 kms

Gibb, 2009

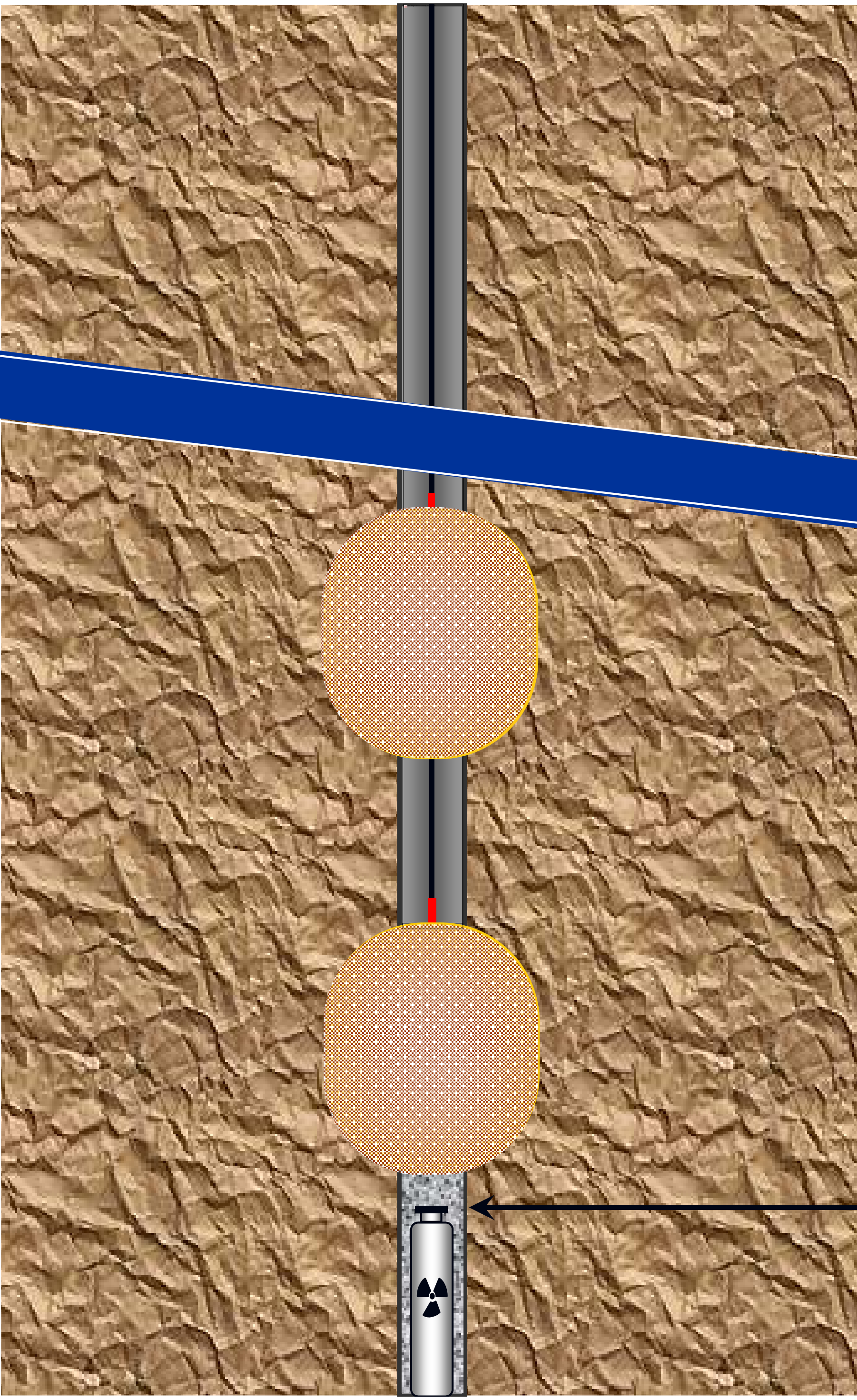


Low Temperature Very Deep Disposal - 2

Cooled, spent UO_2 fuel

- Insert the final casing run *(continuous to surface; bottom 1 km slotted)*
- Insert the containers
- Deploy High Density Support Matrix inside and outside the casing
- Heat from containers melts the HDSM which, in time, slowly cools and solidifies, effectively ‘soldering’ the waste packages into the borehole.

Gibb, 2009



Sealing the borehole

- Pour in some backfill (crushed granite)
- Insert heater and melt backfill & wall-rock to seal the borehole
- Pour in more backfill and seal the borehole again
- Repeat as often as required then fill the rest of the borehole with backfill

3 km deep (topmost canister)

Gibb, 2009

Basic characteristics of DBD

- Conceptually, most appropriate for wastes that have high hazard potential and/or require strong safeguards
  - vitrified HLW, SNF
  - separated Pu, declared waste (glass or ceramic)
- Technically. most appropriate for wastes with SMALL VOLUMES in a national inventory
  - e.g. a 1000 m disposal section in a 4000 m deep, 0.5 m diameter hole would hold <150 m^3 of waste, allowing for packaging and backfill
- Essentially not REVERSIBLE
  - can be designed to be extremely difficult to re-discover a DBD location in future
- Most emphasis is now on lower temperature options, rather than those involving rock melting

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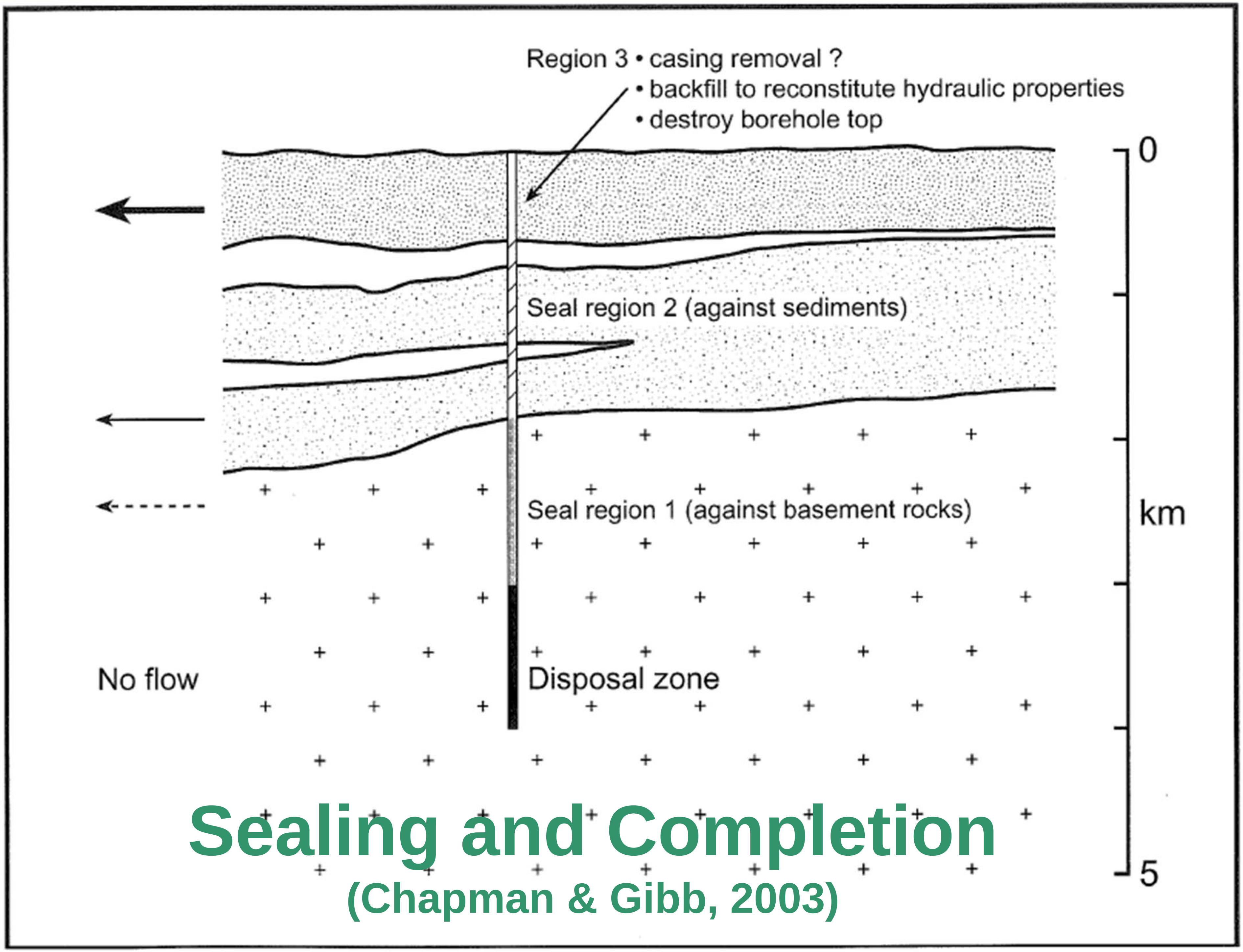
Detailed or comprehensive evaluations

- Sweden: WMO
  - 1980s: an alternative to conventional GDF for SF
- UK: academia and WMO
  - University of Sheffield: technical options
  - Nirex (now NDA-RWMD): borehole technology
- USA
  - MIT: technical options
  - Post Yucca Mountain: Blue Ribbon Commission
  - Sandia NL – overall feasibility and possible full-scale testing
  - 2012 'Road-Map'

Advantages of Very Deep Boreholes	Comparison with Mined Repositories
Extremely high isolation potential of deep geological environments and stable deep brine systems in appropriately selected locations	Only available in some combinations of geological and climatic situations
'Proliferation proof': extreme difficulty in retrieving wastes: emplacement works could be effectively destroyed to provide further problems of accessing wastes	Relatively easily retrievable (advanced as an advantage for public relations purposes)
Small land area requirements feasible, using splayed borehole arrays	Depending on rock type, may require large area for rock spoil and surface facilities
Wide range of locations possible as many environments at depths > 3 km may be suitable	Limited siting potential: must show low groundwater flow and lack of susceptibility to climate change
Not susceptible to surface changes (ice, erosion, sea level change) or to seismic impacts	Depending on site environment, performance can be dominated by surface processes, which can be a significant siting issue.
Very low likelihood of inadvertent intrusion in the far future as can be located in resource-free environments	Rely on preservation of knowledge, lack of curiosity, and siting in resource free regions
Possibly good public acceptability owing to higher isolation capability	Presentational problems owing to broader range of release scenarios that need to be evaluated in most safety cases
No requirement for complex and expensive engineered barriers: isolation based on depth and natural barrier	Must have a massive and expensive container and buffer system, except in some rare, highly stable, zero flow environments
Potentially cheaper, owing to modular nature and absence of pre-closure operational period	Typical repository costs: 10^{9} – 10^{10} USD
Probably reduced requirement for long-term monitoring	Likely public demand for monitoring at all stages of operation and post-closure
Although it is difficult to characterise the geological conditions at disposal depth, the requirement for detailed information for engineering and safety assessment will be limited	Characterising many proposed repository environments is a long and complex exercise, which may also require an underground characterisation facility

Conceptual Strategic/Operational POSITIVES

Chapman and Gibb, 2003

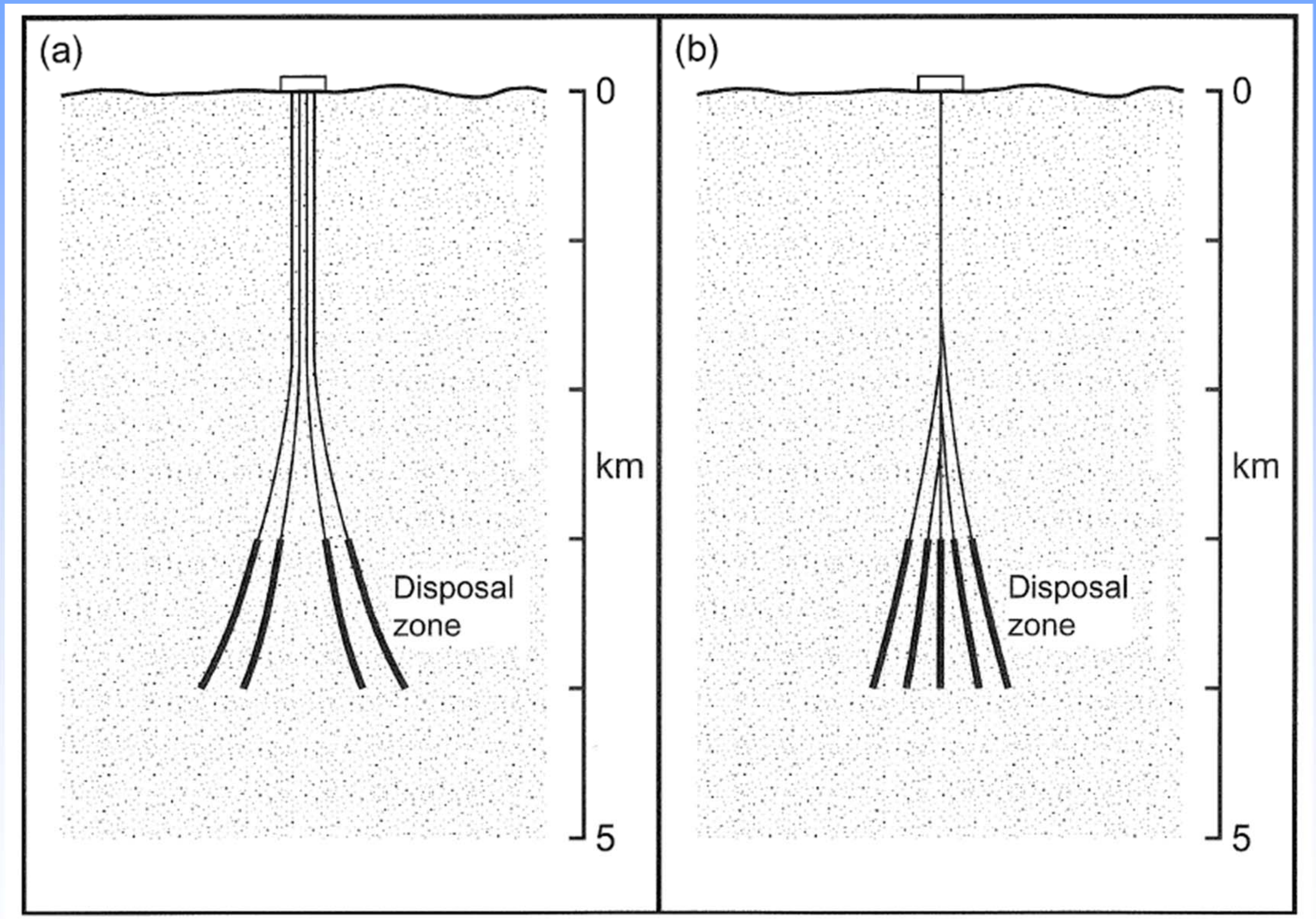


Sealing and Completion

(Chapman & Gibb, 2003)

Minimising Utilised Land Area

(Chapman & Gibb, 2003)



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Disadvantages of Very Deep Boreholes	Comparison with Mined Repositories
Drilling technology for large diameter (~1 m), directed boreholes is not yet well-developed	Underground construction techniques are very well tried and tested
There is no track-record of performance and safety assessment on which to build confidence in the isolation potential	Safety has been investigated in depth for > 25 years
No practical experience of placing packages at great depth on a routine basis, with many runs into a single hole: jams could be hard to recover, especially if package integrity during emplacement cannot be assured	Limited practical experience of package emplacement, either active or full-scale inactive: engineering demonstrations just starting
Dominant factor in overall performance will be ability to seal boreholes	Performance depends to a large extent on the engineered barrier system, which has been well studied and tested
Probably only suitable for smaller waste volumes (~ hundreds m^3) at present	Most suitable for larger waste volumes at present
No capacity to retrieve wastes at any stage, and the weight of the waste package column is likely to deform packages and make them impossible to extract	Waste relatively easily retrievable at all stages
Difficult to install long-term monitoring systems at depth	Also problematic to install post-closure monitoring systems that provide any useful data: possibly more so than for deep boreholes
High ambient stresses and temperatures at disposal depth pose engineering problems. Concept relies on ability to construct stable unlined holes at depths >2000 m and keep them open without undue deformation long enough for emplacement	Elevated temperatures (and, in some environments, significant stress anisotropy) are expected, but should not cause significant operational or engineering problems

2009 Sandia Review Findings

- 1000 holes for c.100,000 tHM (all existing US SF inventory)
- calculated release up borehole with 400 SF assemblies: 10^{-12} mSv/a
- need to:
  - assess scenarios for other release pathways
  - more accurate modelling of THCM behaviour of borehole and surrounding rock
  - consider seal design
  - assess engineered materials that sequester iodine
  - performance assessment of arrays of multiple emplacement holes
- detailed cost analysis would be beneficial
- consideration of changes in legal and regulatory requirements will be needed
- detailed analyses of engineering systems and operational practices for emplacement are needed
- a full-scale pilot project should be undertaken

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MIT-Sandia 2010: R&D Requirements

- Design Pilot Tests: at shallow depth (emplacement engineering) and full depth (to prove DBD can be done and containers recovered)
- Borehole sealing/drilling: what happens if borehole cannot be sealed and how many holes could fail or have to be abandoned.
- Geochemistry: natural indicators of deep hydrogeochemical stability and heterogeneity, including effects on performance and sensitivity to drilling techniques.
- Drilling: is performance perturbed by drilling/emplacement?
- Reliability and Surveillance: how to demonstrate key aspects of system design at depth, including sensor performance and sensor parameter targets
- Hydrogeology: establish lithological heterogeneity controls on large-scale fluid convection in the borehole disturbed zone.
- Waste Form & Package Design: materials; use of consolidation for SF.
- Downhole Testing: tools that may need development, e.g. acoustic and electromagnetic techniques that allow continuous surveillance of vertical fluid motion.
- Geology: how to detect, predict or pre-screen for geopressured zones at depth and how to determine if and when this is important.
- Drilling: establish the value of casing all the way down the borehole.

Sandia 2012 Road-Map (Arnold et al., 2012)

	FY-1	FY-2	FY-3	FY-4	FY-5
Site Selection Guidelines	▲				
List of Candidate Sites	▲				
Prioritize Engineering & Science Needs		▲			
Permits & Licensing of Site for Demonstration		▲			
Drilling Contractor Selection			▲		
Design & Fabricate Canister			▲		
Borehole Construction				▲	
Canister Emplacement Test					▲
Science & Engineering Demonstrations					▲
Finalize Documentation					▲

Specific Issues for Spent Fuel

- potential to contaminate borehole if instant release fraction escapes simple packaging in event of accident/jam
  - more robust packages (as in a GDF)
  - is it easy to recover the situation?
  - are the radiological consequences at surface significant?
  - does it matter economically to loose a single hole?
- pre-disposal storage time flexibility
  - very long storage: cooler to dispose, but doesn't help with nuclear security
  - how early (ex-reactor) could disposal be implemented?
- SF can be considered a resource: DBD is practically irretrievable, if policy changes
  - including a retrievability until sealing option (e.g. Sandia 2010 workshop) could add considerably to cost and technical difficulty
- centralised (multinational?) or many small localised DBDFs?

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Moving Forward

- large scale testing/demonstration is essential if further progress is to be made
- a more comprehensive operational and post-closure safety evaluation is essential – this can be done with available international expertise and data
- the concept is sufficiently non-site-specific to attract an international effort on generic technology aspects
- there is potentially sufficient interest from a number of countries to consider a shared multinational project: would need a host country
- ability to go for 'early' disposal of SF has security implications that could attract international support
- there could be some resistance from established conventional GDF programmes

Some closing thoughts…..

- Safety and nuclear security is enhanced by:
  - interim storage of SF at a small number of secure, well-sited locations
  - preference for dry storage, hardened storage, underground cavern storage?
    - long term storage gives time to consider whether SF is a resource
  - assured availability of a disposal solution – normally a conventional GDF – means c.30 years advance work
    - SF can then be disposed in a timely fashion
    - DBD is unlikely to accelerate this
- Shared regional solutions can help considerably
  - for small NP programmes, shared facilities make considerable sense (disposal facilities, but perhaps not storage facilities)
  - DBD for small amounts of HLW is potentially attractive, but few small (and new) NP countries use reprocessing
  - for large NP programmes, shared R&D and common technologies help (also for smaller programmes)

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