



Performance specifications of concept design for quantitative methods in crystalline rocks: Pre-feasibility study

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Performance specifications of concept design for quantitative methods in crystalline rocks: Pre-feasibility study

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Executive Summary

The BGE is currently carrying out a three-phase process to identify a suitable site for a geological disposal facility for nuclear waste (GDF). Phase 1 Step 1 has identified 90 sub-areas for further investigation in mudstone, salt and crystalline rock. While further ranking criteria (Phase 1 Step 2) have been developed for mudstone and salt areas, no clear criteria have been developed for the seven sub-areas of crystalline rock. The BGE has therefore employed Amentum to investigate the feasibility of developing a methodology for ranking these seven crystalline sub-areas without collecting additional surface or subsurface data.

The BGE has already used multiple geological factors to exclude areas of crystalline rock from the site selection process, including proximity to faults, seismicity, and the presence of historic and active quarrying and mining activities. The most relevant geological factor not considered thus far is the presence and nature of fracture networks in these crystalline rock sub-areas. Fracture networks are recognised as a key risk to the development of a GDF in crystalline rock as they introduce secondary porosity and permeability and are the main fluid conduit for groundwater through these rock types. Detailed geological and geophysical data are required to accurately characterise fracture networks which are not currently available in these sub-areas in Germany. This may lead to the assumption that developing broad assessment criteria for the potential presence of crystalline rock with developed fracture networks at this stage of the BGE siting process is potentially unviable. This report explores whether this is the case or whether there are options to explore further siting criteria for such rock. We do this via two approaches – a review of the level of consideration that has gone into siting in crystalline rocks in other territories, and through a theoretical consideration of the factors affecting fracture network development and whether some degree of broad assessment criteria could be developed. What is clear through this assessment is that any further work will need to be driven by good geological understanding and geoscience data review to establish predictive trends. We consider it unlikely that meaningful criteria development and then application could be derived from any theoretical modelling approaches in lieu of understanding trends in available empirical data; to do so with limited underpinning data would lead to unreliable conclusions accompanied by unhelpfully large uncertainties.

Amentum has investigated the approach used to site GDFs in two countries underlain by significant volumes of crystalline bedrock: Sweden and Canada. We considered the potential to develop some screening tools for identifying presence and potentially nature of fracture networks in early-stage site screening. Sweden carried out extensive geological studies in the 1980s and recognised that crystalline rock represented a suitable host rock in general but judged that it was ineffective on a national scale to identify and characterise fracture networks without the support of real data. Their site selection process was therefore driven by communities expressing interest in hosting a GDF before surface and subsurface investigations began. In Canada, detailed research was undertaken to develop a conceptual model for a GDF in granite bedrock that investigated a variety of factors including geomechanical and thermal properties and the impact of glaciation on a storage site. They recognised the importance of fracture networks in determining the suitability of a site to host a GDF but that they were difficult to characterise without intrusive investigations. They are now, in a similar manner to Sweden, relying on community interest to identify sites before beginning expensive surface and subsurface investigation.

Informed by the case studies from Sweden and Canada, Amentum have considered some of the fundamental controls on fracture network formation and judge that, if suitable data was available (which we believe is the case, even if these datasets are incomplete), there are potential steps that may be taken to further investigate whether some broad siting criteria could be developed to assist BGE. Amentum have identified three possible next steps based on this short investigation which could help further distinguish the seven sub-areas of crystalline rock and assess whether some broad screening criteria could be developed. These include:

- A geomechanical study of the crystalline rock types found in German territory using local areas of high data density such as mines and quarries. This work would aim to look for trends in fracture network extent and nature cross and referenced with understanding of geology, depth at formation, present depth, position in relation to the understood regional tectonic stress history etc. The results may allow sub-area ranking based on rock-type which could be applied in potential broad screening studies.

- An investigation into the impact of glaciation on crystalline rocks. Previous work in Canada investigated how the loading of glaciers changed the vertical stress in the underlying bedrock. Therefore, a relationship may exist between Quaternary age ice extent and thickness across Germany and the degree of deformation in the underlying crystalline bedrock.
- More detailed case studies could further justify the findings of this relatively short investigation while also providing general links from siting processes in other countries on fracturing pre- and post-site investigation.

In summary, the lack of detailed data across large areas of crystalline bedrock in Germany is the main challenge in developing methodologies to further distinguish the seven sub-areas identified in Phase 1 Step 1. However, there is likely to be a range of accessible historical geoscience data from across Germany and other territories which will allow some understanding of broad trends between fracture network presence and key geological controls which are mappable on a national scale. It is considered worthwhile that relevant trends are assessed, at least as a trial, and to determine if some broad assessment criteria could be established and applied at this stage of the siting process. We believe there is the potential to move ahead with initial data collation and review, to the extent that it proves (or not) that sufficient investigation will yield criteria that can be applied on the national scale, and that the time scales for this would be in the range of 1-3 months.

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1. Introduction

The Bundesgesellschaft für Endlagerung (BGE – Federal Company for Radioactive Waste Disposal) is in the process of determining the location for a repository for the final disposal of high-level radioactive waste in Germany (i.e. a Geological Disposal Facility or GDF). This process consists of three phases, with Phase 1 consisting of a desk-based study to identify geologically suitable areas for further study, Phase 2 consisting of surface-based exploration of candidate sites, and Phase 3 consisting of subsurface exploration which will result in the ultimate selection of a suitable repository site (Figure 1).

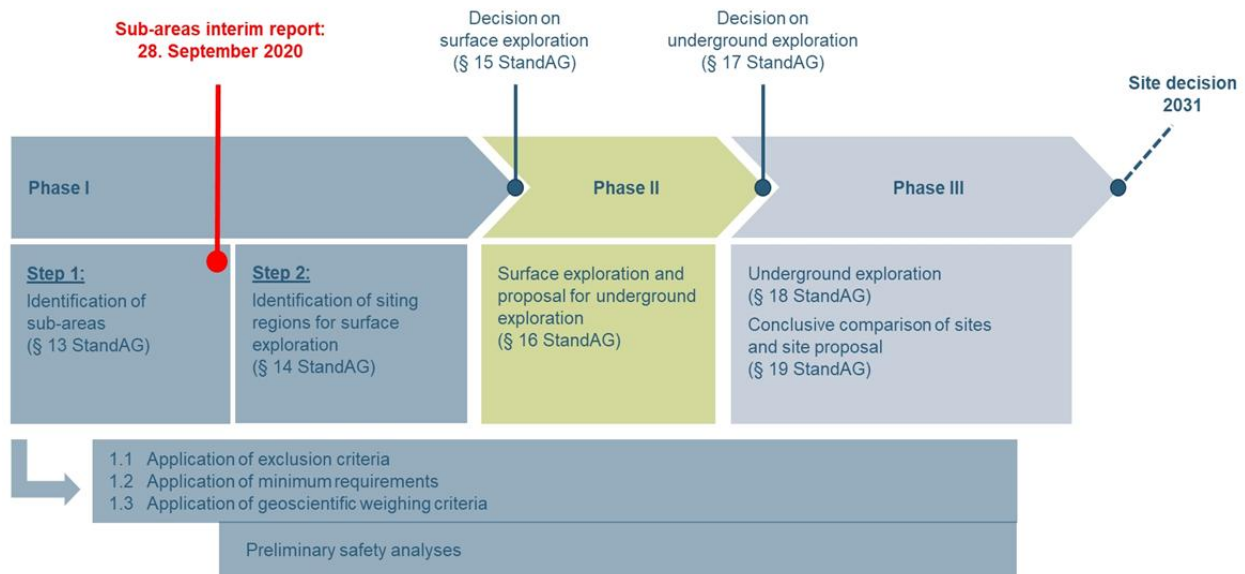


Figure 1: Overview of the BGE site selection process. The publication date of the Phase 1 Step 1 sub-areas interim report is highlighted in red. From BGE 2020.

Phase 1 is currently underway and is subdivided into two steps; Step 1 involves a Geographic Information System (GIS)-based study which has defined 90 'sub-areas' within German territory for further investigation. Step 2 involves a preliminary safety assessment to estimate the expected suitability of each of the 90 sub-areas as a possible host site for a GDF, based on currently available data (Figure 1). It is expected that no additional data is collected during Phase 1. The results of Phase 1, Step 1 were published on September 28th, 2020 (BGE, 2020). Three rock types were identified as possible storage materials: mudstones, salt, and crystalline rocks. Crystalline rocks were identified as possible disposal sites due to their high mechanical strength and lack of natural primary porosity and permeability.

Phase 1 Step 2 is now underway to rank these 90 sub-areas and identify candidates for surface exploration in Phase 2. The BGE has developed methodologies which allow for the ranking of both mudstone and salt sub-areas. Uncertainty remains about the feasibility of developing a similar method that would be applicable to crystalline rocks. The BGE has employed Amentum to investigate the feasibility of developing a methodology to rank the crystalline rock sub-areas. The 'almost-completely non-existent' data over large areas of these crystalline rock masses was identified as a key uncertainty underlying this study.

Amentum first investigated factors that impact the suitability of crystalline rock to host a GDF. Several of these were identified, including proximity to major faults, historic or active mine work, seismicity, and the presence of fracture networks in the rock mass. Several of these had been accounted for in Phase 1 Step 1 of BGE's site

selection process, including the proximity to faults, mining activity and seismicity. The key factor which had not been considered thus far was the nature of fracture networks.

As mentioned above, crystalline rocks have little natural primary porosity and permeability. Fracture networks introduce secondary porosity into crystalline rocks and increase hydraulic conductivity. Therefore, characterising fracture networks is key to assessing the suitability of a crystalline rock mass to host a GDF. Fracture networks are typically characterised with detailed subsurface mapping using borehole and geophysical data and their characteristics are difficult to estimate accurately without intrusive data collection (Nelson, 2001; Spence et al., 2014). As stated above such detailed data across all of the areas of crystalline rock in Germany is not available, nor will it likely ever be.

Amentum examined two case studies, investigating other countries underlain by significant amounts of crystalline rock which have been considered for siting GDFs to determine how those programmes considered crystalline rock and fracture networks on a national scale. The first was the work done in Sweden by the Svensk Kärnbränslehantering AB (SKB), which selected its final GDF site in 2011 (SKB, 2011). After completing regional geological studies, SKB relied on local municipalities expressing interest to determine which sites were suitable for initial local geological studies before investing in further site characterisation. The second case study focused on the on-going work of the Nuclear Waste Management Organisation (NWMO) in Canada to identify a final GDF site. Their approach is built on work done by both the Canadian Nuclear Safety Commission (CNSC) and Atomic Energy of Canada Ltd., who developed conceptual models for a GDF site in Canadian granitic rocks and investigated, in a general sense, the impact of factors including induced seismicity from the GDF development and the impact of glaciation on a GDF site. They are currently undertaking feasibility studies (both desk- and fieldwork-based) in communities that have expressed interest in hosting a GDF (NWMO, 2011).

Both case studies showed that, once it was established that most crystalline rocks were suitable hosts for intrusive studies (similarly to Phase 2 of the BGE site selection process), social license and proactive expressions of interest were used to shortlist sites for further study, rather than strict geological ranking beyond what had been done in the equivalent to BGE's Phase 1 Step 1 process. There was little or no attempt to understand further whether broad understanding of the causes of fracture network development could be used as a geological screening tool in light of the use of these other selection criteria for shortlisting sites. It was acknowledged that assessing potential sites without reliable underpinning data would have carried the risk of excluding potentially suitable sites.

2. Crystalline rock

The BGE define crystalline rocks to include both coarse-grained igneous intrusive rocks (i.e. plutonic rocks at depth in the earth's crust) and high-grade regional metamorphic rocks. Both rock types are expected to have properties that might make them suitable host rocks for a GDF. These properties include high strength, high thermal stability, and low water hydraulic conductivity (BGE, 2020). Other crystalline rocks, including extrusive igneous rocks and fine-grained igneous intrusions as well as low-grade regional metamorphic rocks and metamorphic rocks formed through contact metamorphism, are not considered suitable host rocks by the BGE and were excluded in Phase 1 Step 1 of the site selection process (BGE, 2020).

Seven areas of potentially suitable crystalline rock were identified in Phase 1 Step 1 of the site selection process with a total surface area of 80,786 km². These are found in the southeast of Germany (Figure 2) and belong to the Central European Blocks and the Bohemian Massif. These areas vary in size, with some sub-areas covering large areas of south-eastern Germany, highlighting the need to further rank these sub-areas prior to Phase 2.

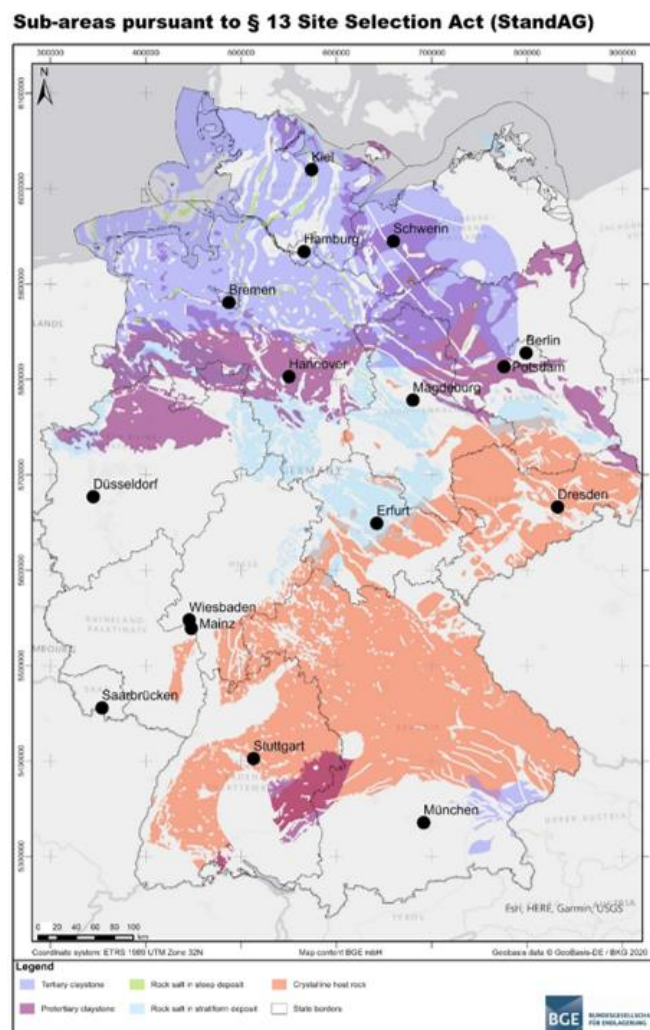


Figure 2: Map showing the sub-areas identified in Phase 1 Step 1 of the BGE siting process. Crystalline rocks are shown in orange. From BGE, 2020.

Phase 1 Step 1 of the BGE site selection process has already applied a variety of geological and seismic filters to exclude unsuitable areas of German territory, including areas underlain by crystalline rock. These include:

- Large-scale vertical ground movements
- Active fault zones
- Presence of historic or active mining activities
- Seismic activity
- Volcanic activity.

Therefore, the most important geological factor not considered thus far is the presence of fracture networks within the crystalline rocks. Several authors have noted the role of fracture networks in changing the permeability of crystalline rocks and the importance of characterising these fracture networks when assessing these rocks for GDF siting (e.g., Bredehoeft and Maini, 1981; Krauskopf, 1988; Follin et al., 2014).

3. Fracture networks

As mentioned above, crystalline rocks typically have no natural pore space, reducing the flow of groundwater through these rocks. Fracture networks create secondary porosity in crystalline rock masses and act as the primary fluid conduit through these rock types. Therefore, a detailed understanding of the fracture networks is key when assessing the suitability of an area of crystalline rock for a GDF.

A fracture represents ‘a naturally occurring macroscopic planar discontinuity in rock due to deformation or physical diagenesis’ sensu Nelson (2001). Fractures are a type of brittle deformation in a rock and form when stress exceeds the rock strength. Factors which affect how rocks deform include the strength of the rock, the depth at which the rock formed, the current depth of the rock and proximity to zones of high deformation such as faults and mountain building. These geomechanical factors can be used to characterise the behaviour of a rock mass when different stresses are applied. Fracture networks are typically described using three main characteristics:

- Fracture orientation: the principal orientations of the fractures in the fracture network typically described using the dip and dip direction or strike of the fractures.
- Fracture intensity: a one-, two- or three-dimensional measure of fractures per unit area or volume.
- Higher fracture intensity would indicate a more broken up rock mass with a higher permeability.
- Connectivity: how connected the individual fractures are. Higher connectivity values would indicate a higher permeability across wider scales.

Additional factors which are important to understanding a fracture network, such as which fractures are critically stressed and the slip-stability of individual fractures, would be investigated later in a candidate sites evaluation. A variety of geological and geophysical data are typically used to characterise fracture networks (Spence et al., 2014):

- Analogous outcrop mapping
- Subsurface mapping (e.g., in mine works)
- Borehole geophysics (e.g., resistivity and acoustic image logs)
- Core
- Reflection seismic data.

These data are collected during surface and subsurface exploration equivalent to Phase 2 and Phase 3 of the BGE’s site selection process. It should also be noted that the expression of a fracture network at surface outcrops are often not representative of fractures at depth due to changing stress conditions, surface weathering, and the potential role of mechanical stratigraphy (Spence et al., 2014).

Whilst it will never be the case that a ubiquitous coverage of detailed data needed to characterise and predict fracture networks in crystalline rock will be available on a full national scale, suitable information from some local areas within Germany may be present. If present in sufficient volume which could be compared to local geological setting in relation to the forcing factors for fracture network development, then some predictive criteria for Germany could in theory be established. It is considered that such detailed datasets could come from historic and active mines and quarries but there is also a range of information on fracture network development available from territories outside of Germany. Mines and quarries were excluded during Phase 1 Step 1 in the BGE’s site selection process and therefore the range of informative data they could provide to inform on fracture networks may not have been fully considered. Additionally, ranking on the basis of data availability at this stage in the site selection process would almost certainly introduce a bias based on data availability. This may lead to sites which ultimately would be suitable for investigation in Phase 2 and Phase 3 being excluded on a non-technical basis (such as a lack of data) before they are reasonably assessed.

4. Case studies

4.1. Case study 1: Sweden

The Svensk Kärnbränslehantering AB (SKB - Swedish Nuclear Fuel and Waste Management Company) is responsible for the siting of a GDF for spent nuclear fuel in Sweden. The SKB's siting activities began in the early 1980s when they conducted a series of general studies to investigate the different aspects of storing nuclear waste. This included a detailed study of the geology of Sweden, which consists predominantly of crystalline rock belonging to the Fennoscandian Shield, an area of Archean and Proterozoic rocks up to 3100 Ma old (SKB, 1983). The SKB defined the following factors to assess the geological suitability of a site to host the final repository (SKB 1992):

- Topography
- Distance between major fracture zones
- Frequency of minor fracture zones and small fissures
- Rock types and their extents
- Structure of the rock mass between fracture zones
- Occurrence of ore mineralisation
- Groundwater capacity in wells drilled in the rock.

When compared with the BGE's site selection process, it is noted that several of these factors have already been considered in Phase 1 Step 1, including distance from major fracture zones, rock types, and ore mineralisation (i.e. historic and active mine sites). The SKB noted that 'on a national scale, no essential difference in these factors can be seen in the various areas containing bedrock in Sweden' (SKB 1992). In the same report the SKB noted that fractures were difficult to accurately predict without detailed intrusive investigation. However, the SKB also noted that the presence of major fracture zones did not necessarily rule out areas for further study, as large volumes of competent rock could typically be identified (SKB, 1995). The SKB (1995) noted:

'If the focus of the siting work is flexible and pragmatic, starting from the fundamental criteria as regards safety, technology, environment, public opinion and local involvement, the possibilities of attaining good results are considerably greater than if detailed criteria and formal systems for, e.g. grading and screening sites, were used.'

The SKB ultimately carried out feasibility studies in eight municipalities around Sweden (SKB, 2011). These were in areas of crystalline rock and in municipalities which had expressed interest in hosting a GDF. In this case societal factors, i.e. the proactive interest of the local government and population to host these feasibility studies, were used to determine which sites should be considered for intrusive investigations equivalent to Phases 2 and 3 of the BGE's siting process.

When SKB proceeded to carry out detailed site investigation studies in these municipalities, geological factors became important in distinguishing suitability. Some sites which were initially thought to be underlain by suitable crystalline bedrock were found to be more intensely fractured at depth than visible from the surface due to difficulties identifying faults in crystalline rocks (SKB, 2011). When the SKB shortlisted the two final candidate sites, detailed ground investigation with the drilling of over 60 cored boreholes were used to help determine the final site for the GDF. The number of conductive fractures present at the Laxemar site was one of the factors which made it less suitable to host a GDF than the Forsmark site which was ultimately chosen to host the GDF. This

highlights both the difficulty in characterising crystalline bedrock sites without detailed subsurface measurements and the importance of these geological, geophysical and hydrogeological studies.

4.2. Case study 2: Canada

The Nuclear Waste Management Organisation (NWMO) is the Canadian body responsible for siting and developing a long-term nuclear waste repository in Canada. They have a multi-step approach similar to BGE and are currently carrying out ‘Step 3: Preliminary assessment of suitability’ which involves engagement with communities which have expressed interest in hosting a nuclear waste repository and conducting initial desk studies, including geological assessment with available data.

Prior to the work done by the NWMO, both the Canadian Nuclear Safety Commission (CNSC) and Atomic Energy of Canada Ltd. (AECL) conducted research into the suitability of Canadian granitic rock to host a GDF. Like the BGE and SKB, they identified a list of geological factors that would be used to evaluate a site as a potential host (CNSC, 2021):

- Containment and isolation characteristics of the host rock and geological system
- Past and expected/projected future geological stability of the site, including the impacts of orogeny, seismicity, glaciation and volcanism
- Sufficient extent of suitable host rock at the repository depth
- Ability of the host rock and geological system to withstand stresses without significant breaching
- Location relative to geological discontinuities
- Demonstrated isolation of groundwater at selected repository depth from shallow groundwater systems
- Characteristics favourable for limiting contaminant release and transport away from the DGR
- Low natural resource potential, which would limit the likelihood of inadvertent future human intrusion by subsequent generations of resource explorers

The CNSC focused on the development of a conceptual model of Canadian granite as a host rock and carried out extensive research investigating aspects including paleo- and present-day hydrogeology, geomechanical properties of Canadian granite and the impact of glaciation on a repository site (CNSC, 2017). With the suitability of granitic rock established, the NWMO is now proceeding with their process for selecting a final repository site. This selection process relies on a community to express their interest in the site evaluation process before more detailed geological investigations will take place (NWMO, 2010). The approach taken by the NWMO to not assess granitic sites prior to community engagement would have been affected by the uncertainties of assessing very large areas of the Canadian Shield and has likely led to optimised expenditure in field work and data collection.

5. Next Steps

A key learning from the case studies presented above is that performing modelling studies or creating screening tools without commensurate support from sufficient data can lead to conclusions affected by unacceptably large uncertainties and carry the risk of excessive expenditure with limited value in Phases 2 and 3 of the BGE's site selection process. Therefore, we have identified a potential avenue towards development a method for site selection in crystalline rock, including further studies which would be underpinned by currently accessible data but does not include full site characterisation:

- **Geomechanical study:** there is potentially a considerable database of geological and geophysical data available from mining and quarry sites in crystalline rock. While these sites themselves have already been excluded in the BGE's siting process, the data here could be used to provide general information on the geomechanical properties of different types of crystalline rock in different settings and assess if any broad trends on fracture network presence and extent could be determined which could be related to broad geological criteria established for the setting. If any broad trends could be established (and it is considered that only broad trends would be achievable) then these could be used to establish broad criteria that could be applied via a high-level screening of the areas of consideration. Success of any study to attempt to define broad and reliable geological criteria cannot be guaranteed (case studies that we considered after all show that such criteria have been abandoned in favour of social license and proactive communities in other territories) but theoretically could prove successful to some degree and at the least demonstrate that sufficient consideration to developing a geological screening criteria has been attempted. Given this uncertainty we would recommend that any future geomechanical study could be undertaken iteratively starting with a feasibility study with data from a small number of locations with future expansion of scope based on these initial outcomes.
- **Impact of glaciation:** as noted in the Canadian case study, the impact of glaciation of the stress-state of crystalline rocks has been studied previously. Mapping of Quaternary aged geologies across Germany indicates some but not all crystalline rocks in the country have been covered by glaciation following the primary rocks formation. The presence of large volumes of ice will increase the vertical stress applied to the rocks beneath them, including crystalline rocks, followed by stress release following deglaciation. In practice crustal depression from ice over burden has been shown to exceed 100m in north-western Europe. It may therefore be possible to investigate the extent of Quaternary glaciations in German territory (e.g., Figure 3) and identify if there is a relationship between these glaciations and deformation in crystalline rocks, in conjunction with a limited geomechanical study of available mining and quarry sites across the country as recommended in the point above.

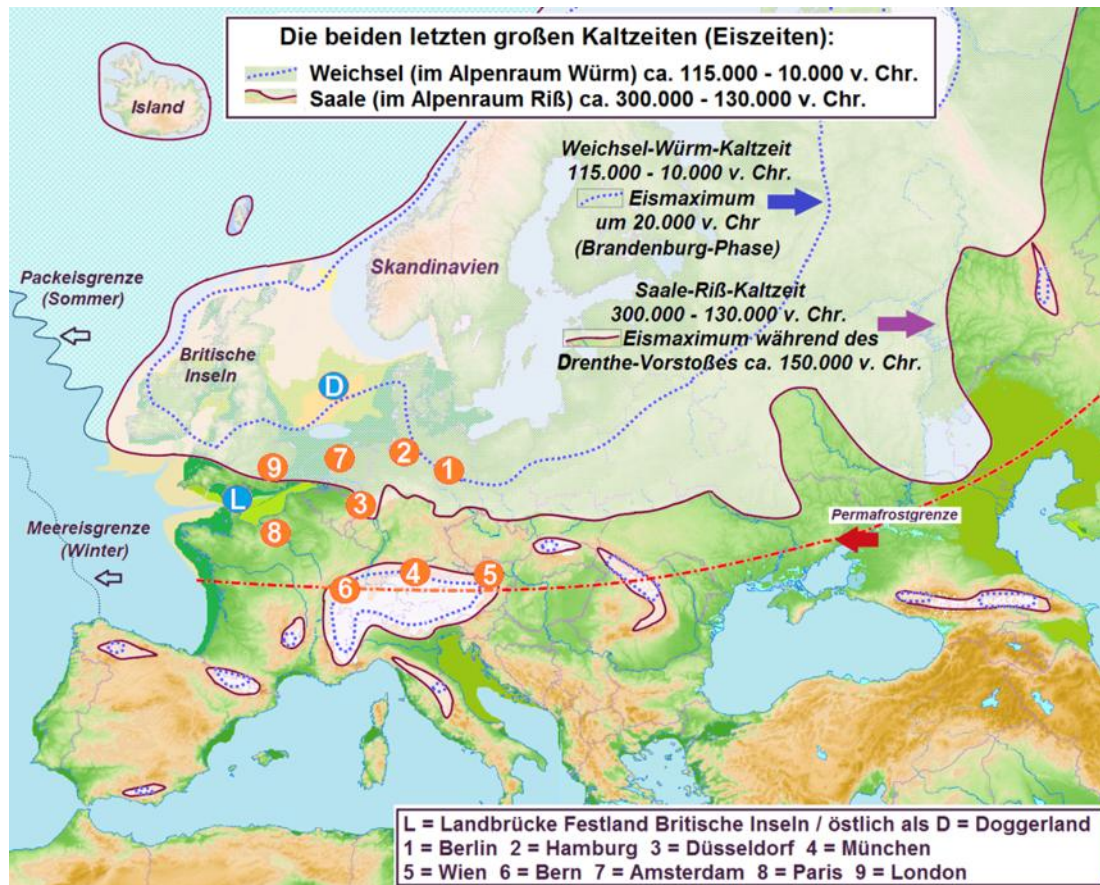


Figure 3: Map of ice extent in Europe during the Quaternary period. From Juschki, 2015. When crystalline rock locations are superimposed it is clear that some areas have and some areas have not been impacted by Saalian and Weichselian age glaciation.

- Further case studies: there is the opportunity to build on the two case studies completed in the short time allotted to this study. A detailed study of the previous work done by both Canadian and Swedish scientists, alongside other areas with crystalline bedrock, may provide indicative trends in the degree of fracturing. This study could be expanded to include examples from the UK where significant work has been undertaken on the nature and cause of fracture networks in regions such as Devon and Cornwall. This may supplement the relatively limited data available on Germany's crystalline bedrock with extensive studies and datasets available in other geographies.

The proposed next steps should be undertaken iteratively and treated initially as a feasibility study before committing to such a task (i.e. development of a method for site selection in crystalline rock) in full. We believe there is the potential to move ahead with initial data collation and review, to the extent that it proves (or not) that sufficient investigation will yield criteria that can be applied on the national scale, and that the time scales for this would be in the range of 1-3 months.

6. Conclusions

The BGE is undertaking a three-phase process to identify a suitable site for a GDF. Phase 1 Step 1 has been completed and identified 90 sub-areas of potentially suitable rock. Seven of these sub-areas are in crystalline bedrock. Some geological factors, including proximity to major faults and mining activities have already been considered. The main factor not considered thus far is the presence and nature of fracture networks in these crystalline rocks.

Fracture networks pose a risk to GDF sites in crystalline rock as they introduce permeability and porosity to the rock mass and are the main fluid conduits in these rock types. They are difficult to accurately characterise without detailed, intrusive subsurface mapping, as fracturing at the surface is not a reliable indication of fracturing at depth. It is therefore difficult to accurately account for the distribution and intensity of fracturing

in the seven crystalline bedrock sub-areas based on this important geological factor at this stage in the BGE's site selection process. However, applying any methodology which does not account for what data is available risks excluding potentially suitable sites from future stages in the site selection process before they have been adequately characterised.

Case-studies from Sweden and Canada, both of which are underlain by significant amounts of crystalline bedrock, confirm the difficulty in assessing the impact of fracture networks on these rocks prior to detailed site investigation. During their respective equivalents to the BGE's Phase 1 process, both countries noted that crystalline rock in general represented a suitable host rock for a repository site and relied on the interest of local communities to focus expenditures to determine where surface and subsurface mapping would take place. This process is on-going in Canada, while in Sweden, both societal and geological conditions were used to determine the final repository location after investigating eight candidate sites.

Despite the decisions taken in Canada and Sweden, Amentum considered the fundamental controls on the formation of fracture networks (such as rock strength, paleo- and present-day stress fields) and identified three possible avenues of further work, all underpinned by real data, which could potentially help the BGE to distinguish between areas of crystalline rock at this early stage:

- A geomechanical study of the crystalline rock types found in German territory using local areas of high data density such as mines and quarries. The geomechanical properties of different types of crystalline rock will influence how likely they are to fracture in certain tectonic setting and paleo- and present-day stress regime. This process could be done iteratively, beginning with a small dataset, and be expanded to larger areas if initial results are favourable.
- An investigation into the impact of glaciation on crystalline rocks. Previous work in Canada investigated how the loading of glaciers changed the vertical stress in the underlying bedrock. Therefore, a relationship may exist between ice extent and thickness and the degree of deformation in the underlying crystalline bedrock.
- More detailed case studies could further justify the findings of this relatively short investigation while also providing general links from siting processes in other countries on fracturing pre- and post-site investigation. This study could be expanded to include examples from the UK where significant work has been undertaken on the nature and cause of fracture networks in regions such as Devon and Cornwall. This may supplement the relatively limited data available on Germany's crystalline bedrock with extensive studies and datasets available in other geographies.

A combination of all three approaches above will likely yield the most comprehensive assessment with currently available data. An iterative approach, beginning with an initial phase of data collation, which expands on the basis of favourable results could prove successful and at the least demonstrate that sufficient consideration has been given to developing a geological screening criteria. It is estimated that the time scale for this exercise would be in the range of 1-3 months.

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