Deep Isolation's Site Evaluation Framework for Deep Borehole Disposal – 24147

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ABSTRACT

The deep borehole disposal concept is rapidly and increasingly being evaluated by waste management organizations around the world as an alternative to long-standing mined repository technologies. Deep borehole disposal appears to be a particularly attractive and cost-effective option for nations with very small inventories of intermediate or high-level nuclear waste (such as in Israel, Slovenia, Denmark, Norway, and Australia) that could fit into a limited number of boreholes (in some cases, a single borehole). Deep borehole disposal is also being studied by large-inventory countries and multi-national repository initiatives, studying the potential to reduce overall costs through a hybrid approach that combines a mined solution for bulkier wastes with disposal of high-heat generating wastes at greater depth in boreholes [1] [2].

International research with policymakers, regulators and waste management professionals shows that the most important perceived benefit of deep borehole disposal is not its lower cost but its potential to offer much greater siting flexibility [3] – which in turn facilitates an inclusive approach to consent-based siting and opens up more potential host communities for geologic disposal. Due to the significantly increased geologic barrier and reduced sensitivity to certain phenomena (e.g., surface flows and flow through permeable faults) deep borehole repositories can offer increased flexibility in siting and enable minimization of the transportation of nuclear waste (e.g., on-site disposal).

However, a clear and evidence-based framework for evaluating this perceived siting flexibility does not currently exist. In the last 10 years, there have been only three site selection criteria or frameworks published specifically for deep borehole repositories. Practical and specific site evaluation criteria are necessary to assess the feasibility of and build interest for deep borehole disposal in any given interested nation. The effort to develop and apply these criteria generically is complicated since they will vary depending on the depth, host rock, and the waste form proposed for disposal.

To address this gap, this paper outlines the criteria and phased approach of Deep Isolation's proposed site evaluation framework for deep borehole disposal to encompass a range of potential host rocks and waste forms. This framework was originally based on IAEA Safety Standard SSG-14: Geological Disposal Facilities for Radioactive Waste. SSG-14 sets out the datasets that should be considered when assessing the site of a geological disposal facility that include palaeohydrology, geothermal flux / volcanism, climate processes and seismicity / rock mechanics. Based on interactions with waste management organizations, deliverability (the ability to construct and operate a repository at a given site) has been added as an additional category of site evaluation criteria. This framework was refined and improved via a detailed review of site evaluation methodologies developed by scientific organizations in Australia, Germany, Sweden, Norway, Japan, the UK and the US.

The proposed site evaluation framework defines 14 site evaluation criteria within these five domains, and for each one identifies at which phase of the IAEA's iterative design process for geological disposal facilities it should be used.

Six are national screening criteria that would be assessed during the (earliest) generic design stage, and the remaining nine are site-specific evaluation criteria that would be assessed during the conceptual design stage. This paper outlines the complete set of criteria and gives the basis for why they are both practical and necessary (from a safety or delivery perspective). Initial applications of this framework to national data suggest that rock formations that comply with each of these evaluation criteria can be accessed from a large proportion of the earth's surface.

DESCRIPTION

Prior Work

The development of a new site evaluation framework began with a comprehensive review of existing site evaluation approaches published for deep borehole disposal. Earlier publications specifying site characteristics for deep borehole repositories were completed by SKB [1], the National Academy of Sciences [2], Los Alamos National Laboratory [3], and Sandia National Laboratories [4], [5]. This review also incorporated more recently published frameworks by Commonwealth Scientific and Industrial Research Organization (CSIRO) [6] and the Norwegian Government in June 2021 [7]. Lastly, this review included criteria for siting geologic disposal facilities published by the governments of Japan [8], Sweden, UK, and Germany [9] for mined repositories. In total, over 100 site evaluation criteria from nine international studies were assessed. The existing criteria were assessed in terms of their usability for site evaluation decisions based on the following factors:

- **Extent of quantification:** whether a criterion is quantified to the point that it can be objectively and clearly compared against data to determine if a site meets the criteria or not.
- **Relevance to deep borehole disposal:** Although deep borehole repositories operate under the same fundamental principles as mined repositories, siting considerations between the two may differ significantly. Thus, criteria that have been developed for mined repositories have limited direct transferability for deep borehole repositories.
- **Data availability:** To be used at the earliest site screening stages, criteria must depend on data that is accessible or readily obtainable by waste management organizations. As the site selection effort progresses, additional data may be collected through preliminary and detailed site investigations.
- **Global relevance:** The criteria should relate to globally relevant factors as opposed to ones that are very specific to national circumstances (e.g., unique geological or socio-economic factors in certain countries).

Out of the 100 evaluation criteria across the nine reports, only fourteen criteria scored high in each of these three factors: quantifiable, relevant to borehole disposal, and globally relevant. Ten out of these fourteen (71%) are usable at a national site screening stage. Figure 1 summarizes the ranking for each of the 100 measures for extent of quantification, relevance to deep borehole disposal, global relevance, and data availability.

Other points to note from the analysis of prior work include:

- Only one quarter of the criteria are explicitly quantified in these studies – although 56% of criteria could be reasonably quantified, they were not quantified within these reports.

- In terms of data availability, 61% of criteria are potentially usable in an initial national site screening exercise, with 39% being less or not useable as they would require data that is not typically available at the early stages of site evaluation.
- Previous efforts lay out concept-specific frameworks focusing on a single deep borehole architecture (e.g., a vertical borehole with disposal sections at depths of 3-5 kilometers). This potentially limits options and site selection in nations where multiple host rocks and configurations could be viable.

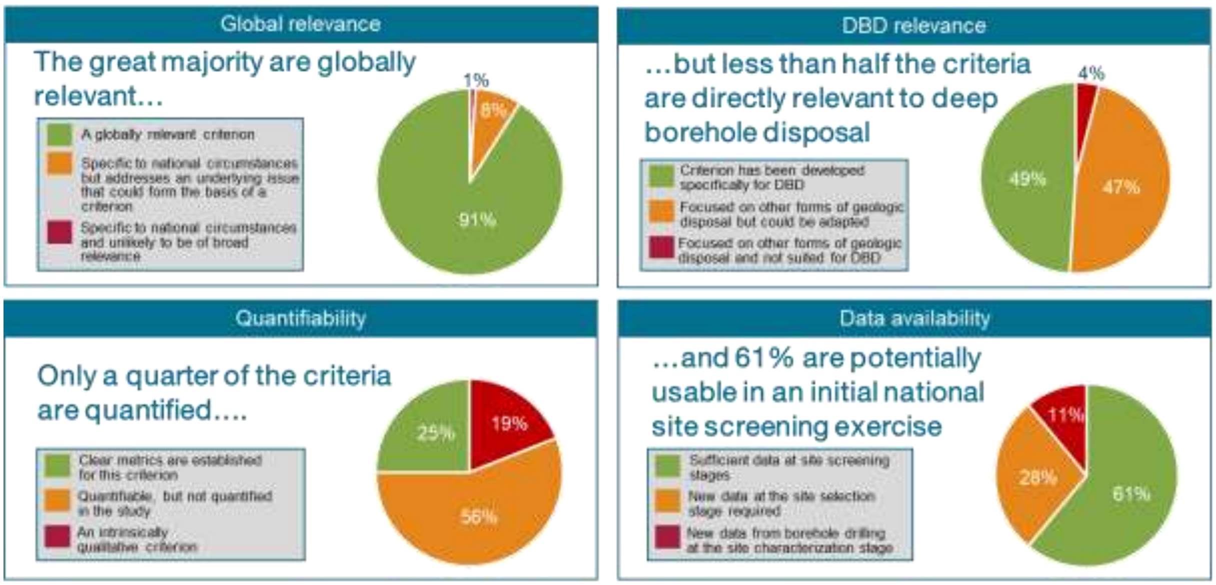

Figure 1. Review of Prior Site Evaluation Criteria that Inform the Development of Site Evaluation Criteria for Deep Borehole Disposal (DBD) Repositories.

DISCUSSION

Description of Site Evaluation Framework

Based on the literature review described above, the International Atomic Energy Agency (IAEA) guidelines [10] for the design process for geologic repositories, and a need to develop a more universal framework (i.e., flexible with respect to designs and host rocks), a phased site evaluation criteria framework was developed. At the top level, three generic geologic conditions are required. The geology at a deep borehole disposal repository must achieve three target outcomes:

- **Isolated:** Based on isotopic testing to demonstrate empirically that fluids in the host rocks have been out of contact with the biosphere over geological timescales.
- **Stable:** The host rocks and pore fluids are not subject to significant driving forces from geothermal heat flux, volcanism and seismic events, and detailed evidence-based modeling of future repository performance supports a safety case that meets regulatory requirements for 1 million years or more into the future – allowing for uncertainties associated with future climate change.
- **Deliverable:** Host rocks can be characterized and accessed to provide a safe and cost-effective basis for construction, operation, and closure of the repository in practice.

The framework's starting point for evaluating sites to achieve isolation and stability is IAEA Safety Standard SSG-14: Geological Disposal Facilities for Radioactive Waste [10]. This sets out a wide range of datasets that should be considered when assessing the long-term safety of a geological disposal facility – which are summarized in Figure 2 under four headings: palaeohydrology, geothermal flux / volcanism, climate change, and seismicity. The current framework adds a fifth heading, focused specifically on deep borehole disposal: deliverability (i.e., the extent to which a deep borehole repository can be constructed and operated safely and cost-effectively in a particular location).

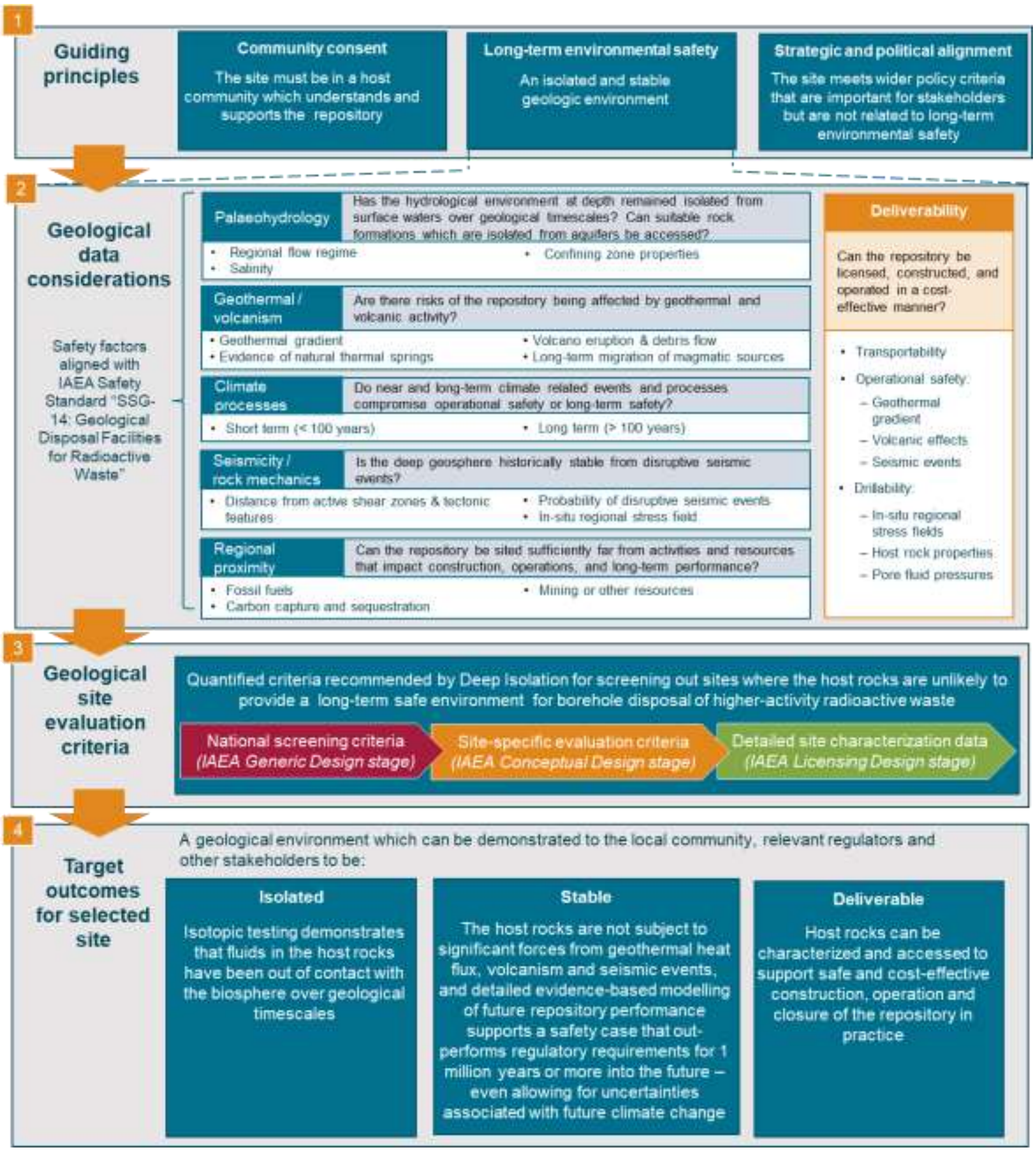

Figure 2. Overview of Deep Isolation's DBD Site Evaluation Framework.

For each of the domains and sub-domains of geologic consideration described in Figure 2 (i.e., palaeohydrology, geothermal flux / volcanism, climate change, seismicity, and deliverability) quantified evaluation criteria have been developed. These criteria are developed and applied across the phases of engineering and site development to correspond with the level of detail on both the design of the repository and potential sites.

In a generic design stage, the exact details of long-term waste behavior, waste forms, regulatory requirements, and repository designs are usually not fully developed, explored, and defined. Furthermore, the site-evaluation process is limited to data that are available to the waste management organization. As a result, it is suitable to apply generic site evaluation criteria, focusing on the aspects of volcanism, proximity to faults, and geothermal gradient, which would broadly affect the safe deployment of any deep borehole concept and typically have datasets available early in the design process. Other criteria (such as those related to transportability and proximity to resources) could also be applied in the generic design stage; however, these will vary from country to country and are difficult to generalize across all deep borehole applications.

As the design of borehole concepts progress, the details of the waste form, regulatory requirements, and trade studies exploring variations in the concept (i.e., depth, host rock, and other site characteristics) are completed. This results in site evaluation criteria that are specific to each concept being explored, capturing the waste form and repository design, and geologies that are representative to the nation. These criteria would be applied at specific sites as a down-selection of multiple candidate sites occurs.

As the concept studies are completed, the site evaluation process progresses to a level of detail where site-specific data (e.g., obtained from seismic surveys and boreholes) can be compared against the requirements developed for each concept. Ultimately, this allows for the down selection to a single site which leads to the licensing stage of design where site characterization and performance modeling of a single site (rather than evaluation of alternative designs and sites) is the primary objective. The phasing of these criteria is described further in Figure 3.

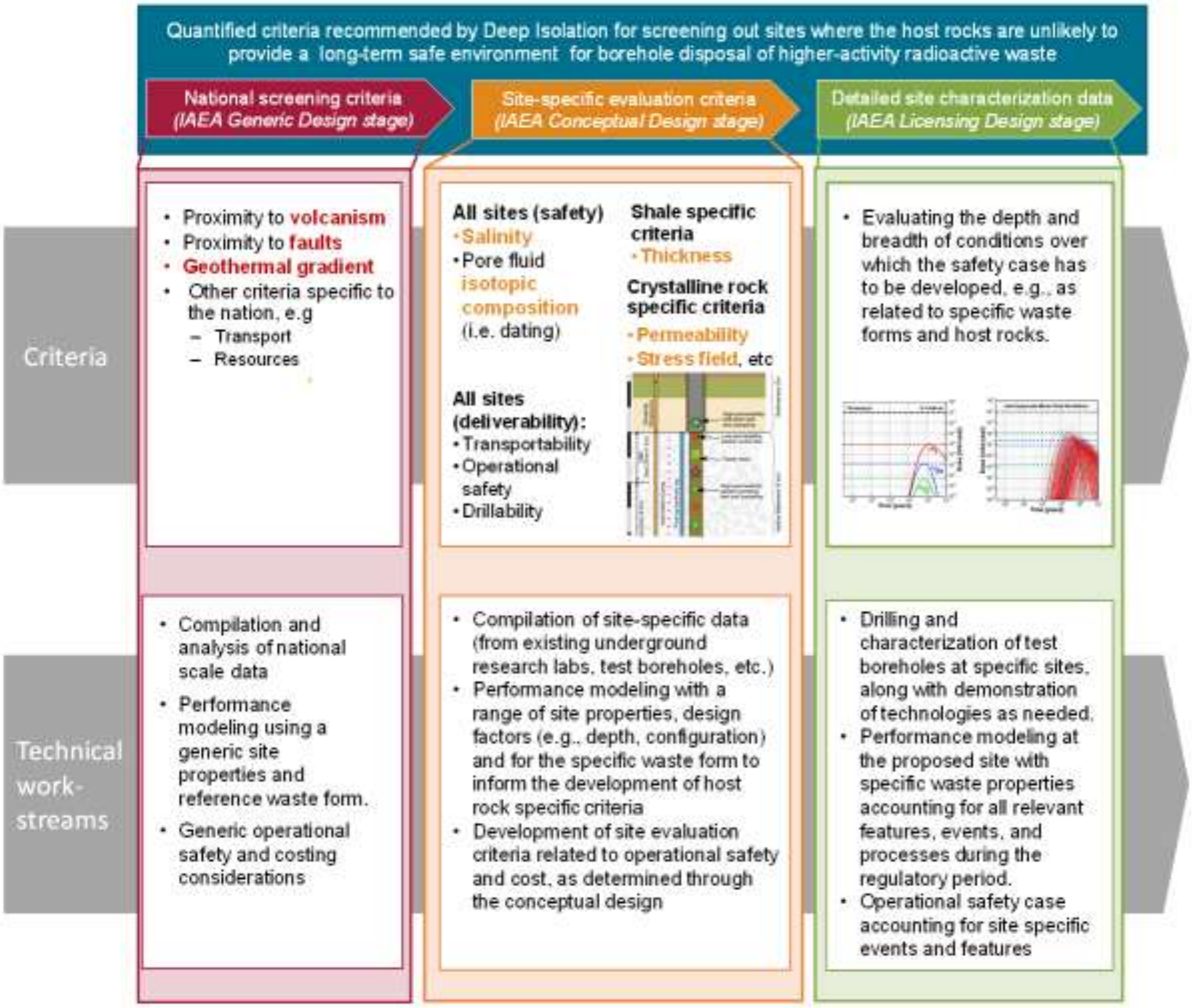

Figure 3. Deep Borehole Site Evaluation Process Across the Repository Design Stages and the Supporting Technical Work Involved.

Detailed Description and Basis for Criteria

The details of the criteria are described for the generic and concept-specific stages are summarized in Table 1 **Error! Reference source not found.**and **Error! Reference source not found.**, respectively.

Table 1. National (Generic Stage) Site Evaluation Criteria for Deep Borehole Repositories.

Site characteristic	Site evaluation criteria	Discussion Summary of basis
DELIVERABILITY: Can the repository be licensed, constructed, and operated in a cost-effective manner?		
Transportability	It should be possible to transport waste to the proposed repository location in a cost-effective manner.	**Economics:** Reliance on existing or lower cost transportation infrastructure could significantly reduce total system costs.
Geothermal gradient	Geothermal heat flux resulting in host rock temperatures of <200 °C.	**Economics:** There is a limitation on temperature-hardened data acquisition equipment deployable in deep boreholes.
Volcanic effects	Pyroclastic flows have not occurred in the last 10,000 years.	**Operational safety:** This criterion reduces the risks of pyroclastic flows affecting surface equipment during the operational period.
Seismic events	The risk of seismic events at the site during construction and operations can be safely accommodated by the design of repository equipment and structures.	**Operational safety:** Any repository equipment and structures will have to be designed to withstand potential seismic events as defined by the regulator. Additional design work and regulatory analysis for borehole repositories is required to develop a useable and quantitative criteria.
Drillability	In-situ regional stress fields, host rock geomechanical properties, and pore fluid pressures at the site enable cost-effective drilling with existing borehole designs.	**Economics:** Future work with drilling partners is needed to determine quantitative bounds on in-situ stresses that can be tolerated with existing well designs and equipment.
GEOTHERMAL / VOLCANISM: Are there risks of the repository being affected by geothermal and volcanic activity?		
Volcanism	Distance to quaternary volcanism > 15 km	**Long-term safety**: Siting at a distance from quaternary volcanism would reduce the risk of repository disruption through (a) direct magmatic intrusion into the repository or (b) indirect effects related to migration of hot or caustic waters and their interaction with engineered barriers and the repository hydrologic environment.
SEISMICITY/ROCK MECHANICS: Is the deep geosphere historically stable from disruptive seismic events?		
Fault proximity	The repository site is at a distance >1/100th of the length of an active fault trace.	**Long-term safety:** Fault disruption of the repository might lead to canister breach and may create or reactivate a fast path to the biosphere

Applicable at the generic/national stages of evaluation

Potentially applicable at the generic stage, based on data availability and additional design work. Otherwise, this criteria would be applicable at the concept/site specific stage.

Table 2. Site-Specific (Concept Stage) Site Evaluation Criteria for Deep Borehole Repositories.

Site characteristic	Site evaluation criteria	Summary of basis
PALAEOHYDROLOGY: Has the hydrological environment at depth remained isolated from surface waters over geological timescales? Can suitable rock formations that are isolated from aquifers be accessed?		
Pore fluid isotopic composition	The hydrological environment at the planned disposal depth should not show interactions with surface aquifers within the last >100,000 years.	**Long-term safety:** A palaeohydrologic record demonstrating that pore fluids are isotopically distinct from surface waters provides added confidence in the projected long-term safety.
Pore fluid salinity	At the planned disposal depth, a brine concentration of >10 g/l is preferred.	**Long-term safety:** The presence of highly saline brines supports density stratification that reduces the potential for advection transport.
Shale host rock thickness*	The disposal zone host rock thickness must be >150 m.	**Long-term safety:** The thickness of host-rock surrounding the disposal zone creates an important geologic barrier.
Shale host rock lateral extent*	The lateral extent of confining layers or disposal zones must be >150 m beyond the planned repository outline is preferred.	**Long-term safety:** Lateral extent of host rock improves the robustness of the barrier and prevents bypassing of the sealing zone directly above the waste.
Shale host rock permeability*	The average permeability of the confining layers or disposal zone should be less than 10^{-18} m^2 (1 microDarcy)	**Long-term safety:** Low permeability host rock reduces the potential for advection transport.
Crystalline host rock* properties	The average permeability of the host rock should be less than 10^{-17} m^2 (10 microDarcy)	**Long-term safety:** Low permeability host rock reduces the potential for advection transport.
GEOTHERMAL / VOLCANISM: Are there risks of the repository being affected by geothermal and volcanic activity?		
Geothermal gradient	It is preferred that the geothermal gradient combined with the long-term effects of heat generation from the waste should not result in boiling of water in the vicinity if the repository.	**Long-term safety:** Uncertainties related to the emergence of a steam phase significantly increase if boiling occurs, and thus it is preferred if temperatures above the boiling point are avoided. However, with additional conceptual design studies it may be possible to show that periods of boiling could be tolerated.
CLIMATE PROCESSES: Do near and long-term climate-related events and processes compromise operational safety or long-term safety?		
Climate related processes affecting the local and regional deep hydrologic system	Expected erosion rates are not sufficiently high to compromise long-term safety.	**Long-term safety:** Erosional processes could reduce the thickness of the geologic barrier. However, in expected settings for deep borehole disposal erosion is modest and this is not expected to be a restrictive factor in site evaluation.

*Additional concept specific criteria will have to be developed separately for shale and crystalline rock concepts for deep borehole disposal. Given the complexity of specifying host-rock property targets, these criteria may not necessarily stated as specific and numerical limits but as preferences.

Regarding proximity of the repository to natural resources or other locations with societal value, this framework does not propose globally relevant criteria and recommends that issues related to proximity be addressed in greater detail at the concept stage and within the context of each nation considering deep borehole disposal.

Initial applications of this framework to national datasets were completed to test the practicality of the framework and suggest that the host rocks that comply with each of these evaluation criteria can be accessed from a large proportion of the earth's surface. Fundamentally, deep borehole disposal expands the range of potential locations for siting a geological repository, enabling a choice between drilling vertically down into the deep crystalline basement, or using directional drilling techniques to create borehole repositories in appropriate geological formations that are now accessible within a greater subsurface geological volume. Overall, this makes deep borehole disposal a flexible option for use in a community-consent-based siting process.

CONCLUSIONS

In this work, a new, structured, and flexible site evaluation framework for deep borehole disposal is proposed. This leveraged an extensive review of prior site evaluation criteria and an existing framework created by the IAEA, respecting the phased approach in which site evaluation occurs in practical settings. Another addition to the IAEA framework was the criteria of deliverability, which also captures the ability to construct and safely operate a repository (rather than just focusing on ensuring long-term safety). The phased approach of this site evaluation framework enables the criteria to be practical and useable because they can be evaluated from data that are available to the waste management organization at that phase of design and site selection. The basis for each criteria are presented in terms of economic, operational safety, or long-term safety reasons.

This site evaluation framework still represents a preliminary framework that would benefit from wider review, feedback, and application with additional data. It is detailed and evidence-based, but still a work-in-progress. Going forward, it is essential to further develop concept-specific criteria tailored to combinations of geologies and waste forms. This would cover:

- Quantitative evaluation of the geologic, hydrologic, rock mechanical and geochemical conditions in potential regions of interest for siting the repository in a country, including regional applications of the site evaluation framework.
- Use of existing geological data to document one or more generic geological environments in which a repository might be sited in a specific country.
- Quantitative modeling of the long-term environmental performance and peak dose at the surface for a DBD repository in each of these generic geological environments, along 1 million year timescales.

This work can be used to further refine and validate the framework based on a nation-specific evidence base, not just a global evidence base.

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