Deep Isolation in Estonia

Qualitative Geological Readiness Assessment of Deep Isolation's borehole solution in Estonia

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Context

As Estonia considers the role that advanced nuclear power generation can play in delivering a low carbon future for the country, citizens and policymakers need to be sure there is a safe and affordable way for Estonia to dispose of the resulting spent nuclear fuel. To inform these considerations, this report presents results from an initial study on the suitability of Deep Isolation's borehole disposal solution within Estonian geology.

The Deep Isolation solution

Deep Isolation delivers the benefits of deep geological disposal, but at a fraction of the cost of the large mined repositories being constructed by some European countries such as Finland, Sweden and France. Deep Isolation's solution places the waste in corrosion-resistant canisters within deep boreholes, drilled into deep rock formations that have been isolated from the biosphere for a million years or more. The waste can be retrieved for several decades if necessary, or left permanently and safely (i.e. disposed of). This disposal can be done at or near the nuclear power plant that produces the waste, avoiding the need for waste to be transported across communities.

Key benefits for Estonia

Deep Isolation's solution is a game-changing innovation that is altering the way governments and the public around the world think about nuclear waste. Our preliminary study suggests that key benefits for Estonia include:

Safety: A Deep Isolation repository in Estonia would be sited in crystalline basement rock. Our preliminary modelling of a generic repository disposing of spent nuclear fuel in similar geology indicates that it will provide robust safety. In this model, the arrival of peak dose at the surface biosphere occurs at 1.3 million years and at a level approximately three orders of magnitude below regulatory requirements.

Affordability: Recent research suggests that the cost of disposing spent nuclear fuel from advanced reactors (such as the Small Modular Reactor under consideration in Estonia) may be between 24% and 31% of the cost of disposal in a traditional mined repository[1].

Flexibility: This preliminary study finds there are no fundamental geologic limitations to siting of nuclear waste in deep horizontal boreholes in Estonia, and that a wide range of siting options are available that could be demonstrated to comply with IAEA Safety Regulations for geologic disposal. We recommend that the optimal areas in which to focus a site selection process are in the north east of Estonia (along with the islands off that coastline). These areas combine preferred geologic conditions from a safety perspective, more extensive existing sub-surface data due to past borehole activity, and evidence for cost-effective drilling.

Simple and phased implementation: The modularity of the Deep Isolation solution allows for a staged pathway to disposal. A phased approach can be taken, beginning with as few as one borehole. Our implementation times can be much shorter than the multiple decade timescales required to construct a mined repository.

Next steps

Extensive further work will be needed to identify and characterise specific potential sites, and to engage with potential host communities. Our recommendations on how this might best be taken forward in Estonia are set out in the report, and we look forward to engaging with stakeholders across Estonia to do so.

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[1] Based on a recent feasibility study by the Electric Power Research Institute on borehole disposal for US advanced nuclear companies ("Feasibility of Borehole Co-Location with Advanced Reactors for Onsite Management of Spent Nuclear Fuel", EPRI, December 2020)

1. Introduction

1.1 About this paper

The purpose of this report is to assess the potential suitability of Deep Isolation's horizontal borehole disposal solution for disposal of SMR nuclear spent fuel in Estonian geology. The study has been undertaken by Deep Isolation EMEA, with local support from Engineering Bureau STEIGER LLC, and sponsored by Fermi Energia.

1.2 Context

Estonia is committed to moving towards a carbon neutral future: its vision is to reduce carbon emissions by 70% by 2030, and by 2035 to close oil shale power generation completely.

To support that vision, the private sector company Fermi Energia was established in 2019 to drive up national electricity production in a way that supports the country's climate goals. Fermi Energia are developing proposals to produce low-carbon nuclear power in Estonia in a Small Modular Reactor (SMR).

In realising these ambitious goals, Fermi Energia understands that Estonia will need to have a clear and viable solution for disposing of the resulting radioactive waste. Historically, many other countries around the world have yet to effectively manage the disposal of radioactive waste. Despite commercial nuclear power being generated as early as the 1950s, none of the global stockpile of spent nuclear fuel has been permanently disposed of. It remains in temporary storage which is extremely costly to operate and continues to be challenging for local communities. Therefore, this is rightly a concern for Estonian citizens as they consider implementation of SMR technology.

One thing is clear: there is global consensus – across governments, regulators, scientists and the nuclear industry – that the only safe solution for the long-term disposal of this waste is through deep geological disposal (see Exhibit 1). That is, encasing the waste within multiple barriers and then burying it deep underground – with the earth's rocks themselves acting as the ultimate and best barrier.

Exhibit 1: Geologic disposal is the safe solution for high level nuclear waste

IAEA
International Atomic Energy Agency

There is presently a broad consensus among technical experts that the preferred method of ensuring long term safety for HLW is isolation in a deep geological disposal facility.

Geological disposal facilities for long lived waste, if properly sited and constructed, provide passive, multibarrier isolation of radioactive materials. Emplacement in carefully engineered structures buried deep within suitable rock formations provides the long-term stability typical of a stable geological environment.

Source: Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA, 2018

However, a key barrier hampering progress globally on this front is cost: the current model for deep geological disposal, which involves mining out massive underground repositories, is complex and expensive. Only a handful of countries have advanced plans for such massive engineering projects, and no such facility is operational anywhere in the world.

It is against this context that Fermi Energia has asked Deep Isolation to complete this study into the suitability within Estonia's geological environment of our alternative lower-cost solution for deep geologic disposal.

1.3 About Deep Isolation

Deep Isolation is a leading innovator in nuclear waste storage and disposal. Launched in 2016, we offer a solution that avoids the need for expensive mined repositories that require human presence underground. Instead, our solution places corrosion-resistant canisters containing spent fuel in deep boreholes 1-3 kilometres underground. We construct these repositories using directional drilling technology within sedimentary, igneous or metamorphic host rocks – rocks that we can demonstrate have been isolated from the biosphere for a million years or more.

As part of our commitment to bring this innovative solution to markets around the world, in 2020 we established a European business, Deep Isolation EMEA Limited. For this project, Deep Isolation's team of international scientists and nuclear waste disposal experts have partnered with Engineering Bureau STEIGER LLC, Estonia's foremost geologic and drilling company, to ensure that our work is informed by deep local expertise on Estonian geology.

1.4 Structure of this report

The report is in the following main sections:

- Section 1 is this introduction.
- Section 2 gives an **overview of Deep Isolation's technical solution** for deep geological disposal of nuclear waste, setting out its key features and how these differ from both a traditional mined GDF and from vertical borehole solutions.
- Section 3 presents the **methodology** for this Geological Readiness Assessment, including our assessment screening criteria aligned to IAEA Safety Standards.
- Section 4 presents our **Safety Assessment**: the extent to which the geologic and hydrologic conditions anticipated at depth support the isolation of radionuclides from the biosphere (at a conceptual level).
- Section 5 presents our **Deliverability Assessment**: the extent to which the geology is conducive to cost-effective drilling and construction of a Deep Isolation repository.
- Section 6 draws together the evidence from Sections 4 and 5 to present our overall **Conclusions** on the potential suitability of Deep Isolation's solution in Estonian geology.
- Finally, Section 7 sets out **Recommendations and Next Steps** – our view on the further work, analysis and R&D that will be helpful to the Government of Estonia to inform further due diligence and future decisions.

Annex A contains the report bibliography.

2. Deep Isolation's technical solution

2.1 Overview

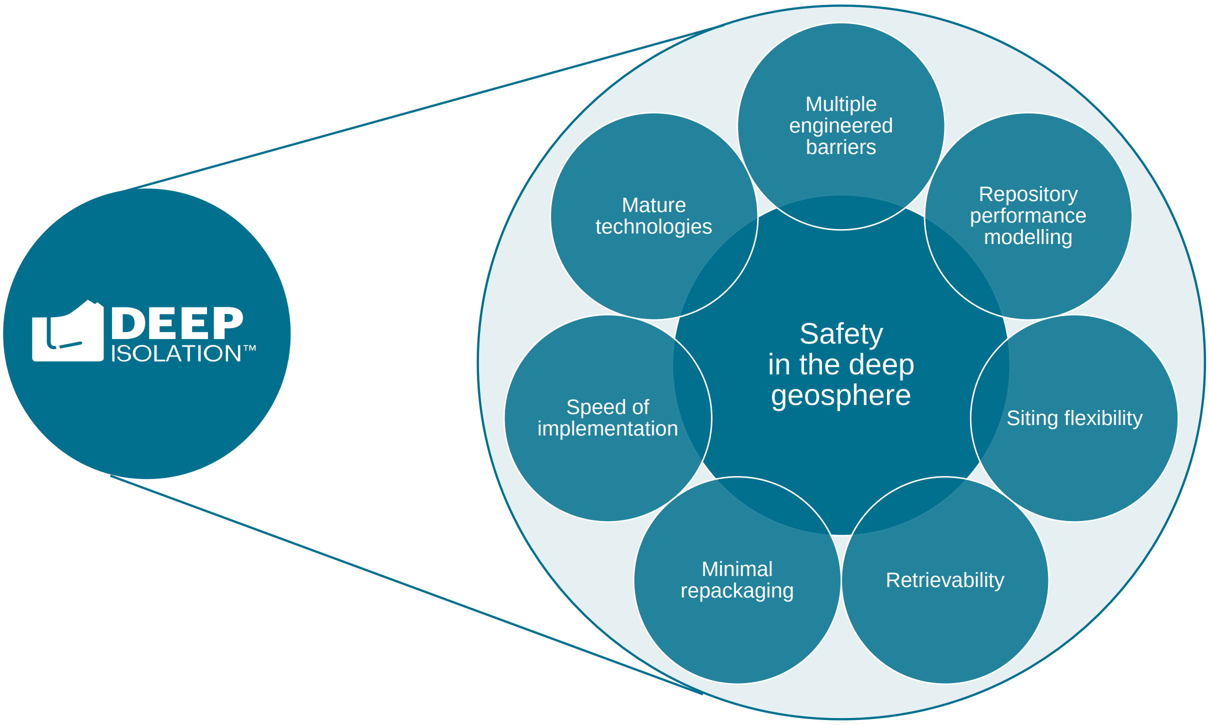
Deep Isolation's solution for Estonia places corrosion-resistant canisters containing nuclear waste in a long horizontal borehole 1-3 kilometres underground[2].

It does so by bringing together two important drivers of technological innovation and scientific advance that are now coming to maturity:

- **Drilling innovation.** Using proven directional drilling technology, horizontal boreholes can be drilled into sedimentary, igneous or metamorphic host rocks. The billion tons of rock between the surface and the buried waste (located in the horizontal section) provide both a permanent and natural barrier that exceeds human health and environmental impact standards by orders of magnitude – and which is supplemented in our solution with multiple engineered barriers.
- **Scientific advances in subsurface geophysical and geological analysis.** These enable us to locate suitable host rocks in a range of geological environments, and to demonstrate that they are low-permeability geologic formations that have remained stable and isolated from humans and the environment for millions of years.

Key features of Deep Isolation's technical solution are illustrated in Exhibit 2, and described in more detail in Exhibits 2.1-2.8 below.

Exhibit 2: Key features of Deep Isolation's solution



[2] In some cases, given particularities of the inventory for disposal or the particular location identified for disposal, we might recommend a vertical borehole instead. In most cases, however, we believe a horizontal disposal zone is the optimum approach, for the reasons set out in this section of our report.

Exhibit 2.1: Safety in the deep geosphere

Disposal of waste in deep isolated geologic formations provides a safe, secure and permanent solution. It offers:

- **Safety in depth:** The 1-3 km depth of disposal offers protection from the long-term effects of climate change and other natural processes that may adversely affect repository integrity. Increased depth also reduces risks associated with inadvertent and potentially malicious forms of human intrusion.
- **Reducing conditions:** The reducing (low oxygen) environment at depth supports the long-term integrity and function of the engineered barrier system. Reducing conditions inhibit both canister and casing corrosion and also slow the degradation of waste forms like vitrified HLW and uranium dioxide (UO_2) spent fuel. This slows the release of radionuclides into the geosphere.
- **Sorption and transport:** The inherent sorptive and hydrologic properties of many rock formations limit the mobility of most radionuclides. In appropriately sited repositories, the combination of sorption, long travel paths through the geosphere to the surface (1-3 kilometres), and slow, often diffusion-limited migration of mobile radionuclides (e.g. ^{129}I, ^{36}Cl, ^{79}Se) contributes to low peak doses at the surface. In our modelling, typical peak doses in the human accessible biosphere are orders of magnitude lower than the limits considered safe by regulators. Most radioactive waste either decays away underground within the engineered barrier system (waste form and canister) or during the long migration from the disposal section to the accessible environment, or is locked permanently in the geosphere.
- **Future safety demonstrated by past performance:** An array of isotopic markers in the deep geosphere can provide critical information on:
  - The relative isolation of the geologic environment from surface waters
  - The long term (>1 million years) mobility of safety relevant radionuclides through the rock formation
  - Formation-scale average permeabilities relevant to repository design and modelling.

  These isotopic systems include a broad range of stable and unstable isotopes, importantly ^{36}Cl, ^{4}He, ^{81}Kr and a range of additional noble gases. Used in combination, these different lines of isotopic evidence can be developed into a compelling case for the past isolation of repository host rock formations and their potential as repository sites. The information stored in isotopic systems provides insight into the integrated performance of the deep hydrogeologic system and its response to long-term and large-scale forcing events (climate change, seismicity). A deep hydrologic system that has maintained isolation for the past million to tens of millions of years is likely to provide isolation and stability for a repository over safety relevant time periods in the future. [3,4,5,6]

Exhibit 2.2: Mature technologies

We deliver this deep geologic safety by leveraging mature technologies that are widely used across the oil and gas sector and that we have integrated and enhanced with our own patented innovations. In particular:

- **Directional Drilling:** Advances in directional drilling technology have made deep horizontal boreholes reliable and relatively inexpensive to develop. In the US in the period 2007-2018, more than 120,000 horizontal wells have been drilled, with typical depths of 0.5 to 3 kilometres, and lengths of 4 kilometres or more.[7] Most of these wells were constructed using small (< 25 cm) diameter casings; however, there are many examples of larger diameter extended-reach well bores in offshore environments, such as the Gulf of Mexico and the Cook inlet area of Alaska, where they are more appropriate for resource extraction. Studies by our partners show that large deep horizontal boreholes (45cm) are feasible in appropriate host rock formations using 'off the shelf' drilling and casing technologies[8]. Industry specialists expect that speciality 57 cm casing for horizontal boreholes will be available shortly.

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[3] Hama, Katsuhiro, and Richard Metcalfe. "Groundwater dating applied for geological disposal of radioactive waste. A review of methods employed worldwide." Nihon Suimon Kagaku Kaishi 44.1 (2014): 39-64.
[4] Warr, Oliver, et al. "Tracing ancient hydrogeological fracture network age and compartmentalisation using noble gases." Geochimica et Cosmochimica Acta 222 (2018): 340-362.
[5] International Atomic Energy Agency. Isotope methods for dating old groundwater. International Atomic Energy Agency, 2013.
[6] Smith, Stanley D., Emeline Mathouchanh, and Dirk Mallants. "Characterisation of fluid flow in aquitards using helium concentrations in quartz, Gunnedah Basin, NSW." (2018).
[7] https://www.eia.gov/
[8] DI internal report, Schlumberger

- **Site Characterization:** A diverse and sophisticated array of subsurface characterization technologies developed by the oil and gas industry (and international research organizations) for well bores can be brought to bear for site evaluation for horizontal borehole repositories. These include methods to characterize fracture networks, regional stress fields, collect fluid samples and cores, and assess local and formation scale rock mechanical and hydrologic properties, among others. In sedimentary basins, high resolution 3-D seismic volumes provide a wealth of data that can be integrated on a much more detailed scale. This is especially true of porosity and permeability mapping, fracture mapping, geo-pressure detection and quantifying the overall coherency of events. The validity of computational data is tested with information provided by well logs, down hole measurements of all kinds and core data. In short, these tools provide superior quality information to inform and assess the potential of a site and host rock formations for application of Deep Isolation's solution.
- **Emplacement and Retrieval:** Daily operations in the oil and gas industry involve the emplacement and retrieval of equipment in the subsurface. Most of these operations are for routine services to the well bore and there are well developed latching mechanisms and fail safes. In addition, the retrieval and removal of objects stuck in well bores is also highly developed. Many elements of these commonly used emplacement and retrieval technologies have essentially 'off the shelf' applicability to emplacement of waste disposal canisters.

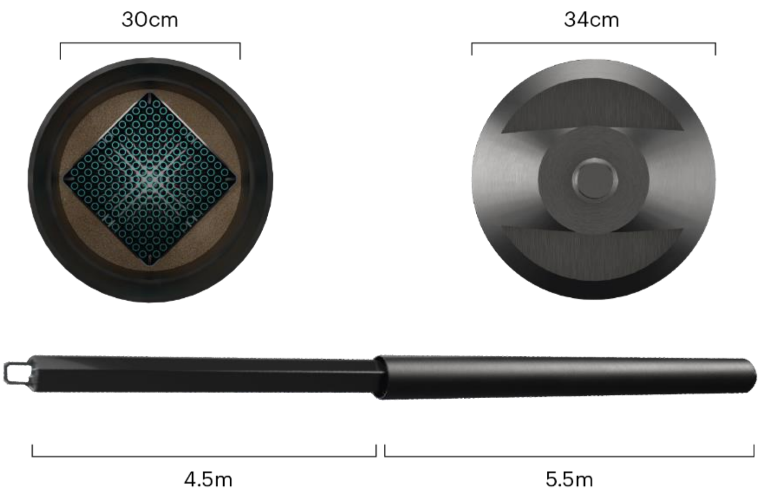
Exhibit 2.3: Multiple engineered barriers

Although the characteristics of the geosphere and great depth of the repositories are central to the long-term one-million-year safety case, there are many elements of the solution that contribute to the nearer term safety case. These engineered barriers perform important safety functions in the emplacement and pre-closure phase of the repository and provide additional long-term protection after the repository is sealed.

Key elements of the Engineered Barrier System (EBS) include:

- **Corrosion-resistant canisters:** Disposal canisters are designed to fit individual geologic environments and provide containment and protection during emplacement and to isolate waste forms from the geosphere for millennia. The disposal canisters themselves will not provide adequate shielding for above-surface radiation protection so a transfer cask is expected to be used to move the loaded disposal canister to the rig for emplacement. Once underground, the geologic environment will provide the shielding to protect the surface.

A standard Deep Isolation waste canister[9]



Our initial canister design is sized to hold complete spent PWR (Pressurized Water Reactor) nuclear fuel assemblies, but can be used for other forms of compact high-level radioactive waste. Additional specialized canisters can be developed as required to provide for smaller or larger waste forms. The oil

[9] Upper left shows the cross section when holding a spent nuclear fuel assembly. Upper right shows the end cap. Bottom shows the assembly being placed in the canister

and gas drilling industry handles drill pipes that are up to 29 m long, so disposal canister lengths should be less than that for handling purposes.

Nickel-chromium-molybdenum alloys (Alloy 22 - UNS N0622, and Alloy 625 - UNS N06625) are expected to be very stable in the saline, reducing conditions expected at depth in Estonia's crystalline basement[10].

- **Durable vitrified and ceramic waste forms:** Many common forms of HLW are themselves very substantial engineered barriers that contribute to long term post closure safety. Vitrified HLW may retain the bulk of its radionuclide inventory for many tens of thousands of years to hundreds of thousands of years post closure.[11],[12] Ceramic fuel forms such as UO_2 fuel pellets are similarly stable in reducing environments and may retain the bulk of their radioactive inventory for similar time frames. The best estimate for the fractional dissolution rate for UO_2 spent fuel in reducing conditions is on the order of 10^{-6} / year to 10^{-7}/ year.[13] This corresponds to ~50% dissolution and consonant release of ~50% radionuclides to the geosphere between 690,000 years and 6,900,000 years. A conservative fractional dissolution rate of 10^{-5} / year, corresponding to 50% release of radionuclides in 69,000 years, is used in our safety calculations.
- **Casings, backfills and seals**: Casing made of low alloy carbon steel (9Cr-L80, P 110) or other appropriate alloys provide a reliable and smooth conduit for canister placement and retrieval. In appropriate reducing environments casings are expected to retain their functionality for many decades to support emplacement and pre-closure retrieval.

For permanent closure, the disposal section is plugged, the casing is removed from the vertical access hole, and the borehole is then sealed using methods in alignment with those being developed and tested by the international community. Potential sealing materials include - where technically appropriate - bentonite clays, cements, asphaltic compounds, and various crushed rock forms used in combination. The backfilled and sealed portion of the borehole may be over a kilometre in length and provides a robust barrier to radionuclide transport.

- **Repository geometry:** There are a number of passive design features of the Deep Isolation repository that perform engineered barrier functions and provide enhanced safety. These include:
  - A slight upward inclination of the horizontal repository section of the borehole (2-3 degrees) which directs fluid flow driven by thermal gradients or upward directed pressure gradients toward the 'dead end' section of the repository and away from the access hole.
  - An offset of the vertical access hole from the horizontal repository which similarly decouples simple hydrologic gradients from driving radionuclide migration upward through the vertical access hole and associated Excavation Disturbed Zone (EDZ).

Exhibit 2.4: Repository performance modelling

- Deep Isolation uses numerical modelling to improve system understanding, to identify key factors affecting repository performance, and to calculate safety-relevant performance metrics.
- For the assessment of the long-term safety of a deep horizontal borehole repository, Deep Isolation simulates coupled thermal-hydrological processes as well as radionuclide transport in an integrated model that includes the source term, engineered barrier components, near field, geosphere, and biosphere. Chemical and mechanical aspects are represented by effective parameters. The model is used to evaluate the long-term safety for a wide range of conditions and alternative system evolutions, using deterministic simulations, sensitivity analyses, and a sampling-based uncertainty propagation analysis.

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[10] Our current canister corrosion analyses have focussed not on crystalline basement but on a 'generic' shale geochemical environment, where we are considering a number of alloys. For example, our initial corrosion analysis for Alloy 625 suggests a lifespan of >40,000 years under conditions of passive corrosion (Payer, J.; Finsterle, S.; Apps, J.; Muller, R.A. Corrosion performance of engineered barrier system in deep horizontal drillholes. Energies 2019, 12, 1491). A more recent study on Alloy 22 predicts a >500,000-year time frame for the passive corrosion of a 1cm wall thickness canister at 1 km depth in a nominal shale environment (Macdonald, Digby. "The general Corrosion of Alloy 22", Deep Isolation internal report, 2020).
[11] Clayton, D., et al. *Generic Disposal System Modeling-Fiscal Year 2011 Progress Report. SAND 2011-5828P*. FCRD-USED-2011-000184. Sandia National Laboratories, Albuquerque, New Mexico, 2011.
[12] Vernaz, Étienne Y. "Estimating the lifetime of R7T7 glass in various media." *Comptes Rendus Physique* 3.7-8 (2002): 813-825.
[13] Posiva, Oy. *Safety case for the disposal of spent nuclear fuel at Olkiluoto-Synthesis 2012*. No. POSIVA--12-12. Posiva Oy, 2012

- Our modelling results for a generic deep horizontal borehole repository demonstrate that the combined effect of the features described in Exhibits 2.1 – 2.3 above (deep geologic barrier, mature technologies for horizontal repository development, and the EBS features of our solution) deliver a high level of safety and provide confidence in the robustness of the repository solution.

Exhibit 2.5: Minimal repackaging

- In many cases, the spent nuclear fuel assemblies that hold the waste can be placed directly in disposal canisters without modification; so too can the internal fuel rods within the assemblies if these have already been removed for storage purposes. The standard dimensions of the fuel assemblies used across the nuclear industry (up to around 30 centimetres in diameter and up to 5 metres long), are extremely well matched to borehole sizes.

Exhibit 2.6: Retrievability

- Borehole retrieval technology is highly developed and, if desired, waste canisters can be retrieved for several decades in a pre-closure phase.
- As discussed at Exhibit 2.2 above, retrieval of objects from deep boreholes is routine in the drilling industry, including uncooperative retrieval. Placement and retrieval of borehole equipment are highly developed and are commonly performed using wirelines with a tractor, coiled tubing, or drill-pipe methods. Deep Isolation's drilling partners are confident that much of this experience is directly transferable to retrieval of disposal canisters containing nuclear waste. (It is worth noting that although we can manage retrievability, it would be practically impossible for any unauthorised party to do so.)
- Deep Isolation builds on this industry experience and is developing additional retrieval technologies that are tailored to our solution. The ability to retrieve waste from horizontal boreholes has been designed into Deep Isolation's solution from the start, including the overarching patented horizontal borehole solution and our emplacement and retrieval systems.
- Deep Isolation's disposal canister design includes a latching mechanism and release elements specifically incorporated to facilitate retrieval - even if stuck during emplacement.
- We have demonstrated the ease of retrieval of small disposal canisters using standard technologies as an initial proof of principle – as illustrated by the short video at https://www.youtube.com/watch?v=3GZ4TC8ttbE. A full-scale demonstration awaits the development of a regional testing facility or potential host site.

Exhibit 2.7: Siting flexibility

- In principle, the Deep Isolation model provides access to an increased number of geologic environments that are appropriate for deep geologic disposal, in settings from 1-3 kilometre depths.
- In addition, Deep Isolation's solution is modular and relatively lower cost, opening up the potential to dispose of waste either at a single site or at multiple locations.
- This combination of siting flexibility and modular delivery opens up a wide range of opportunities, including – subject to community consent, suitable geology and regulatory approval – enabling disposal at or near many of the sites where nuclear waste is produced and stored. In such scenarios, there is potential to minimise transport, and hence to reduce transport costs and the management of associated risks.

Exhibit 2.8: Speed of implementation

- The governments that are currently engaged in developing mined geologic disposal facilities measure the timescales for planning and constructing these in decades. Partly this is due to the lengthy timescales needed for public consultation and regulatory scrutiny, which will be broadly similar for both mined and borehole facilities. But even after regulatory approval is given, implementation of a mined facility is a very lengthy process. For example, analysis of plans published by the Canadian, Swedish and US governments shows[14]:
    - An average of 1 year between regulatory approval and start of construction

[14] See Deep Isolation: An introduction for policy-makers, May 2020

- An average construction period of 8.3 years
- An average emplacement period of 10 years.

- Deep Isolation's solution, by contrast, can start disposing of waste in 1-2 years following regulatory approval:
  - Assuming the Deep Isolation facility is a disposal only facility without a repackaging facility, the mobilization of the drilling equipment and handling facilities can be accomplished in six months.
  - Each borehole can be drilled in a few weeks[15], allowing disposal operations to begin in less than a year from regulatory approval.
  - Borehole construction can be done outside of emplacement activities so construction should never impede the disposal operations after the first borehole is completed and ready for disposal operations.

[15] Detailed timings will vary according to geology and site-specific conditions. Recent horizontal drilling offshore in complex crystalline basement in Vietnam that is similar to, but younger than, the paleoproterozoic rocks comprising the crystalline basement in Estonia have demonstrated that a 3000m horizontal section at a depth of about 2 km (so longer and deeper than in a Deep Isolation repository) can be drilled in less than 45 days.

3. Methodology

We have carried out desk research and evaluation with local geological experts, Engineering Bureau STEIGER LLC, undertaking an initial screening assessment of the extent to which Estonia offers suitable host geology for a Deep Isolation repository. Our starting point was to consider all geologies across the whole of Estonia, looking both at:

- **Safety:** the extent to which the geologic and hydrologic conditions anticipated at depth support the isolation of radionuclides from the biosphere (at a conceptual level).
- **Deliverability:** the extent to which the geology is conducive to cost-effective drilling and construction of a Deep Isolation repository.

Exhibit 3 below illustrates our high-level assessment criteria. For the safety screening assessment, we used criteria aligned with the requirements for geologic disposal sites set out in the IAEA Safety Standards[16]: seismicity, geothermal heat flux / volcanism, climate change and paleohydrology.

Exhibit 3: High level assessment criteria

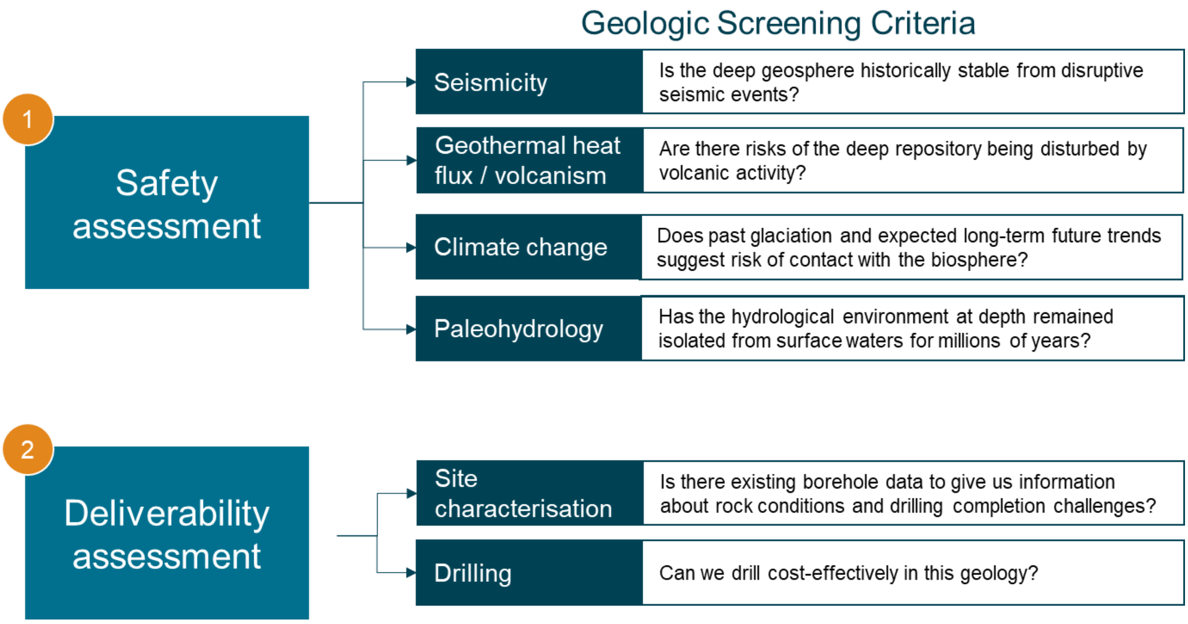


Exhibit 4 on the following page describes the safety assessment factors we have considered within each assessment criterion, as well as the factors we have deliverability assessment criteria for site characterization and drilling. Exhibit 4 also shows the scale we have used to summarise the results of our assessment. This rates the suitability of each region on a scale from 0-3, on which 0 = unsuitable and 3 = highly suitable.

[16] IAEA Safety Standards SSG-14; Geological Disposal Facilities for Radioactive Waste

Exhibit 4: Detailed assessment criteria and associated rating scale

Seismicity

- Tectonic history and framework of the geological setting at a local and regional scale and its historical seismicity
- Evidence of active (Quaternary and possibly late Tertiary) neotectonic processes, such as uplift, subsidence, tilting, folding and faulting
- Presence of faults in the geological setting (e.g. their location, length, depth and information on the age of latest movement)
- Estimates of the characteristics and maximum intensity of earthquake that would be possible at the site on the basis of its seismotectonic context;
- The in situ regional stress field

Geothermal heat flux / volcanism

- Estimates of the geothermal gradient and evidence of thermal springs
- Evidence of active (Quaternary and possibly late Tertiary) volcanism

Climate change

- Climatic history (local and regional) and expected long term future trends at regional and more global scales
- Impact of isostatic rebound from glaciation
- Penetration of freshwater into deep rock formations

Paleohydrology

- What is the regional paleo-hydrologic setting
- Depth of aquifers
- Regional flow regime, recharge time
- Interaction of aquifers with deeper water sources

Deliverability

- Site characterization data availability
- Drilling cost-effectiveness

	0: Unsuitable	1: Potentially suitable	2: Suitable	3: Highly suitable
Safety	Significant risks at region-wide scale: region should be ruled out for repository siting.	Significant risks at region-wide scale, but there may be some suitable host geologies at a more localised level.	No significant risks at region-wide scale, but there may be localised problem areas that will need to be avoided.	No significant risks throughout region; high probability of many locations that are suitable
Site data	There is no existing core data on sub-surface conditions.	Sparse drill hole data, some regional geophysical data.	Numerous drill holes in comparable rock with some measurement data. Regional Geophysical data.	Extensive drill hole data at the depth and in comparable rocks to the anticipated repository drill hole. Detailed Geophysical Data.
Drilling	The region is unlikely to provide any sites in which we could drill cost-effectively.	The region is likely to provide some sites where we could drill cost effectively.	The region provides a wide range of potential sites where we could drill cost effectively, although at the higher end of our cost range.	The region provides a wide range of potential sites where we could drill cost effectively, and at the lower end of our cost range.

We assessed the whole of Estonia, as illustrated below.

Exhibit 5: Counties of Estonia[17]

The following two sections set out our findings of the safety and deliverability assessment.

[17] Source: Wikipedia, 11 January 2021, based on data supplied by the Estonian Land Board

4. Safety assessment

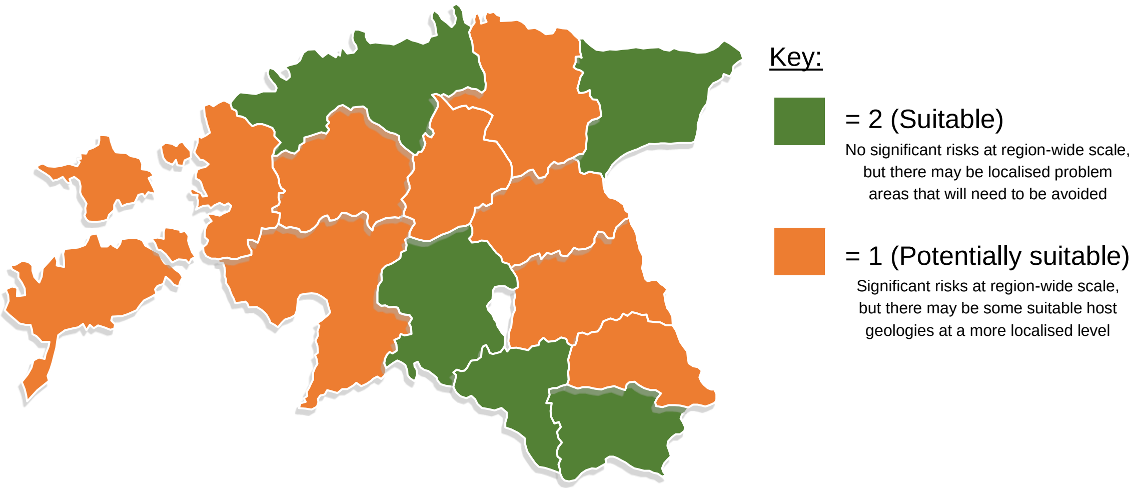
4.1 Seismicity

Overview

Seismicity: assessment criterion
Is the deep geosphere historically stable from disruptive seismic events?

Summary conclusions

All areas of Estonia are at least potentially suitable on this criterion. However, ancient fracture zones in the centre of the country may pose some risk for fault reactivation in response to long term climate change (>100,000 years); this risk needs to be addressed in detailed site characterization efforts.



Detailed findings

There are two assessment criteria here, (1) the current state of seismic risk as evidenced by historical (past 1000 years) and modern seismic data, and (2) a seismic assessment hazard that reflects the somewhat uncertain potential for the effects of climate change on 100,000 year time frames (glacial loading and unloading) to potentially reactivate existing ancient faults.

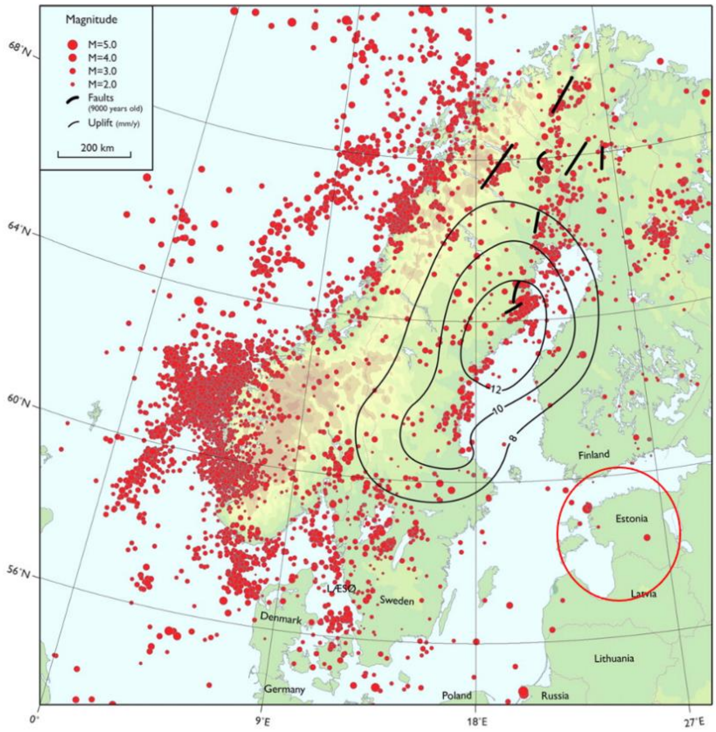
In general, the risk of a major disruptive seismic event in Estonia is quite small. Estonia sits on the East European Craton, a thick continental crust in a relatively quiescent tectonic region of the world. The deep crustal structures which underlie Estonia are generally >1.8Ga in age and represent an assemblage of diverse geologic terranes which have been in place and sutured together through tectonic processes that have long been completed[18]. Estonia is not in proximity to active subduction zones or areas of crustal thinning related to large scale tectonic plate boundaries.

Perhaps the greatest potential for seismicity / fault activation is related to glaciation and isostatic rebound which occurs in the region on roughly 100,000 year cycles. However, compiled historical

18 Alvar, Soesoo, Nirgi Siim, and Plado Jüri. "The evolution of the Estonian Precambrian basement: Geological, geophysical and geochronological constraints." Труды Карельского научного центра Российской академии наук 2 (2020).

earthquake data and maps of modern ground surface uplift indicate that Estonia has been relatively isolated from these effects for at least the most recent glacial period. Post-glacial uplift in Estonia ranges from 0-3 mm per annum - a level of uplift that is many times lower than in Scandinavia, as illustrated in Exhibit 6 . In the last 1000 years of recorded history there have been few earthquakes in Estonia of magnitudes sufficient to cause damage or be recorded by local populations[19][20]. A singular modern exception is the is the 1976 Osmussaar earthquake which had a magnitude 4.7. which caused minor damage.

Exhibit 6: Map of seismicity in Scandinavia from January 1970 to December 2004. Contour lines show post-glacial uplift in millimetres per year.[21]



In terms of deep borehole repository safety, earthquakes can cause damage directly via fault rupture and indirectly via large amplitude seismic waves created by the earthquake. Surface damage is primarily due to the latter and is most prevalent in weak soil[22]. The potential for damage away from the earthquake fault diminishes with increasing depth due to attenuation of the surface waves and the increase in rock strength[23]. Thousands of deep drill holes in the oil and gas industry have been subjected to vibrations from large nearby earthquakes over the past 100 years, and there is no documented evidence that any drill hole in competent rock was damaged.

A repository disruption scenario – though unlikely – can occur when seismic activity creates a new fault or reactivates an old fault, which intersects the repository causing damage to the borehole.

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[19] Stucchi, Max, et al. "The SHARE European earthquake catalogue (SHEEC) 1000–1899." Journal of Seismology 17.2 (2013): 523-544.

[20] Grünthal, Gottfried, and Rutger Wahlström. "The European-Mediterranean earthquake catalogue (EMEC) for the last millennium." Journal of Seismology 16.3 (2012): 535-570.

[21] Gregersen, Soren, and Peter Voss. "Stress change over short geological time: the case of Scandinavia over 9000 years since the Ice Age." Geological Society, London, Special Publications 316.1 (2009): 173-178.

[22] Soil Mechanics, Rock Mechanics and Soft Rock Technology, I.W. Johnston, Proceedings of the Institute of Civil Engineers: Geotechnical Engineering, 1994, pp. 3-9.

[23] Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results, G. Bäckblom, C.R. Munier, Technical Report TR-02-24, Svensk Kärnbränslehantering AB, Swedish Nuclear Fuel and Waste Management Co. June 2002.

Earthquake damage to oil fields and to the Paloma cycling plant in the San Joaquin Valley, R.L. Johnston, Earthquakes in Kern County, California during 1952, 1952.

Studies[24] have shown that if a borehole intersects an active fault, it can be sheared if that fault slips for a moderate earthquake. Borehole repository design features (such as aligning boreholes parallel to existing fault structures and in relation to regional stress fields) can help mitigate risks and reduce the probability of a fault disruption event. Even so, one must consider the impact that direct fault disruption might have on the long-term performance of a repository, and the resulting peak dose at the surface. A number of modelling efforts by Deep Isolation exploring fault disruption have found that there is relatively little impact on overall repository safety, even in extreme circumstances[25].

Given the low seismic activity throughout Estonia and the general high strength nature of the Paleoproterozoic rocks at the disposal depth, the earthquake vibration risk in Estonia appears to be extremely small. Though there are known fault structures which penetrate both basement and overlying Paleozoic sediments, the potential for fault reactivation in most areas appears to be modest due to the low regional seismicity. Strategies to mitigate seismic hazards are also addressed both by site characterization and in repository design. In light of all of these factors we consider the overall seismic risks to borehole repository performance to be relatively low throughout most of Estonia.

In summary, all areas of Estonia are at least potentially suitable for borehole disposal on this criterion, but the ancient fracture zones in the centre of the country may pose some risk for fault reactivation in response to long term climate change (>100,000 years) – a risk that would need to be addressed in detailed site characterization efforts.

For example, the map at the start of this section rates Lääne-Viru county overall as “potentially suitable” (compared with the stronger classification of the other northern counties as “suitable”), because two fault lines are present in the east and west of the county. At a more localized level, however, more central parts of Lääne-Viru are likely to provide a range of sites that a full site characterization study could demonstrate as safe on this criterion: for example, Kunda, the community where Fermi Energia is currently engaged with local stakeholders about its potential as a host site for Estonia’s small modular reactor, is located a safe 10-15 kilometres away from these fault lines.

[24] The Dominguez Hills, California, earthquake of June 18, 1944, S.T. Martner, Bulletin of the Seismological Society of America, 1948.
Tank damage during the May 1983 Coalinga earthquake, G.C. Manos, R.W. Clough, Earthquake Engineering & Structural, 1985.
All historical data on earthquakes are from J. Daniell and A. Schaefer, “Eastern Europe and Central Asia Region Earthquake Risk Assessment Country and Province Profiling,” final report to GFDRR, 2014.
Stucchi, Max, et al. "The SHARE European earthquake catalogue (SHEEC) 1000–1899." Journal of Seismology 17.2 (2013): 523-544.
Grünthal, Gottfried, and Rutger Wahlström. "The European-Mediterranean earthquake catalogue (EMEC) for the last millennium." Journal of Seismology 16.3 (2012): 535-570.
Gregersen, Soren, and Peter Voss. "Stress change over short geological time: the case of Scandinavia over 9000 years since the Ice Age." Geological Society, London, Special Publications 316.1 (2009): 173-178.
Alvar, Soesoo, Nirgi Siim, and Plado Jüri. "The evolution of the Estonian Precambrian basement: Geological, geophysical and geochronological constraints." Труды Карельского научного центра Российской академии наук 2 (2020).
[25] Finsterle et al., 2020; Finsterle et al., 2021

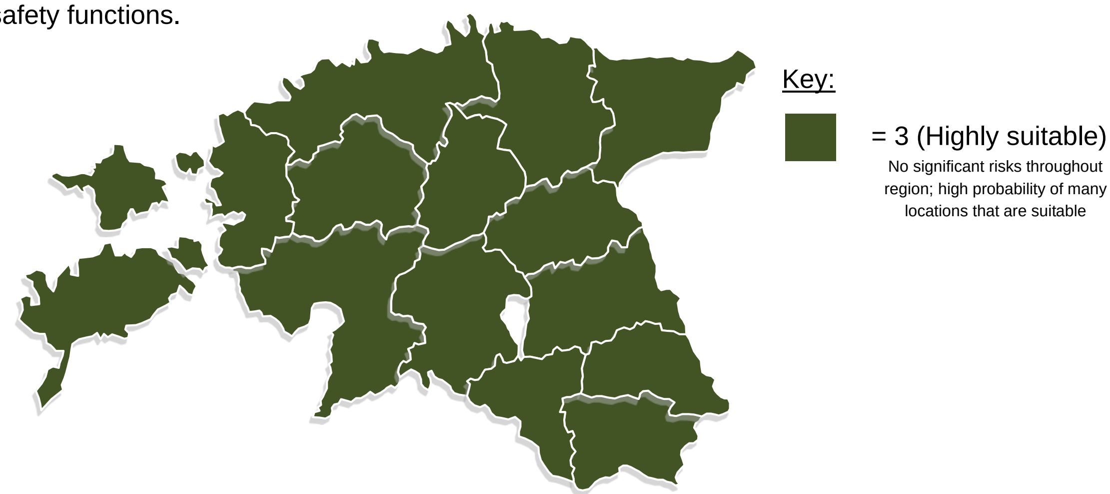
4.2 Geothermal heat flux / volcanism

Overview

Geothermal heat flux / volcanism: assessment criterion
Are there risks of the deep repository being disturbed by geothermal activity?

Summary conclusions

All areas of Estonia are rated as highly suitable on this criterion. Estonia is located in a region with no volcanism and relatively low crustal heat flow. There is no evidence we see that thermal driving forces exist beneath Estonia that might compromise repository integrity or adversely affect its safety functions.



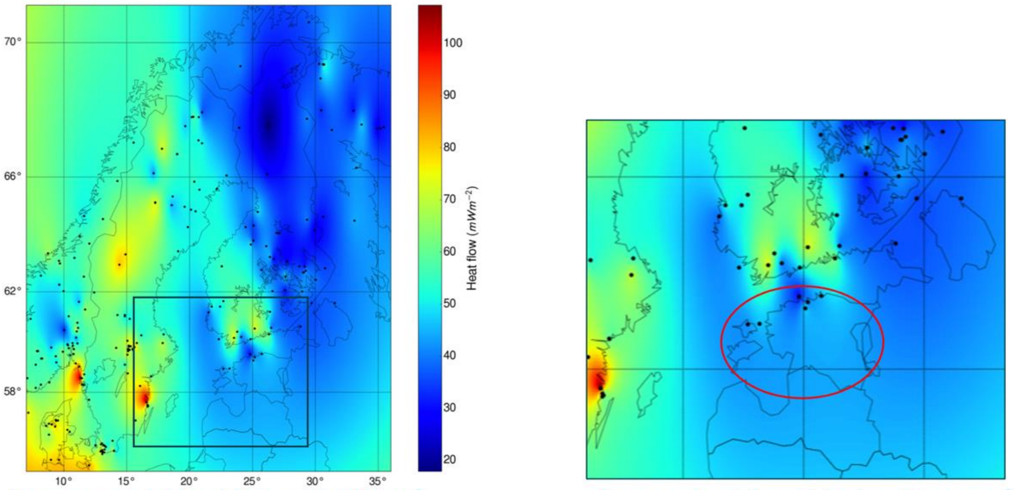
Detailed findings

Heat flow over all of Estonia is extremely low since Estonia is located in a tectonically less active area and has a thick crust. There is no active volcanism in Estonia and basement rocks indicate that any volcanism ended over 1 billion years ago. There is no evidence we see that thermal driving forces exist beneath Estonia that might compromise repository integrity or adversely affect its safety functions.

This is illustrated in the diagrams below:

- Exhibit 7 shows that the average heat flow in Estonia is almost half the average level of the wider region.
- Exhibits 8 and 9 look in more detail at Estonia, and show that the heat flux density in Estonia is extremely low (20-70 mW / m2). The heat flux density is stable over most of Estonia, with the exception being the Northeast Estonia where it is somewhat elevated (40-70 mW / m2) and more similar to the average values seen in Scandinavia (Exhibit 7.). This anomalous area is supposedly linked with the Jõhvi basement zone and continues east to Russia. While the elevated heat flux density in Northeast Estonia is interesting in terms of regional basement geology, it does not compromise repository integrity or adversely affect its safety functions.

Exhibit 7: Average crustal heat flow



Average crustal heat flow: ~80 mW m-2 Average heat flow Estonia ~45 mw m-2

Exhibit 8: Conservative view of measured heat flux density (Jõeleht, 2002). The figure shows only reliable data for which temperature data have been available, and it has been possible to check the absence of effects related to water flow. When excluding the Northeast Estonia, the rest of the Estonia has a heat flux density in the range of 30-40 mW / m2.

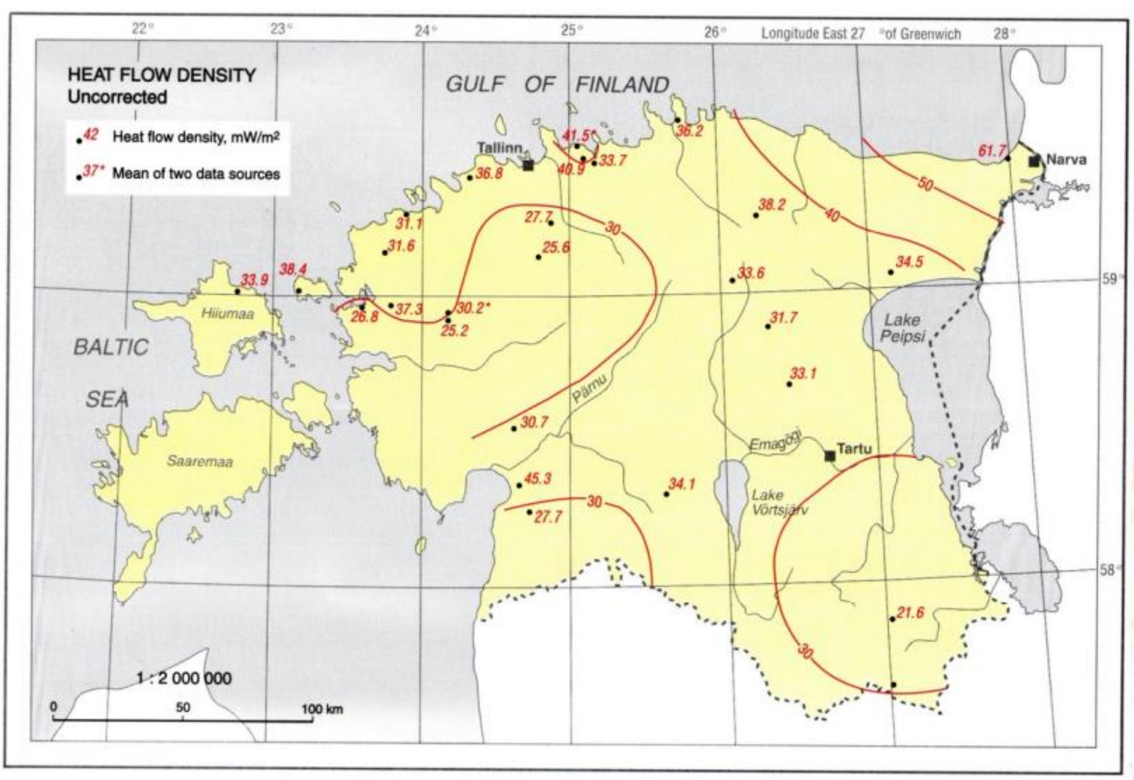
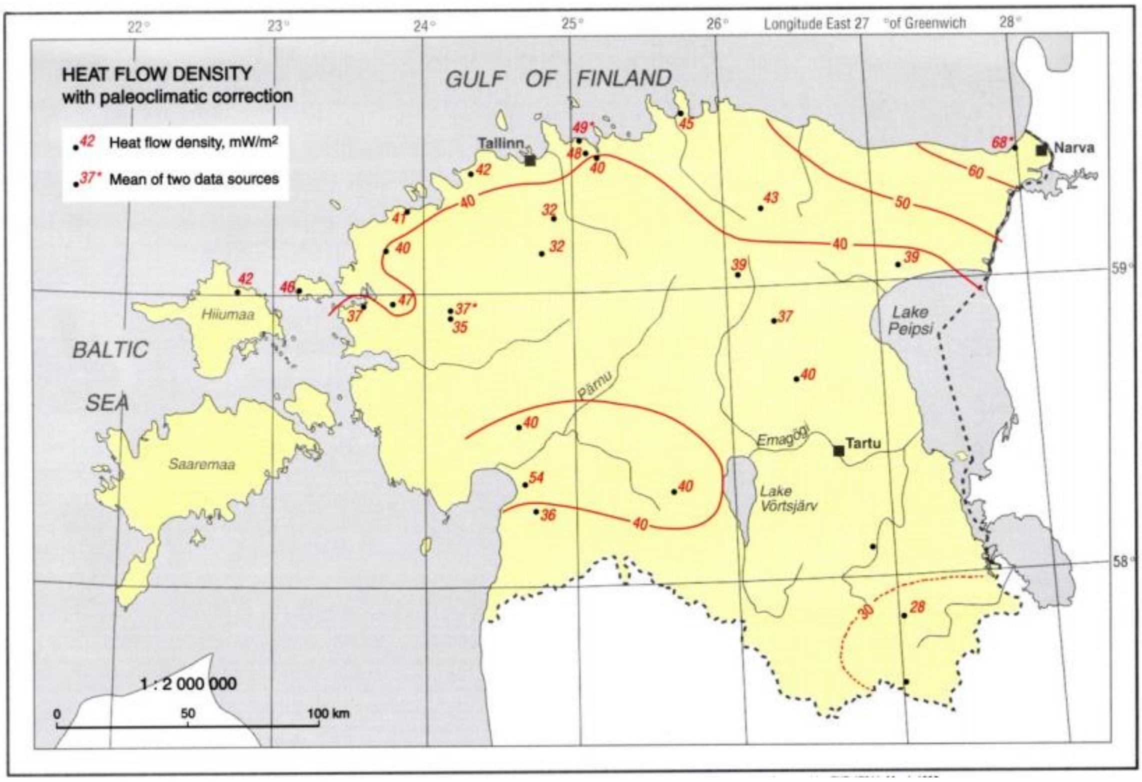


Exhibit 9: Improved heat flux density map with respect to past climate change effects that better describes the heat flow coming from deeper underground (Jõeleht, 2002).

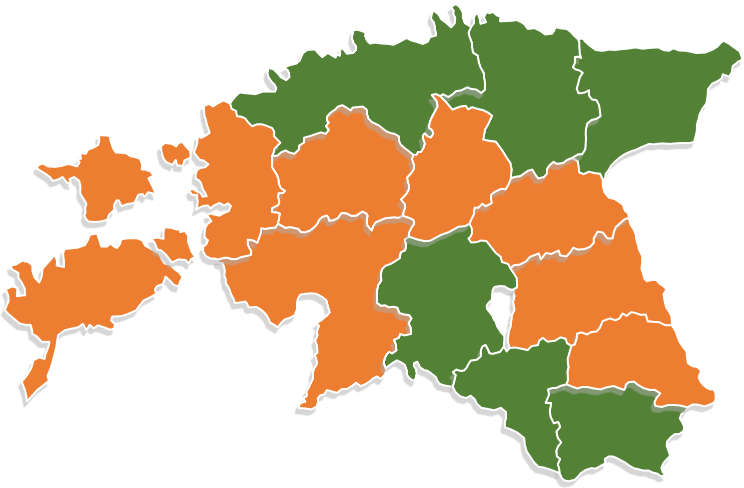


4.3 Climate change

Overview

Climate change: assessment criterion
Does past glaciation and expected long-term future trends suggest risk of contact with the biosphere?

Summary conclusions
Climate change impacts including the crustal effects glacial loading and unloading appear to be quite small in Estonia.



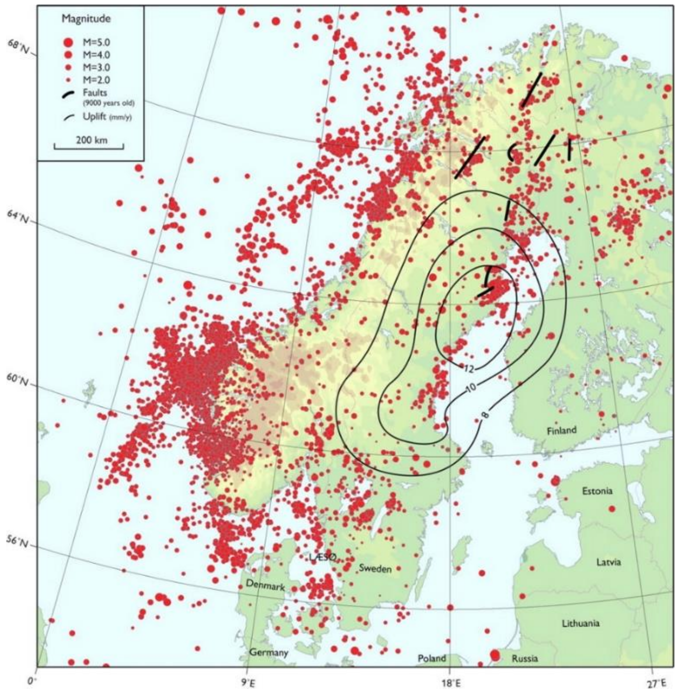
Detailed findings

Estonia is located near 59° northern latitude and is vulnerable to variations in climate associated with ice ages. In the recent geologic past, ice ages have recurred on a roughly 100,000 year cycle and we are currently living in an interglacial period which began roughly 10,000 years ago. The major repository and safety relevant impacts of climate change in Estonia are related to (1) the tectonic and seismic effects of glacial loading (weight of 1-3 km of ice) and isostatic rebound (uplift when the ice melts), (2) surface erosion due to migration of ice sheets, and (3) the potential incursion of fresh water into the deep basement hydrologic system.

Within the Scandinavian region it appears that Estonia is relatively isolated from the tectonic effects of at least the most recent glacial cycle. (Gregerson and Voss, 2014.) (Exhibit 10) Nearby areas in Norway, Sweden and Finland all show elevated seismicity and relatively rapid post glacial uplift. By contrast, Estonia which experienced lighter ice loading shows a remarkable lack of seismicity and is outside the region of rapid uplift. (Artemieva and Thybo, 2013; Simon et al. 2018.)

In terms of erosion there is evidence of some glacial incision into the Paleozoic formations above the crystalline basement rock in Estonia. (Tavast, 1997.) However, there is no indication that general rates of glacial erosion in the region would threaten repositories located 1.5 km below the current land surface. Estimates of the long-term erosion rates for other areas in Scandinavia suggest mean regional erosion rates from glaciation in Estonia might be on the order of 5 m over the last million years. (Olymo, 2010; Påsse, 2004.)

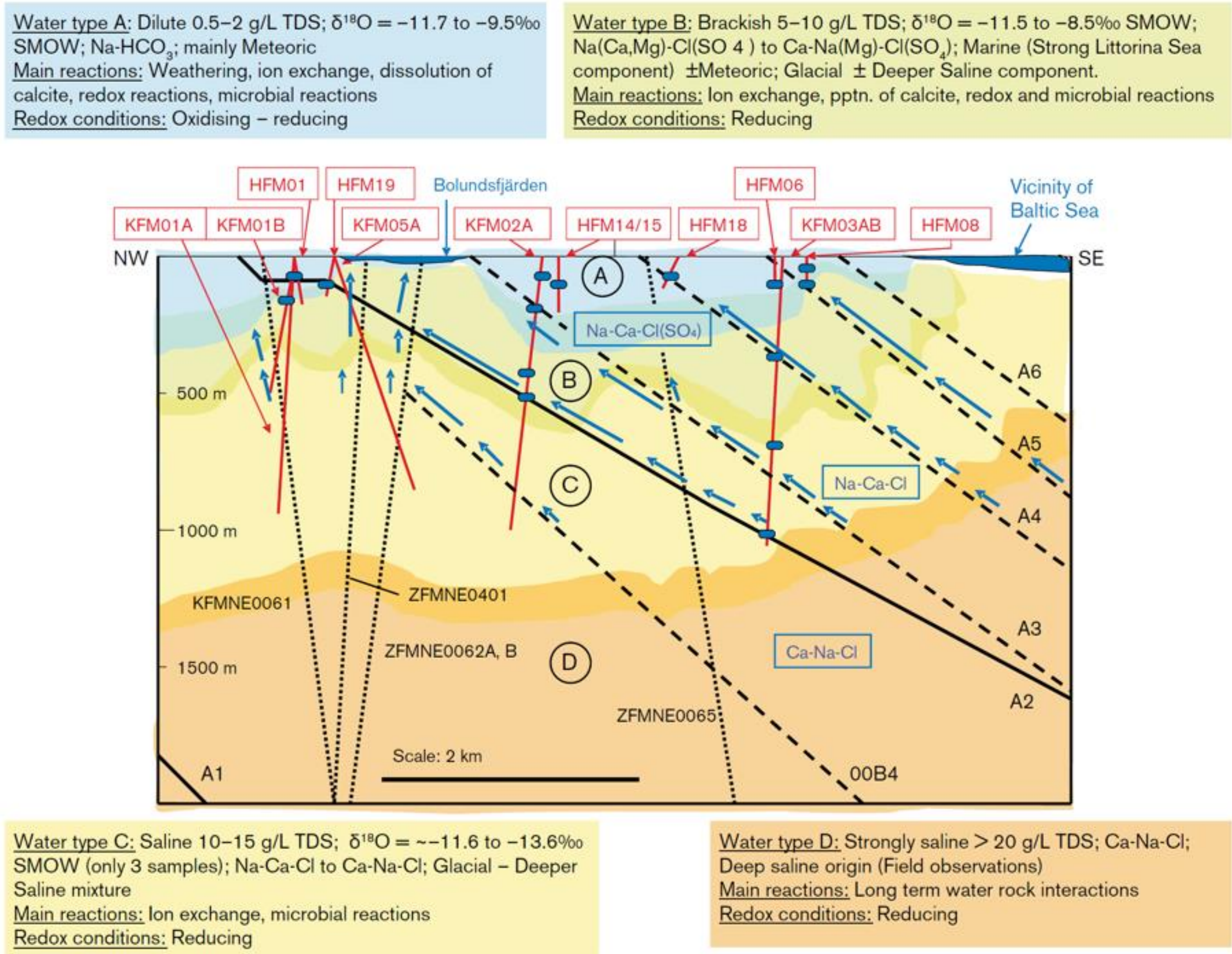
Exhibit 10: Map showing seismicity in Scandinavia from January 1970 to December 2004. Contour lines show post-glacial uplift in millimeters per year. (Gregersen and Voss, 2014.)



The effects of sea level change and ice melting on the depth of penetration of glacial freshwater into the crystalline basement rock of Estonia are unknown, but are likely to be modest. Data from some freshwater aquifers in Estonia show a strong negative delta $\delta^{18}O$ signature, indicative of relatively recent recharge with isotopically light glacial meltwater. However, waters sampled in crystalline basement are generally highly saline, and are clearly isotopically distinct from the glacial meltwater. (Vaikmäe et al., 2001; Raidla, et al., 2009.) As there is currently no isotopic or chemical data for waters at repository depths (~1.5 km) in Estonia for insight one needs to look to studies done in other nearby regions with a similar geology and glacial history. The Forsmark site in Sweden provides a reasonable analogue and offers information on the impacts of glaciation on a deep hydrologic system in crystalline basement.

At Forsmark data from a number of deep drillholes identify four relatively distinct hydrologic zones which are stratified according to depth, salinity, chemistry and oxidation state. (Exhibit 11, Hedin 2006.) Oxygen rich meteoric waters low in dissolved solids penetrate approximately 300m beneath the ground surface. As depth increases from 300-1000 meters there is a transition through two distinct hydrologic regions, each with progressively increasing salinity, higher total dissolved solids, more reducing conditions and - implicitly - greater isolation from the surface. Below about 1200 meters, the waters are hypersaline with characteristics that suggest the composition is derived from long term water rock interactions and that it has been largely isolated from the effects of glaciation and freshwater intrusion. One might expect a similar level of isolation from glacial effects in Estonian crystalline basement.

Exhibit 11: Schematic hydrologic model of Forsmark repository site Sweden. (Hedin, 2006 SKB-TR-06-09)



Without site specific data, one cannot make a case that the hydrologic environment at depth in Estonia has been entirely insulated from the effects of climate change and glaciation. However, regional studies, like the work done at the Forsmark site in Sweden, as well as isotopic studies of deep crystalline basement in other regions (Warr et. al. 2018, Gascoyne 2014) all provide some confidence that deep crystalline basement in Estonia is likely to have remained protected from many effects of climate change over the past >1 Ma.

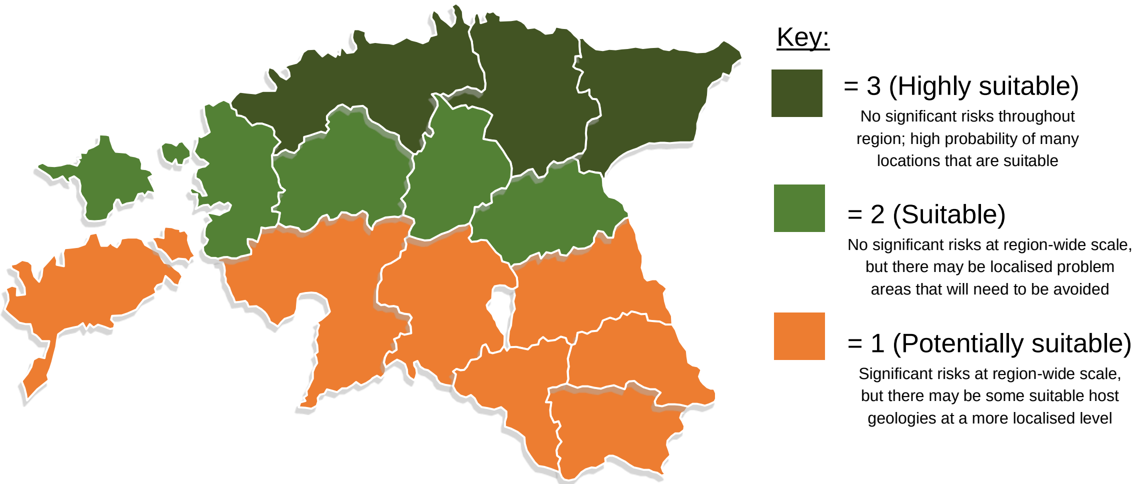
DEEP ISOLATION™

4.4 Paleohydrology

Overview

Paleohydrology: assessment criterion
Has the hydrological environment at depth remained isolated from surface waters for millions of years? Can we access suitable rock formations which are isolated from aquifers?

Summary conclusions
Many regions in Estonia are likely to have geologic formations at repository depths (~1.5 km) which could be demonstrated to have remained isolated from the biosphere for millions of years. However, in southern Estonia the greater depth of aquifers requires drilling to greater depth to find suitable isolated crystalline basement strata. From the standpoint of modern aquifer protection, siting a repository in the south creates a potential connection point where the general northward flow of interconnected deep aquifers might disperse contaminants throughout the entire aquifer system. The northern coastal areas of Estonia provide the most suitable locations, with shallower aquifers, regional flow directed northward offshore, and likely less connectivity between the deep geosphere and surface waters.



Detailed findings

All Estonian regions are likely to provide host rocks which can be demonstrated to have remained isolated from the biosphere for millions of years, but in southern Estonia the presence of aquifers at greater depth will make this more difficult to demonstrate. The northern coastal areas of Estonia provide the most suitable locations, with shallower aquifers and less connectivity between the deep geosphere and surface waters.

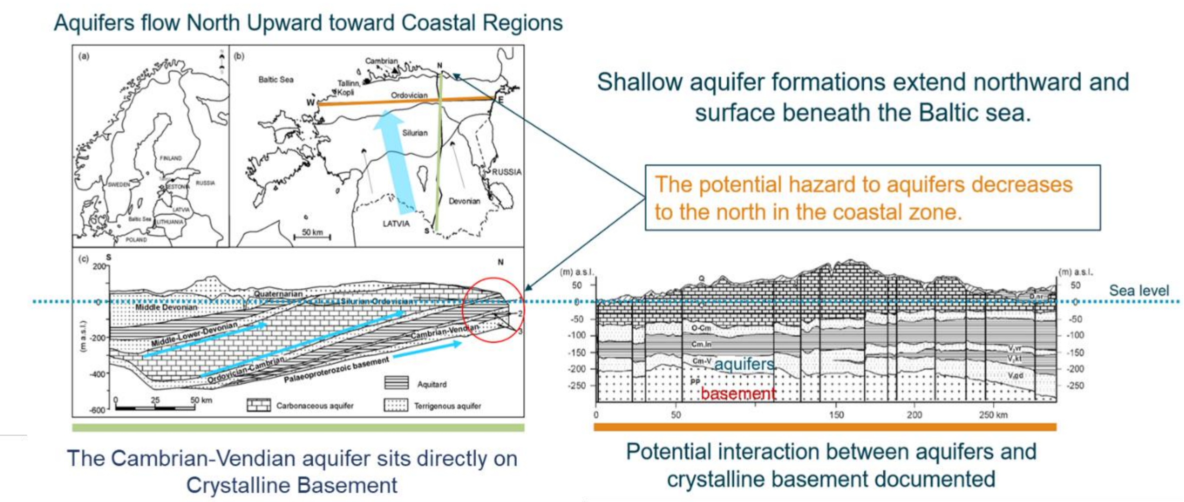
Below we look in turn at:

1. Aquifer-related safety considerations in Estonia
2. The use of isotopic evidence to demonstrate paleohydrological isolation in the past.

1: Modern aquifer systems in Estonia in relation to repository siting

Estonia relies on a number of shallow regional freshwater aquifers at varying depths for much of its municipal and agricultural water supply. The relationship between these aquifers and the underlying crystalline basement strata has potential implications for repository siting and safety evaluation. A hydrogeologic map of Estonia reveals a suite of stacked aquifers shallowing from South to North, with the deepest aquifers at close to 500m depth in the south and less than 100m depth the north. (Perens & Vallner 1997; Vaikmae et. al., 2007.) The aquifers are largely continuous and follow gently dipping regional bedding planes of Paleozoic sedimentary strata. Importantly, many areas of the deep Cambrian-Vendian aquifer are in direct contact with the underlying crystalline basement – as are some more limited areas of the Ordovician-Cambrian aquifer in the south of Estonia. Clay aquitards which interleave between aquifers and provide some isolation are penetrated locally by incised glacial valleys. (Tavast, 1997.) This creates connections between aquifers at different depths and because of this the entire region should be conservatively considered as an interconnected hydrologic system. Though competent crystalline basement generally acts as an aquitard, there is some evidence of fluid exchange and interaction between the lower aquifers and the uppermost weathered basement strata. (Karo et. al. 2004; Marandi, 2007.)

Exhibit 12: Map and schematic cross sections showing the depth and location of aquifer systems in Estonia. *North-south section line (green) shows the upward trend of basement and aquifer strata to the north. East-west section line (orange) shows the relatively flat profile of the aquifers in this direction. Regional northern trending aquifer flow lines highlighted in blue. (after Marandi, 2007; Perens & Vallner 1997.)*



Understanding recharge patterns and regional flow regimes in the aquifers provides some guidance for risk assessment and repository siting considerations. The basal Cambrian-Vendian aquifer which is in direct contact with crystalline basement in much of Estonia has multiple recharge sources. In a highly simplified analysis, geochemical markers indicate primarily a mixture of old saline sources high in dissolved solids with young freshwaters stemming from either modern surface sources or glacial recharge. Though there is significant local complexity, regional aquifer flow patterns suggest a consistent southern recharge zone and northward flow regime for the slightly over pressured Cambrian-Vendian system. Estimated flow velocities of groundwater in the Cambrian-Vendian aquifer are on the order of 10^{-3} and 10^{-4} m d^{-1}. (Perens & Vallner, 1997; Raidle, et al. 2009; Republic of Estonian Land Board GIS maps.)

Based on these observations contaminants which enter the aquifer system in southern Estonia from below might passively spread throughout the entire regional aquifer system by natural flow mechanisms. By contrast, contamination to aquifers that might occur in the northern coastal regions would likely migrate northward beneath the Baltic Sea. From a repository siting standpoint there is increased passive protection of aquifers in the northern coastal regions of Estonia, where (1) the depth of aquifers is shallower (further from repository depth) and (2) the natural northward flow regime tends to isolate contaminants from the municipal and agricultural water sources.

2: Using Isotopes to evaluate the past Isolation of the Deep Geosphere

Evidence of past isolation provides a measure of the integrated response of the deep hydrologic-geologic system to long-term forcing mechanisms, like climate change, glacial loading, seismic activity, erosion, and other events that may be unforeseen and difficult to predict. This past behaviour increases confidence in the capacity of the geosphere to maintain a central safety function, irrespective of the longevity of engineered barriers. It is likely that if a deep hydrologic-geologic system has remained isolated from the surface and demonstrated retention of mobile elements over the past > 1 Ma it will retain these safety relevant capacities over similar time frames in the future.

The primary evidence for past isolation is developed from study of a wide range of isotopes and isotopic systems which carry information on (1) the incursion and mixing of isotopes carried in surface waters (e.g. ^{81}Kr, ^{36}Cl) and (2) the long-term isolation of pore waters and fracture fluids determined by the concentration of isotopes produced and retained *in situ* at depth (e.g. ^{36}Cl, ^{4}He, and other noble gases). The measurement of such isotopes in conjunction with other independent geochemical markers ($\delta^{18}O$, δ D, among many others) provides a powerful means to assess both the past isolation of the deep geosphere and its capacity to retain mobile radionuclides. (IAEA, 2013; Hama and Metcalfe, 2014.)

Currently there is no known work on the isotopic composition of fracture fluids from greater than several hundred meters depth in crystalline basement in Estonia. In the absence of data from Estonia, one must look to case studies from similar or adjacent geologic environments for preliminary assessment. A review of ^{36}Cl data collected for the Onkalo repository site in Finland and the Forsmark repository in Sweden suggests that ^{36}Cl has at both sites reached secular equilibrium concentrations at depth. (Gascoyne, 2014.) This indicates that the ^{36}Cl has been produced and retained in situ for a minimum of 1- 1.5 Ma. Studies of noble gas accumulation at 1-2 km depths at the Outokumpo deep drillhole site in Finland report mean residence times of ^{4}He on the order of 20-50 Ma. (Kietäväinen et al., 2014.) Further away in the Canadian shield, studies of fracture fluids at 1.4 - 2.5 km depths in widely separated deep mines indicate noble gases produced at depth (He, Ar, Ne, Xe) have been accumulating underground for tremendous time periods, indicating residence times of 100Ma->1Ga. (Holland et. al. 2014, Warr et. al. 2018.)

In general, there is evidence in the literature that many ancient crystalline basement environments in similar climate zones contain waters in deep fracture networks that have been isolated for many millions or tens of millions of years. The evidence suggests these rock strata can provide both isolation from the surface biosphere and have the potential to retain many mobile safety relevant isotopes (e.g. 36Cl, and by corollary ^{129}I). One might reasonably expect to find similar conditions exist in deep crystalline basement formations in Estonia. The development of an isotopic study program in Estonia would help support repository siting efforts and provide a basis for evaluating the long-term geologic safety case for different regions in Estonia.

5. Deliverability assessment

5.1 Site characterisation

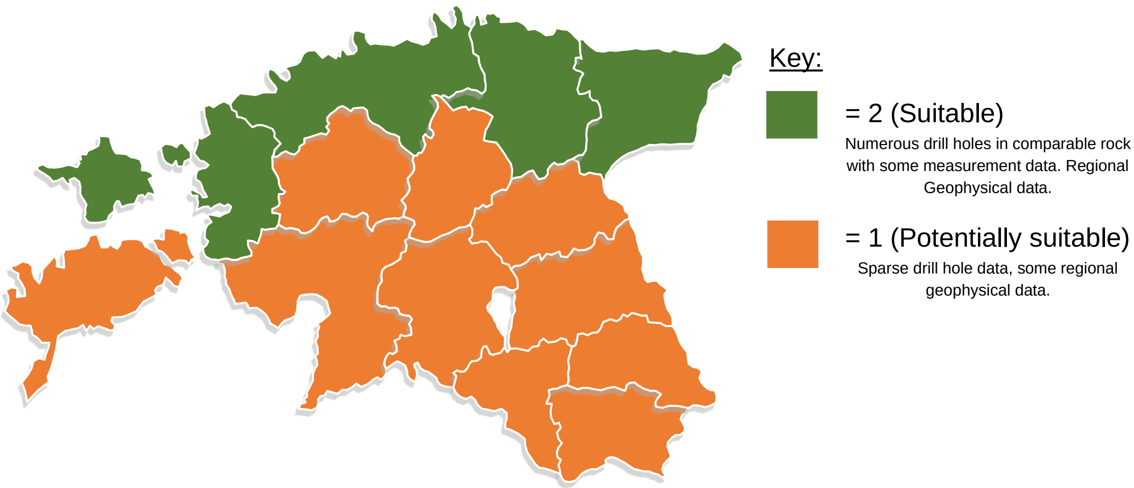
Overview

Site characterization: assessment criteria

Is there existing borehole data to give us information about rock conditions and drilling completion challenges?

Summary conclusions

There are currently no drill holes or core samples drilled to the anticipated repository depth of ~1500 m. However, existing shallower cores and data provide some evidence of regional continuity/heterogeneity in the basement rock that may extend to similar crystalline basement rocks at greater depth. The available drill hole data is focused on the northern coastal regions.

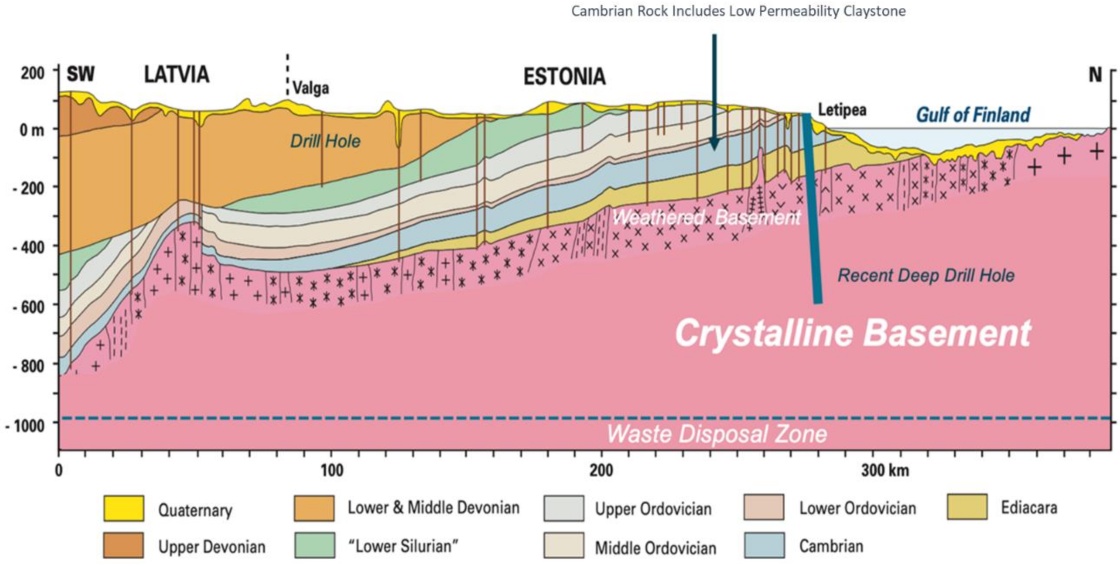


Detailed findings

It is anticipated that the waste isolation/disposal interval of the horizontal drill holes will be at a depth of approximately 1.5 km below the surface. As shown in Exhibit 13, throughout Estonia, this depth is associated with intact (unweathered) crystalline basement. Depending upon the location chosen for the drill holes, the vertical section will encounter an (0-100 m) interval of Quaternary sediments consisting of glacial, glacifluvial and glaciolacustrine sediments[26]. Beneath the Quaternary sediments are Paleozoic sediments (30-500 m) ranging in age from 540 to 360 million years ago. Below the Paleozoic sediments, is a (0-100 m) interval of weathered and possibly fractured crystalline basement of Paleoproterozoic age. Beneath the weathered crystalline basement, the drill hole curve and the 2 km horizontal disposal interval will be located in intact Paleoproterozoic (1.9-1.5 billion year old) crystalline basement.

[26] Heikki Bauert (UPPSALA UNIVERSITY FIELD TRIP in Estonia, NGO GEOGUIDE BALTOSCANDIA). April 13 – 16, 2013

Exhibit 13[27]: Generalized geologic cross-section of Estonia. Paleozoic and some Quaternary rocks conformably overly crystalline basement formed between 1.5 and 1.9 billion years ago. The regional basement surface dips gently to the south.



Soesoo et al.[28] and Kirs el al.[29] provide a comprehensive review of the petrographical, petrophysical and geochemical properties Estonian basement rock types and their evolution. The data were derived from investigations of 32,500 m of drill cores from about 500 drill holes as well as regional gravity and magnetic surveys. The drill holes, generally located in the north of Estonia, terminated the weathered basement (and in some instances the intact basement beneath). The extrapolation and thus the interpretation of basement rock types is likely less reliable where drill holes are sparse, primarily in the south of Estonia.

Exhibit 14 (left) shows a map of the basement rock types and basement fracture and fault zones in Estonia while Exhibit 14 (right) shows the Bouger gravity anomaly and the total magnetic anomaly. The regional gravity and magnetic highs in southern Estonia correspond to the granulite facies terrain, while the gravity and magnetic lows of northern Estonia correspond to the mainly amphibolitic facies terrain[30].

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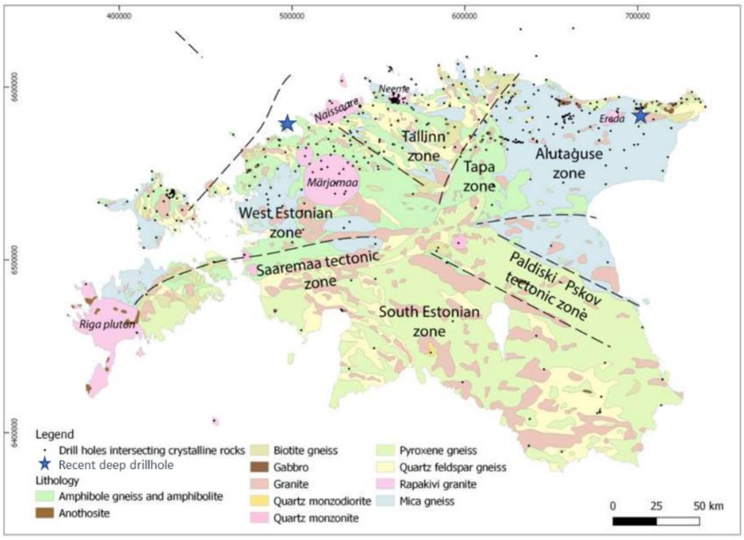
27 Adapted from *Heikki Bauert (UPPSALA UNIVERSITY FIELD TRIP in Estonia, NGO GEOGUIDE BALTOSCANDIA). April 13 – 16, 2013*

28 Soesoo, A., S. Nirgi, J. Plado, THE EVOLUTION OF THE ESTONIAN PRECAMBRIAN BASEMENT: GEOLOGICAL, GEOPHYSICAL AND GEOCHRONOLOGICAL CONSTRAINTS Transactions of the Karelian Research Centre of the PAH Russian Academy of Sciences No. 2. 2020. P. 18–33

29 Juho Kirs, Vaino Puura, Alvar Soesoo, Vello Klein, Mare Konsa, Heino Koppelmaa, Mati Niin, and Kristjan Urtson. The crystalline basement of Estonia: rock complexes of the palaeoproterozoic Orosirian and Statherian and Mesoproterozoic Calymmian periods, and regional correlations

30 Ibid, footnote 30

Exhibit 14: ***Estonian basement provinces/zones, separated by fault and fracture zones.*** *The depth to top of basement ranges from less than 200m along the Gulf of Finland to over 600m near the Latvia border in the south. Note that most of the basement drilling has been conducted in the north of Estonia. Recent basement drilling sampled intact crystalline basement at the Paldiski and Jõhvi areas.*



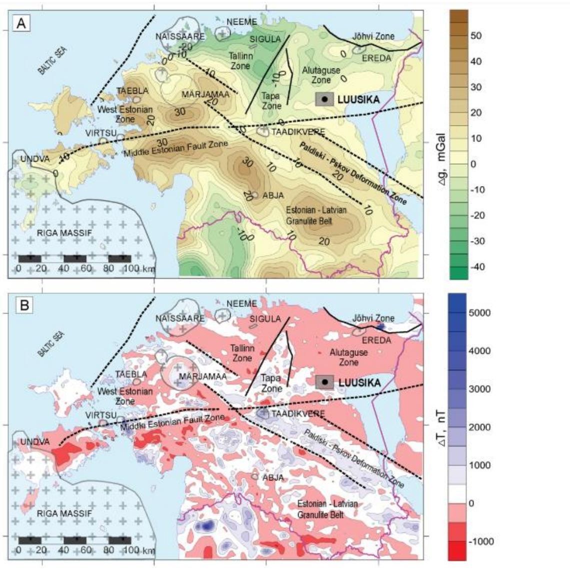


Fig. 1. Structural features and metamorphic complexes of the Precambrian basement compared to (A) Bouguer gravity and (B) magnetic anomaly maps. Non-marked areas represent Svecofennian metamorphic and plutonic rocks; crossed areas are anorogenic complexes of rapakivi and related granites. Geological data are after Puura et al. (1997) and Bogdanova et al. (2015). Geophysical overview maps are by the Geological Survey of Estonia. The grey square indicates the location of the studied Luusika area.

Regional Lithology and History of Basement Rocks

At least five regional basement provinces separated by fracture zones and faults are interpreted to subdivide the basement rocks of Estonia. The Paleoproterozoic basement rocks of Estonia range in age from approximately 1.5 to 1.9 billion years old and were emplaced during the Svecofennian Orogen. The Svecofennian Orogen is interpreted as subduction-related collisions of several island-arc structures[31]. The youngest rocks (Rapakivi granitic plutons) may have less intense deformation as they were emplaced after the orogen. A number of these plutons are in the W and NW of Estonia.

The drillhole sampled basement rocks in Estonia are principally metamorphosed rocks (primarily gneisses), although syn- and late- orogenic granitic facies are present in more than 400 of the drill cores[32]. In the north of Estonia, particularly in the Altugese Zone, basement consists of metamorphosed turbidites, gneisses, marbles and quartzites, as well as intrusive rocks (gabbros and granites) and migmatites. The zone represents a deformed and strongly folded marginal part of a sedimentary basin that extends to St Petersburg and Novgorod. These rocks are believed to belong to a section of Svecofennian rocks cropping out in Southern Finland[33]. Consequently, the geology in Finland, including the rocks in the vicinity of the Onkalo nuclear waste repository, may be a proxy for the intact basement rocks in the north of Estonia.

Mafic facies are less common, occurring in less than 100 drill cores primarily in western Estonia[34], and ultrabasic rocks are exceedingly rare (4 drill cores). Most of these rocks show evidence of both metamorphism and migmatisation. Migmatisation of these rocks was likely due to the melting of lower crust under granulite facies conditions along with the emplacement of some mafic dykes.

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31 Meidla, Tonu, Estonia- a Paleozoic country 4th Annual Meeting of IGCP, Estonia, 2014. Regional correlations Estonian Journal of Earth Sciences, 2009, 58, 4

32 Ibid, footnote 33

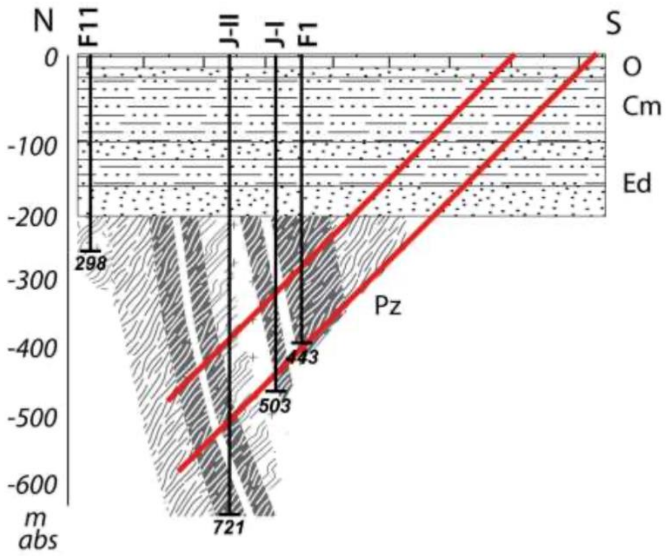
33 Outlines of the Precambrian basement of Estonia Proceedings of the Estonian Academy of Sciences · September 2004

34 Ibid, footnote 33

Structure and Geomechanical Properties of Basement Rocks

Recent core holes drilled in northern Estonia provide data on important rock properties for the deep drill hole repository such as local structure and geomechanical properties. Exhibit 15 is a geologic cross-section obtained from 1980's vertical drill holes and recent slant holes with interpreted geologic structure. Dips are near vertical and layers consist of alternating gneiss and granitic rock and thus horizontal disposal holes may encounter highly variable lithologies over short distances.

Exhibit 15: Geologic Interpretation from the Jõhvi drill holes. The dark colours represent gneisses while the light colours represent granitic rocks (primarily quartzite).



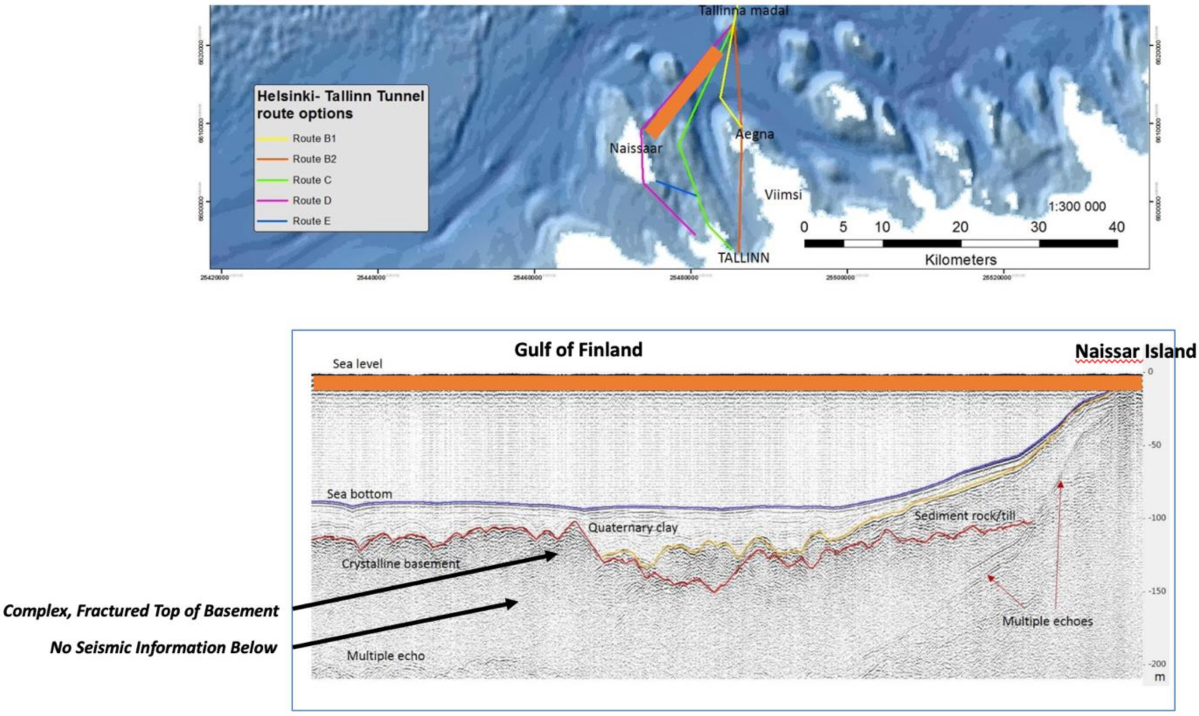
The geotechnical data obtained from these drill holes included fracture number, core recovery, and rock quality designation (RQD[35]. Based on RQD values (80%-100%) the rock is considered good (75-90%) and excellent (>90%) with minimal fracturing 1-6 fractures/m and no weathering except on the surface of fractures. Based on core photographs, the fractures present in the intact core appear to be filled. These measurements suggest a rock strength in the range of 100-200 MPa.

Unlike the interpretation in Exhibit 15, the true basement surface appears to be highly fractured and faulted based on shallow seismic data from the Gulf of Finland (Exhibit 16 below[36]). It is possible that many of these faults and fractures extend down to the repository level at 1.5 km.

[35] Deere and Deere, 1988, The Rock Quality Designation Index (RQD) in Practice. Rock Classification Systems for Engineering Purposes, ASTM STP, American Society for Testing and Materials, 91-101.

[36] Acoustic-seismic survey along the proposed railway tunnel route options, between Helsinki and Tallinn. 19.8.-1.11.2016 GEOLOGICAL SURVEY OF FINLAND MARINE GEOLOGY 10.1.2017 Kimmo Alvi

Exhibit 16: Shallow seismic survey near the coast of Estonia



Rocks with minimal fracture zones have been encountered in deep basement drill holes, but even if we encounter extensive fracture zones in the horizontal sections, early simulations demonstrate that dose levels travelling up through basement rock – with matrix and fracture permeabilities comparable to Finnish cores – could be significantly below international regulatory limits. Consequently, avoiding fracture zones is obviously desirable but might not be critical to the safety case.

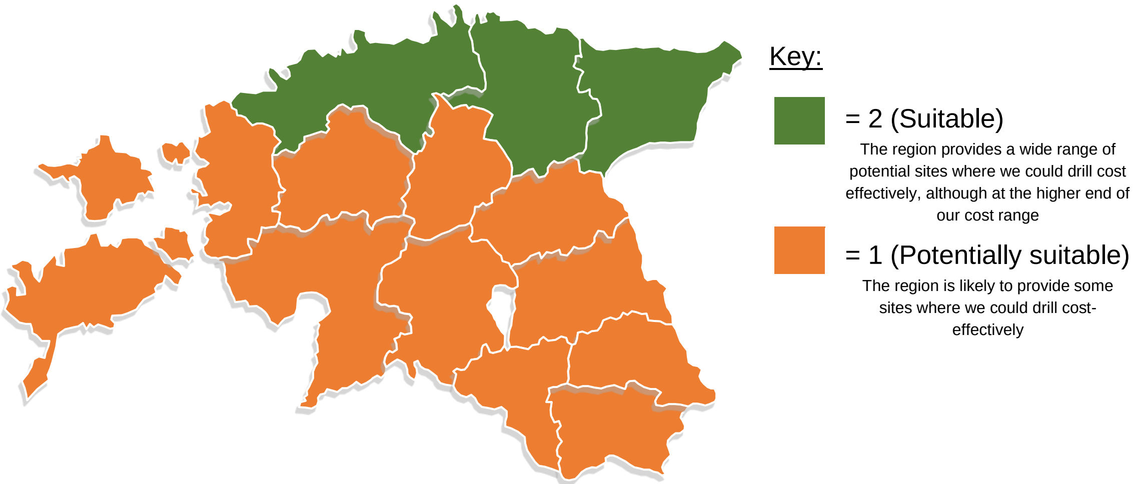
5.2 Drilling

Overview

Drilling: assessment criterion
Can we cost-effectively drill in this geologic environment?

Summary conclusions

There is extensive core drilling experience in Estonia for drilling paleoproterozoic basement rocks within 700 m of the surface. Horizontal drill holes at the repository depth of 1500 m have not been drilled in Estonia, but are routinely drilled in different (Paleozoic carbonates) but comparably hard formations in numerous oil and gas basins throughout the world. For example, in Finland there are many deep drillholes (both core holes and geothermal) reaching deep into the crystalline basement. Consequently, there are no fundamental restrictions to drilling anywhere in Estonia, although avoiding heavily fractured and faulted regions may result in more efficient drilling.



Detailed findings

Most deep drilling in crystalline basement is done in mining exploration and appraisal drill holes or in geothermal environments. Mining drill holes are typically continuously cored with a 76-123 mm diameter diamond coring bit. In some areas where continuous core is not needed, downhole hammer (percussion drilling) is used, sometimes in tandem with reverse circulation of the drilling fluid, where the fluid and cuttings return up the drill pipe rather than the annulus. This approach provides less contaminated drill cuttings. In addition, it is common to drill blast holes and test holes using conventional rotary drilling rigs with tricone bits. Deep drill holes (up to 5 km depth) for geothermal resources contend with very high temperatures and are typically drilled with rotary rigs having specialized high temperature downhole equipment.

The core drilling rates achieved in the Estonia test holes were around 2-4 m per hour, comparable to rates achieved in the oil and gas industry. Non-coring drilling using the aforementioned techniques typically exhibit drilling rates of between 2 and 20 m/hour in crystalline basement. The rates are primarily dependent upon the bulk rock strength. The faster rates are comparable to oil and gas drilling rates in harder sedimentary rock such as Paleozoic limestones, dolomites, and chert[37].

There are several oil and gas provinces where there is extensive experience (hundreds of drill holes) drilling with a similar drill hole geometry to that proposed for the Estonian nuclear waste. For example, in the Mississippi Lime reservoir of northern Oklahoma, the reservoir rocks are Mississippian Age containing limestones, often cemented with quartz, and diagenetic cherts. Like the unweathered crystalline basement rocks of Estonia, these rocks typically have minimal porosity and permeability. To recover any oil or gas (or water) requires massive hydraulic stimulation (fracking) of the reservoir interval. The hard Paleozoic sedimentary rocks there should be somewhat comparable in hardness/strength to crystalline basement rocks in Estonia although the geologic complexity of the Paleoproterozoic rocks could be greater. Consequently, with the aforementioned caveats, drilling experience in the Mississippi Lime may be a reasonable proxy to drilling rates that can be achieved in Estonia.

The drilling and casing cost, without fracking, of a typical Mississippi Lime well is about $300-$600 per meter[38]. Of course, there will be no fracking in the nuclear waste disposal holes. Costs will be substantially higher in Estonia, as there is less oil and gas infrastructure, more safety and drill hole requirements, more logging/testing, and less experience drilling in the particular deep crystalline basement rocks (especially initially). Additionally, drill holes with diameters at least double that of typically oil and gas drill holes will be required.   Nevertheless, given that the hole geometry and rock strengths are similar, we at least have some analogous horizontal well experience with which to estimate costs.

[37] https://www.enidnews.com/news/mississippi-lime-still-is-producing-for-the-area/article_0f0d7a4c-deee-11e4-9a93-fb0e16cf4240.html
[38] https://www.ogj.com/general-interest/article/14036183/permian-basin-operators-cut-drilling-time-lower-expense

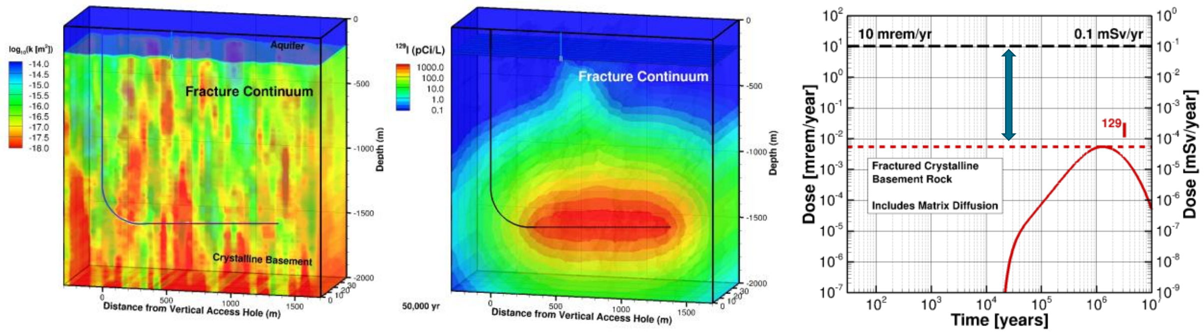
6. Conclusions

Our overall conclusion is that there are no fundamental geologic limitations to disposing nuclear spent fuel safely in deep horizontal boreholes in Estonia, and that a wide range of siting options are available.

6.1 A safe option for Estonia

Siting will be in crystalline basement geology as this is the only host rock option of sufficient depth. Our initial safety calculations for a generic crystalline basement repository suggest that a high level of safety can be achieved. Exhibit 17 shows modelling results for a 1.5 km depth horizontal repository in crystalline basement with heterogeneous sub-vertical fracture networks similar to those seen in Estonia and with a similar depth of aquifer as found in northern Estonia. Radionuclides are safely isolated from the biosphere with peak dose at the surface occurring after 1.3 Ma – and at a level orders of magnitude below regulatory requirements.

Exhibit 17: Preliminary generic safety calculations for a horizontal repository in crystalline basement at a depth of 1.5 km[39]



Crystalline Basement Host Rock
- 1.5 Kilometre Depth Repository
- Shallow aquifer at 200m depth
- Fracture + matrix continuums
- Heterogeneous fracture networks

Migration of 129I at 50,000 years
- 129I just reaches aquifer
- Deep water well pumps contamination to surface
- 5 bar overpressure driving force

Peak Dose Arrival at 1.3 Ma
- Peak dose at surface < 10^{-2} mSv/yr
- 1000x below dose standard
- Fracture and matrix affects modelled

6.2 An affordable option for Estonia

Consideration of advanced nuclear in Estonia has not yet reached decisions on the type of reactor that might be deployed and hence the volume and characteristics of spent fuel that it would produce for disposal are unknown. Accordingly, we are not currently in a position to provide detailed cost estimates for deployment of the Deep Isolation solution; costs will also be impacted by the nature of the site that is selected for the repository, and on the type of fuel used in the selected design for Estonia's SMR.

That said, research suggests that the costs for Estonia would be a fraction of those required for construction of a mined repository. We recently completed a project with the Electric Power Research Institute (EPRI) on siting an advanced reactor[40] with onsite waste disposal in a horizontal borehole.

[39] Source: Deep Isolation analysis, in preparation for publication and peer reviewed journal during 2021
[40] The study was generic and not specific to a type of advanced reactor or spent fuel; assumptions were developed in order to ensure broad applicability to a wide range of advanced reactor technologies.

The result indicates savings of 69% for a single reactor on a site to a mined repository. The savings grew to 76% for a single site with two reactors.

Exhibit 18: Estimated unit disposal costs (USD per MTU) by scenario

	Ongoing Borehole Disposal	Two Unit Plant: Ongoing Borehole Disposal	Mined Repository
Base disposal	$469	$362	$1,240
Mobilization and demobilization	9	9	—
Storage during reactor operation	—	—	$130
Storage after reactor shutdown	—	—	$192
Total costs	$478	$370	$1,562
Savings relative to mined repository	$1,085	$1,192	
Savings relative to mined repository (%)	69%	76%	

6.3 A flexible option for Estonia

As highlighted in Sections 4 and 5 of this report, all regions of Estonia are likely to contain potential host rock formations which provide safe and cost-effective sites for a Deep Isolation repository. This brings significant flexibility for Estonia when considering siting. Moreover, a Deep Isolation repository can be drilled horizontally from a shoreline facility out under coastal waters, which is an option for Estonia given its coastal positioning.

Within this, our advice is that northern coastal regions in particular provide the best promise for suitable host rock characteristics.

Exhibit 19 below summarises the results of our safety assessment and our deliverability assessment. The horizontal axis shows the average score of different areas of Estonia across the four safety criteria; the vertical axis shows the average score across the deliverability criteria; and the size of the bubbles illustrate the relative share that each area represents of Estonia's total landmass.

This chart is not intended as a precise quantified comparison of relative suitability[41], but simply to illustrate that our assessment has identified 'clusters' of areas with broadly similar suitability profiles.

[41] The assessment is not quantitative because the 0-3 scale we have used on each criterion itself represents a simplified summary of qualitative judgments, i.e., not an empirical data point; and because in a detailed safety case there would be no assumption that these different criteria are equally weighted.

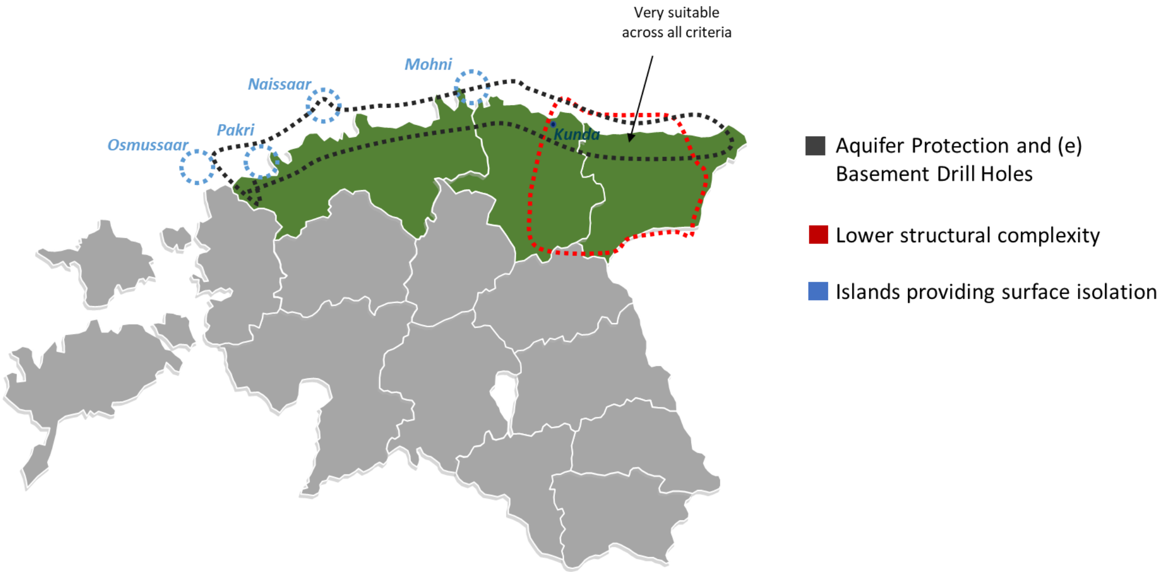
Exhibit 19: Mapping the suitability of Estonian regions

The areas with the greatest likelihood of providing appropriate host rock formations from both a safety perspective and a drilling/completion perspective are Harju County and Ida-Viru County, and to a slightly lesser extent Lääne-Viru, on the north coast of Estonia (along with the islands off that coastline). These areas combine optimal conditions including:

- Aquifer isolation.
- Coastal sites that will facilitate seismic surveys.
- Proximity to existing basement boreholes (facilitating the process for site characterization and safety case development.

In the map below, we have highlighted key features of the geology in these areas, including the town of Kunda - where Fermi Energia is currently engaged with the local community about its potential as a host site for Estonia's small modular reactor. This opens up the possibility of co-locating the nuclear plant and the disposal facility, reducing the need for transportation of nuclear waste between communities.

Exhibit 20: Key elements of suitability in north Estonia



These preliminary conclusions are based on existing data, desk research, and dialogue and review with experts in Estonian geology; no site-specific work or new field research has been undertaken. Significant further work will be needed to refine this initial analysis, and to identify and characterize specific sites that would in practice provide suitable rock formations. Our recommendations on this future work are set out in the next section.

7. Recommendations and next steps

The findings of this preliminary study are that:

- Deep borehole disposal (DBD) represents a safe, affordable and flexible disposal route for spent fuel, in the event that the Estonian government decides to take forward the SMR option as a potential part of Estonia's future energy strategy.
- There are potential geological host environments across Estonia, and the optimum area in which to focus a site selection process is situated in the north east of Estonia and the islands off the north-eastern coastline.
- However, significant further study is needed to provide a fuller evidence base for this conclusion, and to identify and characterise specific potential sites.

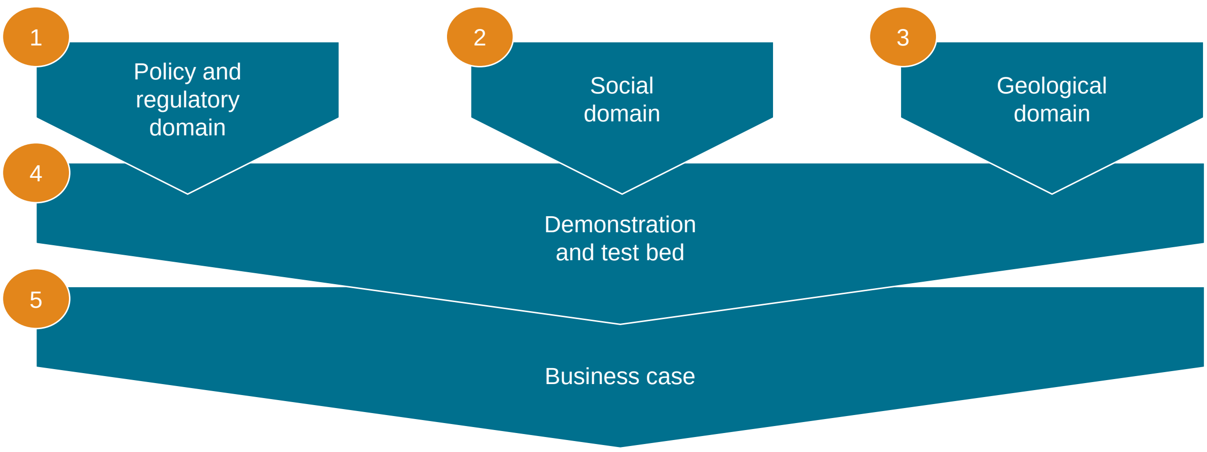
Against that background, our principal recommendation is therefore that: **the Estonian Government should, in parallel with its consideration of the SMR option, also develop a strategy for managing the resulting spent fuel**. This strategy should:

- Be based on deep borehole disposal
- Aim to establish a clear implementation plan at or before grant of the operating license for the nuclear power plant.

This will establish Estonia as a world-leader in responsible, sustainable energy production: the only country in the world to have established a clear disposal route for nuclear waste before it starts to produce that waste.

As the world's only company bringing together all the success factors for borehole disposal of nuclear waste, Deep Isolation is uniquely positioned to support Estonia in this process. We therefore recommend that the Estonian government should consider partnering with Deep Isolation to develop the detailed business case, safety case and implementation plan for its disposal strategy. In particular, this more detailed planning work should address the five areas that are illustrated at Exhibit 21 below and then discussed in more detail in the rest of this section.

Exhibit 21: Areas for further study



7.1 The policy and regulatory domain

Explicit consideration of policy, legal and regulatory issues in Estonia was out of scope for this assignment. So while the Deep Isolation solution is aligned with international regulatory requirements from IAEA and Euratom, further work is needed within the Estonian context.

We therefore recommend that the Estonian Government consider partnering with Deep Isolation engage and consult with key policy and regulatory stakeholders to:

- Identify any specific Estonian requirements or concerns that might impact on the baseline design of a Deep Isolation repository.
- Map out the pathway for securing regulatory and licencing approval of a borehole repository in Estonia, in line with the requirements of the Estonian Planning Act[42] and the Radiation Act[43].

7.2 The social domain

Deep Isolation is committed to engagement and collaboration with local communities and governments to determine if deep geological disposal is not only right for that location but supportive of their community vision. Our model of community partnership is built around a shared understanding of what comprises the safest practices for nuclear waste management. We work with all stakeholders and interested members of the public to ensure that all the information necessary to make the decision is available to them and if/when there is an agreement, a partnership is created that is built to transcend to the future. We expect that a government agency will take the lead in management of the siting process and community engagement, and Deep Isolation is able to support this work with people, skills and processes necessary to facilitate a fully immersive and two-way dialogue between local communities and decision-makers.

As a first step in this process, and to support policy making, we recommend that the Estonian Government consider partnering with Deep Isolation to research community attitudes towards different options for nuclear waste disposal, both through quantitative research and through transparent and collaborative community discussions.

7.3 The geological domain

Significant further work will be needed following the initial geologic assessment undertaken in this study, in order to develop a detailed understanding of both the drilling and completion issues involved in different candidate sites and the long-term safety performance of a Deep Isolation repository within the relevant geological environment(s).

In particular, we recommend that the Estonian Government consider partnering with the Estonian Geological Survey and Deep Isolation to:

- Undertake more detailed quantitative analysis of potential candidate geologies, particularly in north-eastern Estonia, including through isotopic analysis of existing core samples (which could be used to test and validate isotopic benchmarks used in our safety calculations for crystalline basement repositories) and drilling new core samples at greater depth (current boreholes only go to around 700 metres).

[42] Which in § 27. Section 2 directs siting of a final repository for dangerous waste to be executed following National Spatial Planning procedure.

[43] Which in § 61. Section (4) states "The intermediate storage and final disposal of radioactive waste shall be organized by the Ministry of Economic Affairs and Communications"

- Development of site selection criteria (covering both safety considerations and wider policy considerations), to inform more detailed analysis of potential candidate sites.
- Implement a site characterization program at one or more candidate sites, enabling site-specific hydrologic and geologic conditions to inform repository design and a fully developed safety case.

7.4 Demonstration and test-bed

All of the actions recommended above will be strongly supported through development of a demonstration borehole in Estonia. This would:

- **Demonstrate the technology within an Estonian geological environment**; and provide illustrative site characterisation data to inform further peer review of the developing safety case.
- **Provide a pilot facility that stakeholders and representatives from candidate communities can engage with,** supporting informed debate, and increased transparency and scrutiny.
- **Provide a Centre of Excellence for R&D and testing of Estonian supply chain companies** that might partner with Deep Isolation and its global supply chain partners in delivery of a full disposal repository.

7.5 Business case

Finally, more work is needed to evaluate in more detail the financial and strategic business case for implementing Deep Isolation's solution in Estonia. Our initial view is that the strategic benefits for this would be significant. As discussed in Section 5, they would enable safe disposal of spent nuclear fuel at a fraction of the costs involved with a traditional mined repository. In addition, there are a wide range of other potential benefits that would need quantifying in a full business case, as illustrated in Exhibit 22 below.

Exhibit 22: Potential wider benefits from borehole disposal

✓ **Putting radioactive waste safely and permanently beyond reach decades more quickly than possible with other disposal routes**	A phased approach can be taken to construction and operation of a Deep Isolation repository, beginning with as few as one borehole. And our implementation times are much shorter than the many years required to construct a mined repository.
✓ **Avoiding the expense of interim storage**	The faster disposal times with horizontal boreholes could enable site licence operators to save many years of expenditure on storage.
✓ **Reduced financial risk**	The bulk of the costs for a borehole repository are based on off-the-shelf technologies that are deployed on a daily basis in the oil and gas sector. This reduces the risk of cost and delivery overruns.
✓ **A significant export opportunity for Estonia's high-tech manufacturing sector**	As an early adopter of horizontal borehole technology, Estonia would be well placed to develop a significant manufacturing advantage in the infrastructure and consumables needed to support this.

We recommend that the Estonian Government consider partnering with Deep Isolation to undertake a Deep Isolation Foundation Study for Estonia. As illustrated below, this uses a 'six case' structure that is designed to ensure compliance with IAEA, World Bank and European Commission guidance on options appraisal for infrastructure schemes of national and regional importance.

Exhibit 23: The 'six case' structure of Deep Isolation's Foundation Study

Annex A: Bibliography

Artemieva, Irina M., and Hans Thybo. "EUNAseis: A seismic model for Moho and crustal structure in Europe, Greenland, and the North Atlantic region." *Tectonophysics* 609 (2013): 97-153.

Finsterle, S., R.A. Muller, J. Grimsich, J. Apps, and R. Baltzer, Post-closure safety calculations for the disposal of spent nuclear fuel in a generic horizontal drillhole repository, *Energies*, *13*, 2599, doi: 10.3390/en13102599, https://www.mdpi.com/1996-1073/13/10/2599/pdf, 2020.

Finsterle, S., C. Cooper, R.A. Muller, J. Grimsich, and J. Apps, Sealing of a deep horizontal borehole repository for nuclear waste, *Energies*, *14*(1), 91, doi: 10.3390/en14010091, https://www.mdpi.com/1996-1073/14/1/91/pdf, 2021.

Gascoyne, Mel. *Chlorine isotopes and their application to groundwater dating at Olkiluoto*. No. POSIVA-WR--14-38. Posiva Oy, 2014.

Gregersen, Soren, and Peter Voss. "Stress change over short geological time: the case of Scandinavia over 9000 years since the Ice Age." *Geological Society, London, Special Publications* 316.1 (2009): 173-178.

Hama, Katsuhiro, and Richard Metcalfe. "Groundwater dating applied for geological disposal of radioactive waste. A review of methods employed worldwide." *Nihon Suimon Kagaku Kaishi* 44.1 (2014): 39-64.

Hedin, Allan. *Long-term safety for KBS-3 repositories at Forsmark and Laxemar-a first evaluation. Main Report of the SR-Can project*. No. SKB-TR--06-09. Swedish Nuclear Fuel and Waste Management Co., 2006.

Holland, Greg, et al. "Deep fracture fluids isolated in the crust since the Precambrian era." *Nature* 497.7449 (2013): 357-360.

Hurter, S. and Haenel, R. (eds) *Atlas of geothermal resources in Europe, European Commission, 2002*

International Atomic Energy Agency. *Isotope methods for dating old groundwater*. International Atomic Energy Agency, 2013.

Karro E, Marandi A (2003) Mapping of potentially hazardous elements in Cambrian-Vendian aquifer system, northern Estonia. Bull Geol Soc Finland 75: 17–27

Karro E, Marandi A, Vaikmäe R (2004) The origin of increased salinity in the Cambrian-Vendian aquifer system on the Kopli Peninsula, northern Estonia. Hydrogeology Journal 12:424–435. ISSN 1431–2174

Kietäväinen, Riikka, et al. "Noble gas residence times of Saline waters within crystalline bedrock, Outokumpu Deep Drill Hole, Finland." *Geochimica et Cosmochimica Acta* 145 (2014): 159-174.

Marandi, Andres. *Natural chemical composition of groundwater as a basis for groundwater management in Cambrian-Vendian aquifer system in Estonia*. Diss. 2007.

Marandi, A., Karro, E. & Puura, E. 2004. Barium anomaly in the Cambrian-Vendian aquifer system in Northern Estonia. Environmental Geology, 47 (1), 132–139.

Nirgi, Siim (2019). Mineral exploration in crystalline basement rocks of Estonia.

Olvmo, Mats (2010). Review of denudation processes and quantification of weathering and erosion rates at a 01 to 1 Ma time scale (SKB-TR--09-18). Sweden

Påsse, Tore. *The amount of glacial erosion of the bedrock*. No. SKB-TR--04-25. Swedish Nuclear Fuel and Waste Management Co., 2004.

Payer, J.H., S. Finsterle, J.A. Apps, and R.A. Muller, Corrosion performance of engineered barrier system in deep horizontal drillholes, *Energies*, *12*(8), 1491, doi: 1020193390/en12081491, https://www.mdpi.com/1996-1073/12/8/1491/pdf, 2019.

Perens, R. and Vallner, L. (1997) Water-bearing formation. In: Raukas, A. & Teedumäe, A. (eds), Geology and mineral resources of Estonia, Estonian Academy Publishers, Tallinn, 137–145.

Puura, V. 1997. Basement features. In: Raukas, A. & Teedumäe, A. (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 163–167.

Puura & Vaher, 1997. Deep structure. In: Raukas, A. & Teedumäe, A. (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 163.

Puura, V. & Vaher, R. 1997b. Cover structure. In: Raukas, A. & Teedumäe, A. (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 167–177.

Puura et al., 1997. Precambrian basement. In: Raukas, A. & Teedumäe, A. (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 27–34.

Raidla, Valle, et al. "Geochemical evolution of groundwater in the Cambrian–Vendian aquifer system of the Baltic Basin." *Chemical Geology* 258.3-4 (2009): 219-231.

Simon, Karen M., et al. "The glacial isostatic adjustment signal at present day in northern Europe and the British Isles estimated from geodetic observations and geophysical models." *Solid Earth* 9.3 (2018): 777.

Tavast, E. (1997) Bedrock topography. In: Raukas, A. and Teedumäe, A. (eds) Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 252–255.

Vaikmäe, R., Vallner, L., Loosli, et al. (2001) Palaeogroundwater of glacial origin in the Cambrian-Vendian aquifer of Northern Estonia. In: Edmunds, W.M and Milne, C. (Eds.), Palaeowaters in Coastal Europe: evolution of groundwater since the late Pleistocene. Geological Society, London, Special Publication, 189, 17–22.

Veikkolainen, Toni, Ilmo T. Kukkonen, and Timo Tiira. "Heat flow, seismic cut-off depth and thermal modeling of the Fennoscandian Shield." *Geophysical Journal International* 211.3 (2017): 1414-1427.

Warr, Oliver, et al. "Tracing ancient hydrogeological fracture network age and compartmentalisation using noble gases." *Geochimica et Cosmochimica Acta* 222 (2018): 340-362.

