

Performance specifications of concept design for quantitative methods in crystalline rocks

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Executive summary

The BGE is undertaking a process of site selection for the long-term disposal of intermediate- and high-level radioactive waste. This is a multiple phase process which is currently at the desk study stage. The BGE has shortlisted 90 sub-areas using GIS analysis. Seven of these sub-areas are in crystalline rock (either plutonic igneous rocks or high-grade regional metamorphic rocks). While the BGE has developed internal criteria for the two other rock types being considered (salt and mudstone), there remains uncertainty in the feasibility of defining suitable criteria to rank these seven crystalline rock sub-areas to shortlist localities for further study in the following phases of their site selection process. Amentum were employed to carry out a feasibility study to determine if this could be done and how such a methodology could be deployed (Jacobs, 2023). That study concluded that it would be conceivable to develop high-level relationship between various geological factors that could inform the BGE's siting process using what data is available to build a geomechanical and stress database and combine it with mapped extents of Quaternary glaciations. This study arises from that earlier project. Amentum determined that the most relevant characteristic of crystalline rocks that would determine their suitability to host a geological disposal facility (GDF) is the fracture networks present in the rocks. This introduces permeability into an otherwise impermeable rock and is the main pathways for the egress of radionuclides. Amentum determined that three properties of the rocks could be used to potentially predict areas of deformation, albeit as a first-order assessment with multiple caveats:

- The geomechanical properties of the rocks.
- The in-situ stress state.
- The impact of recent glaciations.

These properties could be mapped across the seven crystalline rock sub-areas to identify broad trends and then identify areas where significant deformation could be expected. This is unlikely to result in definitive findings that can be used to exclude or include sub-areas of crystalline rock in the BGE's siting process but can be used to constrain the extent of future phases of the siting process and to highlight areas of interest geographically. To achieve this, Amentum carried out the following three Tasks:

- Task 1: collate and analyse all available geomechanical and stress magnitude data.
- Task 2: map the extent and thicknesses of Quaternary glaciations in Germany and understand their influence on crystalline rocks.
- Task 3: combine the results of Task 1 and Task 2 to map out areas where greater deformation might be expected.

Amentum collated all available geomechanical data for Task 1, including both data provided by the BGE through the geological surveys of the individual German states, alongside open-access academic databases. High-level trends were identified which are discussed below. Analysis of the stress magnitude data did not reveal any areas of anomalously high vertical or horizontal stresses. It was noted that the present-day tectonic regime does vary locally, with most areas experiencing a compressional tectonic regime with local areas experiencing a strike-slip tectonic regime. This is an important finding when deciding where to place a GDF and should be studied further to better define this local variation.

Analysis of published literature on Quaternary glaciations in Task 2 revealed that three major glaciations affected the area: the Elsterian, Weichselian and Saalian glaciations. Their extents were mapped, with most sub-areas covered by these glaciations to some extent in Brandenburg, Saxony, and Thuringia. Literature review also highlighted the impacts of glaciations on rocks, which are twofold:

- Vertical loading of the ice-sheets on the rocks they overlie, which increases the vertical stress gradient which may lead to fracture modification during ice-sheet advance or retreat.
- Glacio-isostatic readjustment of the Earth's crust caused by the advance and retreat of ice-sheets can cause changes in the horizontal stresses, which can lead to glacially-induced faulting and associated seismicity.

These three factors were mapped and combined in Task 3, to produce a composite map combining these three rock properties to determine areas of potential deformation. The sparsity of the available data on crystalline rocks, which was made clear from the project outset and in the previous feasibility study, was demonstrated with this composite map, and highlighted the need for more data to suitably characterise these rocks. Nevertheless, the methodology used was found to be a valid combination of geomechanical, stress magnitude and glaciation data to support a GDF siting programme which did identify areas where we would expect to find largely undeformed rocks. Additionally, some high-level conclusions could be made:

- All rock types investigated in this study have been found to have a predicted rock quality designation (RQD) of 'Excellent' in at least one locality. This means that we predict one fracture per metre of rock core or less. It is therefore difficult to exclude any igneous or metamorphic rock types that have thus far been approved by the BGE from the on-going GDF site selection process.
- The available stress magnitude database does not highlight any areas of exceedingly high in-situ stress.
- The stress magnitude data does reveal some local variability in the present-day tectonic stress regime, with most localities experiencing a compressional tectonic regime with some outliers experiencing a strike-slip tectonic regime. The local variability in the orientation of the stress field and the resultant tectonic regime is important in any GDF site selection process and the driving factors behind this variability warrants further study.
- Glaciation has played an important role in the evolution of the Quaternary geology of Germany. Glaciers/icesheets have also overlain areas of crystalline rock, likely causing increased stresses due to both the loading of the ice-sheets and the adjustments of the lithosphere caused by the advance and retreat of the ice-sheets.
- Glacio-isostatic adjustment as a result of ice-sheet advance and retreat has a much wider area of influence beyond the mapped extents of ice-sheets. This has important implications for the reactivation of faults and resultant seismicity this may cause across all German territory. It also appears to be an area of research that has received relatively little attention and warrants further research in support of GDF siting.

Acronyms and abbreviations

BGE	Bundes-Gesellschaft Für Endlagerung MbH
EU	European Union
GDF	Geological Disposal Facility
GIS	Geographic Information System
LGM	Last Glacial Maximum
MIS	Marine Isotope Stage
RQD	Rock Quality Designation
UCS	Uniaxial Compressive Strength

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1 Introduction

The Bundes-Gesellschaft für Endlagerung MbH (BGE) are in the process of selecting a location to host a Geological Disposal Facility (GDF) for the long-term storage of high- and medium-level nuclear waste on German territory. This process is being undertaken in three phases:

- Phase 1: desk-based study to identify candidate sites for surface mapping and exploration.
- Phase 2: surface exploration of candidate sites.
- Phase 3: intrusive subsurface exploration of candidate sites.

Phase 1 is currently underway and has been subdivided into two steps; Step 1 is a Geographic Information System (GIS)-based study which has resulted in 90 'sub-areas' being defined within German territory. These sub-areas are composed of three rock types: salt, mudstone, and crystalline rock. Step 2 of Phase 1 is now underway to rank these 90 sub-areas to shortlist candidates for surface exploration in Phase 2 of the GDF siting process. The BGE has developed criteria to rank both mudstone and salt sub-areas, but uncertainty remains about the feasibility of selecting candidate sites from crystalline rock sub-areas. Both mudstone and salt sub-areas are typically covered by pre-existing surface and subsurface data collected for a variety of industrial purposes, including hydrocarbon, mineral and geothermal energy exploration and production. Conversely, crystalline rock sub-areas have a relative lack of legacy subsurface data apart from small data-rich areas such as quarries or mines.

The BGE employed Amentum to carry out a pre-feasibility study on developing siting criteria in crystalline rocks which might inform a future ranking in Phase 1, Step 2 of the BGE's GDF siting process. Amentum's investigation revealed that the presence of fracture networks within crystalline rocks has been repeatedly identified as a key risk to GDF integrity (Jacobs, 2023); these fracture networks introduce secondary porosity into rocks which typically have no pore space and will act as the main conduit for groundwater flow and potential pathway for the migration of radionuclides into regional groundwater systems. Several previous studies have noted the difficulty of characterising the intensity and extent of fracture networks in the subsurface without significant intrusive investigations alongside the variation between fracture networks at surface and those in the subsurface. Other national nuclear organisations had ultimately relied on non-technical factors, such as social license and communities volunteering to host a GDF, to shortlist locations for surface and subsurface investigations. Nevertheless, Amentum identified three aspects of crystalline rocks which could be investigated to help inform the BGE as they develop siting criteria:

- The geomechanical properties of the crystalline rocks, which would be used to characterise their strength and how they might deform.
- The present-day, in-situ stress magnitude data could be used to understand the current stress regime which influences fracture formation, and to identify areas of high present-day stress.
- The extent of recent glaciations, which have been observed in other countries to reactivate faults leading to seismicity.

This study aims to gather as much pre-existing data as possible from both public and private sources where available, to characterise the strength of the various crystalline rock types, the in-situ stress state of these rocks, and the extents of Quaternary glaciations, to understand how these characteristics combine to influence the amount of deformation, and therefore predicted fracture sizes and intensity, present in the crystalline rock sub-areas. These objectives were subdivided into three main tasks which would make up the bulk of the work carried out in this study; Task 1 involved the collation and data analysis of all available geomechanical and stress magnitude data, Task 2 focused on mapping the extents and thicknesses of Quaternary glaciations in Germany, and Task 3 then combined these results to produce a composite map which would aim to predict the degree of deformation across the crystalline rock sub-areas, which could be used to inform the BGE's generation of criteria for these sub-areas to shortlist those for further study.

2 BGE's site selection process

The BGE are undertaking a multi-stage process to select a suitable site for the long-term repository for high-level radioactive waste in German territory. This process began in 2013 when legislation was passed in the German parliament. A commission consisting of legislators and technical experts then developed rules and criteria which would guide the site selection process through the 'Act on the search and selection of a site for a repository for high-level radioactive waste' (Site Selection Act - StandAG) in 2017. The key guiding principles for the site selection process are:

- science-based
- participative
- transparent
- self-questioning
- learning

The process to determine a suitable site for the placement of a GDF is structured to honour these guiding principles and consists of three phases:

- Phase 1: a desk-based study using geospatial and geological data to exclude areas from the GDF siting process. This is subdivided into two steps. Step 1 has been completed and consisted of a GIS-based mapping exercise. Areas were excluded during this phase based on proximity to clear risks to a GDF, including large faults, historic and active mines and quarries, areas of recent seismicity and volcanic activity. This has led to the identification of 90 'sub-areas' which remain under active consideration as host rocks for the GDF site. Step 2 of Phase 1 is the development of ranking criteria for these 90 sub-areas to shortlist which sites will be investigated in Phase 2 of the GDF siting process.
- Phase 2: surface exploration of the shortlisted sites identified in Phase 1 will make up the bulk of the work of Phase 2. This will include mapping, sample collection and laboratory-based analysis of collected samples. Information collected during this phase will be used to inform which sub-areas will be shortlisted for study in Phase 3 of the GDF siting process.
- Phase 3: the final sub-areas shortlisted in Phase 2 will be explored in detail, with intrusive investigations including drilling and the acquisition of geophysical data. The results of Phase 3 will be the identification of a suitable site to host a long-term disposal site for Germany's intermediate- and high-level radioactive waste.

To date, Step 1 of Phase 1 has been completed, and Step 2 of Phase 1 is currently on-going. This study makes up some of the work being done to satisfy the requirements to complete Phase 1 of the siting process. As noted above, Step 1 of Phase 1 has resulted in 90 sub-areas being identified as potential host sites for a GDF. These 90 sub-areas consist of three principal rock types:

- Mudstone
- Salt
- Crystalline Rock

These are broadly similar to the host lithologies identified in the GDF siting processes of other national nuclear agencies in countries with varied geology, including the UK, USA and France.

3 Overview of the shortlisted crystalline rock sub-areas

As outlined above, the BGE identified 90 sub-areas for further investigation in Step 1 of Phase 1 of their GDF siting process. Of these, seven have been identified in various types of crystalline rock (Figure 1). These seven sub-areas cover a total surface area of 80,786 km². The BGE use the term ‘crystalline rock’ to describe both igneous plutonic rocks such as granites, diorites and gabbros, and high-grade regional metamorphic rocks such as gneisses and granulites. These rock types are expected to have favourable properties suitable to host a GDF, dependent on the heterogeneity, geomechanical and thermal properties [Appendix A]. Crystalline rocks such as smaller igneous intrusions (i.e. sills and dykes) as well as low-grade regional metamorphic rocks and contact metamorphic rocks are not considered to have suitable properties to host a GDF. The seven sub-areas in crystalline rock have been given the following titles:

- Sub-area 009_00TG_194_00IG_K_g_SO
- Sub-area 010_00TG_193_00IG_K_g_MKZ
- Sub-area 011_00TG_200_00IG_K_g_SPZ
- Sub-area 012_01TG_198_01IG_K_g_RHE
- Sub-area 012_02TG_198_02IG_K_i_RHE
- Sub-area 013_00TG_195_00IG_K_g_MO
- Sub-area 014_00TG_199_00IG_K_g_NPZ

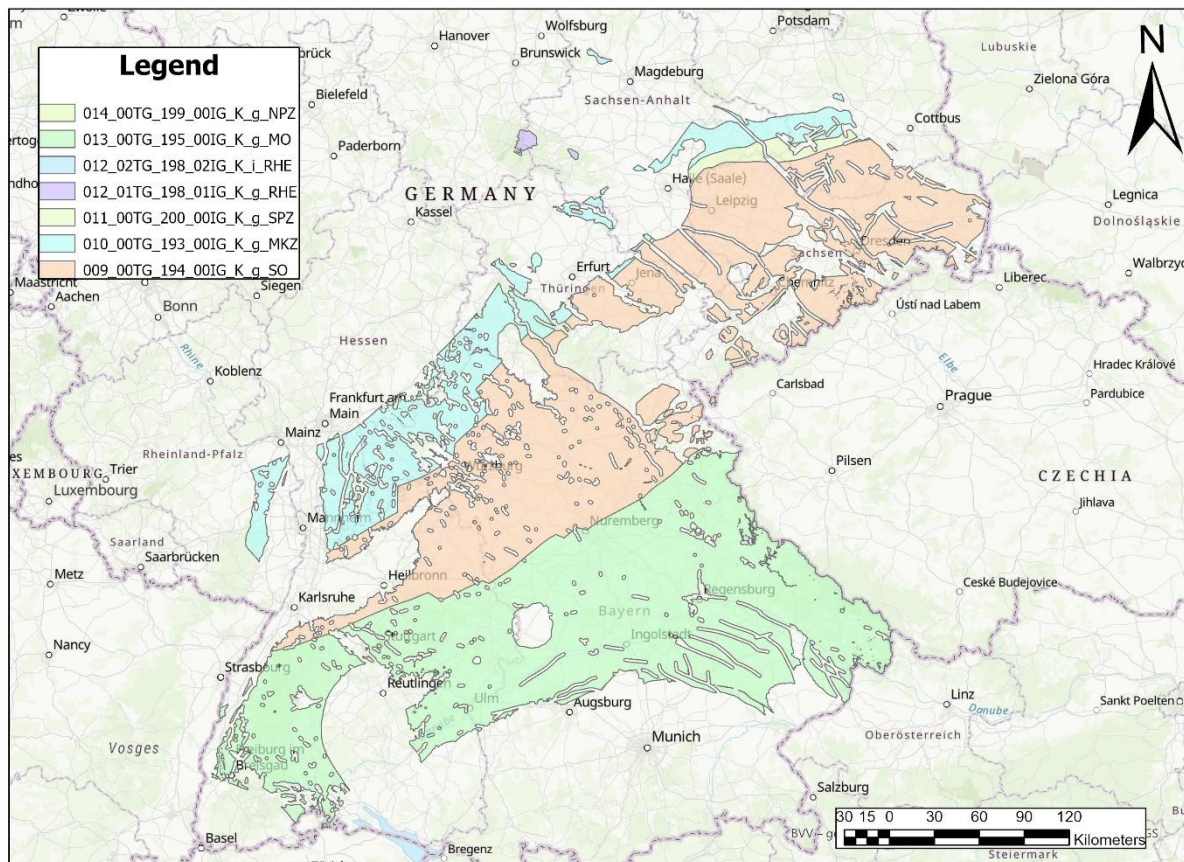


Figure 1: Overview map showing the extent of the seven crystalline rock sub-areas.

A table outlining the key characteristics of these sub-areas is presented below.

Sub-area	Area (km ²)	Geological Zone	Thickness (m)	Depth below surface (m)
009	32,655	Saxothuringian	200-1200	300-1300
010	10,066	Mid-German Crystalline Rise	200-1200	300-1300
011	991	Southern Phyllite	210-1200	300-1290
012_01	175	Renohercynian	350-1200	300-1150
012_02	52	Renohercynian	210-920	580-1290
013	36,836	Moldanubian	200-1200	300-1300
014	10	Northern Phyllite	1180-1200	300-320

Table 1: Spatial details of the seven crystalline rock sub-areas.

It is apparent that these sub-areas of crystalline rock have been divided using their location within the various metamorphic units of the Variscan orogeny. These are likely to have varying metamorphic grades and density of igneous intrusions which will impact their suitability as hosts for a GDF. This is reflected in the total area of these sub-areas, with those in the lower grade phyllite zones having significantly smaller areas than the higher grade Saxothuringian and Mid-German Crystalline zones following Step 1 of Phase 1 of the BGE's GdF siting process. The geological history of these zones of the Variscan Orogen are explored in detail in the following section.

3.1 Geological evolution of Germany with reference to the Crystalline Rock sub-areas

The oldest relevant geological episode for the crystalline rocks which make up the seven sub-areas is rifting during the Early Devonian following the culmination of the Caledonian Orogeny which dominated northwest Europe. The Early Devonian sediments filling these rift basins consisted of non-marine and shallow marine clastic sediments, which graded upwards into clastic shelf sediments and shallow-water carbonates from the Middle Devonian through to the Early Carboniferous. The clastic shelf sediments were derived primarily from the Baltoscandian region to the north. The final sedimentary fill was northwards-verging flysch and molasse deposits derived from the growing Variscan Orogeny to the south.

These rocks then underwent metamorphism as the Variscan Orogeny proceeded during the Late Carboniferous and Early Permian. This involved the collision between the continental plates of Laurussia and Gondwana to form the supercontinent of Pangea alongside the closure of the intervening Rheic Ocean. Across Germany this resulted in the formation of primarily NE-SW oriented structural grain, with large, northwards verging thrust faults separating the principal zones of varying metamorphic grade. The main phase of mountain building occurred during the Late Carboniferous. The intrusion of several granitic plutons also occurred alongside this orogen, likely sourced by the interaction of subducting water-saturated rocks and magma in the lithosphere.

The Pangean supercontinent began to break-up following the Variscan Orogeny. A series of rift basins began to form, accommodated by movement on basin-bounding normal faults, some of which reactivated and inverted thrust faults, reverse faults and shear zones formed during the Variscan Orogeny. These basins were filled with arid clastic sediments of the Rotliegende Group and the salt of the Zechstein Group. A period of tectonic quiescence followed during the Triassic and Jurassic, where relatively uniform thicknesses of these sediments were deposited across large areas of Germany.

The region experienced compression during the Cretaceous, as Iberia collided with Europe, creating the Pyrenean Orogen, and leading to the reactivation of several pre-existing syn-rift faults of Permian age. Examples of these reactivated faults include the Harz Mountains Boundary Fault and the Osning Thrust. The region then experienced uplift and erosion during the Cenozoic as the African continent collided with Eurasia, creating the Alpine Orogeny to the south of Germany. During the Quaternary, Germany and Central Europe were subject to repeat glaciations, with the advance and retreat of ice-sheets from both Scandinavia to the north and the Alpine glaciers to the south.

4 Data and Methodology

This study is a data-driven assessment of the seven crystalline rock sub-areas with an aim to identify trends in the available data through geomechanical first principals that can be used to support the BGE's site selection process. A key risk that was identified at the start of this project was the relative lack of subsurface data for the crystalline rock sub-areas when compared with the salt and mudstone sub-areas. This data bias comes from the greater economic interest in sedimentary rocks for oil and gas, geothermal and raw materials when compared to crystalline rocks. To understand deformation in the crystalline rocks of Germany, three principal data types were required:

- Geomechanical measurements taken from the various crystalline rock types which make up the crystalline rock sub-areas, including the uniaxial compressive strength (UCS), Youngs modules, and Poisson's ratio.
- Stress magnitude data acquired from the in-situ rock mass.
- Mapped maximum extents and ranges of thicknesses of ice sheets within the study area.

This study was to incorporate all existing geomechanical, stress magnitude and ice-sheet information that was readily available. No new data collection was to take place. Data for this study was derived primarily from two key sources: the database of subsurface data collected by the BGE, and open-access databases compiled by academic institutions. Additional data was taken from individual academic publications which focused on the crystalline rocks of Germany.

4.1 Geomechanical Data

4.1.1 Data Provided by BGE

An initial data request was made by Amentum to the BGE outlining the various types of data that would be required to investigate the seven crystalline rock sub-areas. Data was delivered to Amentum in two batches. The data provided included a variety of data sources. The first batch of data was sourced from the Bavarian Geological Survey (Bayerisches Landesamt für Umwelt) and primarily covered the state of Bavaria in southeastern Germany. The data in this batch included:

- Geological maps of Bavaria outlining the surface exposure of the various rock types and geological structures. These maps also included some simplified geological cross-sections.
- Shapefiles mapping various geological features including active and inactive faults, active and inactive extractive mines and quarries, recent seismicity and the location of known but undeveloped mineral deposits and coal seams.
- Geophysical surveys including airborne gravity and magnetic data alongside 2D and 3D seismic reflection surveys.
- A variety of subsurface test data, including hydrological pumping tests, geomechanical strength tests and grain size analyses.

The second batch of data covered the remaining provinces which contain any part of the seven crystalline rock sub-areas (Baden-Württemberg, Brandenburg, Hesse, Rhineland-Palatinate, Saxony, Saxony-Anhalt, and Thuringia). This batch of data included similar formats to the first, with geological maps and sections, shapefiles, geophysical surveys, and subsurface test data, alongside 3D geological models (in the GOCAD format) for select localities. A full list of the data provided is included in Appendix A.

Three principal sources of geomechanical data were available from the database provided by the BGE. Two of these were included in the data collections provided to the BGE by the Bavarian Geological Survey (Dok ID 11879793). The first was a now defunct database originally developed by the Bavarian Geological Survey titled 'Stontec' from 1999 to 2008. Development of this database and the rock lab which was used to test rock samples were closed in 2010. The values originally included in this database was included in the BGE data transfer in an .xlsx file (Druckfestigkeiten_Stonetec.xlsx) which contained locality names, an identification number, rock type, and uniaxial compressive strength values. An example of the data in this file is shown in Table 2 below:

Objekt Name	BIS-ID	Probenart	DF Druckfestigkeit
Stbr. Höhenberg, SW Bruch		Gr	82.85 [MPa]
Schloßbergbruch N Hörmannsdorf		Gr	157.19 [MPa]
...	...	...	...

Table 2: Example of the structure of the Druckfestigkeiten_Stonetec.xlsx spreadsheet.

Note the BIS-ID column was only partially populated. This BIS-ID column referenced outcrops which were stored in the Bavarian Soil Institutes information systems. A notable shortcoming of this database was the lack of coordinate data, with only vague names indicating where the samples were collected. Amentum attempted to geolocate these locations with some success; of the 381 data points included in the database, 209 could be geolocated to an obvious quarry or large outcrop. Given there were several data points for individual localities, this totalled to 21 distinct localities of crystalline rock across Bavaria. This database does not contain any other geomechanical data, such as Young's modulus values. This database also came with the following warning from the Bavarian Geological Survey regarding uncertainty in the provenance of the data (translated from German on page three of the Datendokumentation.pdf file):

"The significance of the values regarding the balancing criteria according to StandAG is from the perspective of LfU [Bavarian Geological Survey] should be viewed very critically. The documentation of the values (and the values themselves) are out from the LfU [Bavarian Geological Survey]'s point of view, it is not suitable for these scientific purposes. Neither source, experimental number nor interpretations can be seen in the database design. The location (coordinates) of the sampling locations is not exactly known (reference objects, if known, are the outcrops and their generalized or averaged location coordinates)."

Therefore, this first source of geomechanical data comes with a large degree of uncertainty given the lack of information on data collection methods, collection location, quality of samples and specific coordinates. However, given the severe lack of data available for this study this data was included in initial analysis with the caveat that there is significant uncertainty associated with these data points.

The second file containing geomechanical data that was derived from the Bavarian Geological Survey comes from a triaxial testing campaign carried out on samples collected from granites located in the Bavarian Forest region in eastern Bavaria. The samples were collected by the Structural Geology Working Group at the GeoZentrum Nordbayern based at Friedrich-Alexander University (FAU) in Nuremberg and were tested in the laboratory of Dr. Eberhard Jahns. This dataset covers five granite plutons located in eastern Bavaria:

- Hauzenberg Pluton
- Fürstenstein Pluton
- Patersdorf Pluton
- Metten Pluton
- Kristallgranit Pluton

Strength testing and Mohr-Coulomb analyses were carried out on samples from these five localities. Details of the laboratory equipment, sample preparation and testing procedures are outlined in the accompany report (Abschlussbericht_Triaxialtests.pdf). This dataset includes several key geomechanical properties, including the uniaxial compressive strength, Young's modulus, and Poisson's ratio.

A third file containing geomechanical information was delivered in the second batch of data and comes from the borehole database (Dok ID 11965212) of the Geological Survey of Saxony (Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie). Details of this database is included in the accompanying word document (Hinweise_Bohrdaten_20012022.docx) which outlines the background of the data. It mentions plans to update the database with additional boreholes as they become available.

This database is spread across multiple excel spreadsheets which contain different characteristics, including borehole geometry and geochemical data. One spreadsheet (ING_GEOL_KENNWERTE_100M.xlsx) contains geomechanical data, including uniaxial compressive strength values. The geology in this database includes samples and measurements taken from both sedimentary and metamorphic rocks. There are three entries for gneisses from southern Saxony which were included in our analyses. Like the data derived from the Druckfestigkeiten_Stonetec.xlsx file above, there is little information outlining the condition of the rock samples or the testing procedures that were used to determine the UCS values, although coordinates are provided to locate these values accurately.

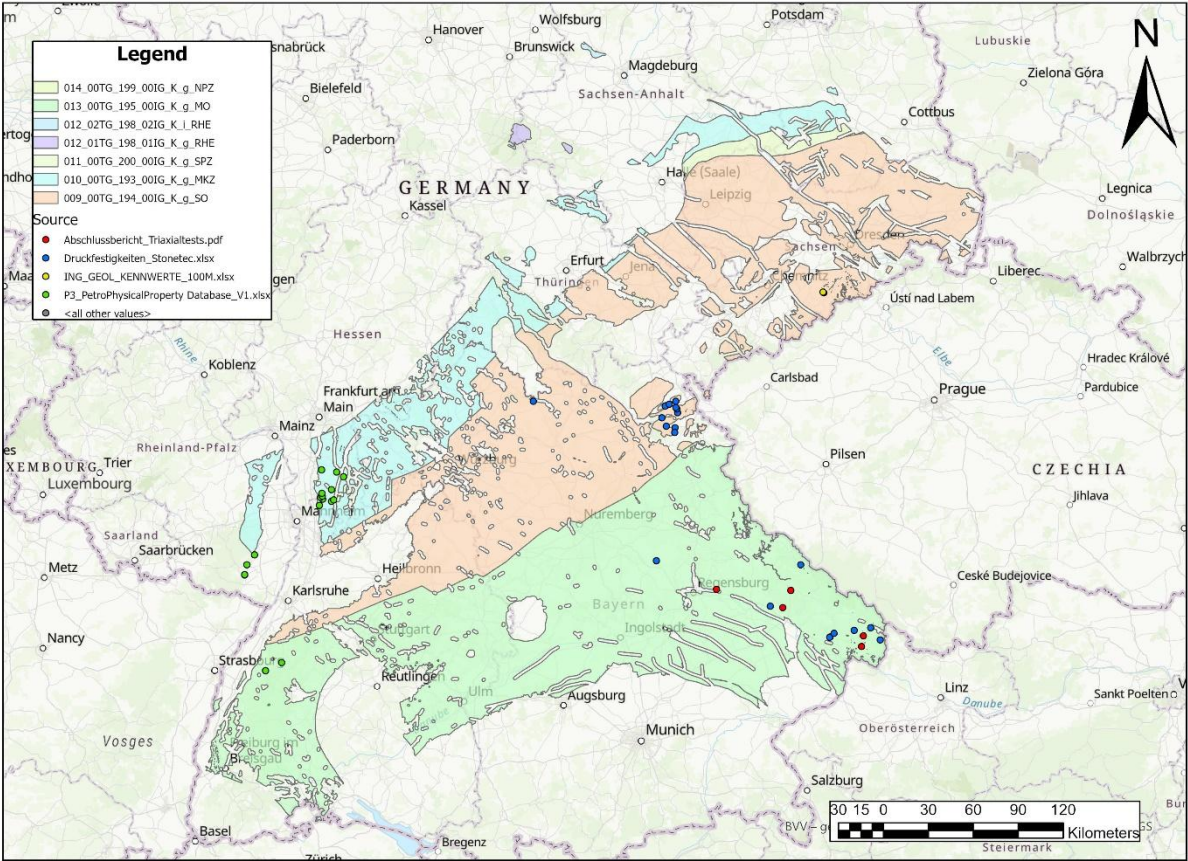


Figure 2: Overview map showing the location of UCS measurements. Points are coloured by data source.

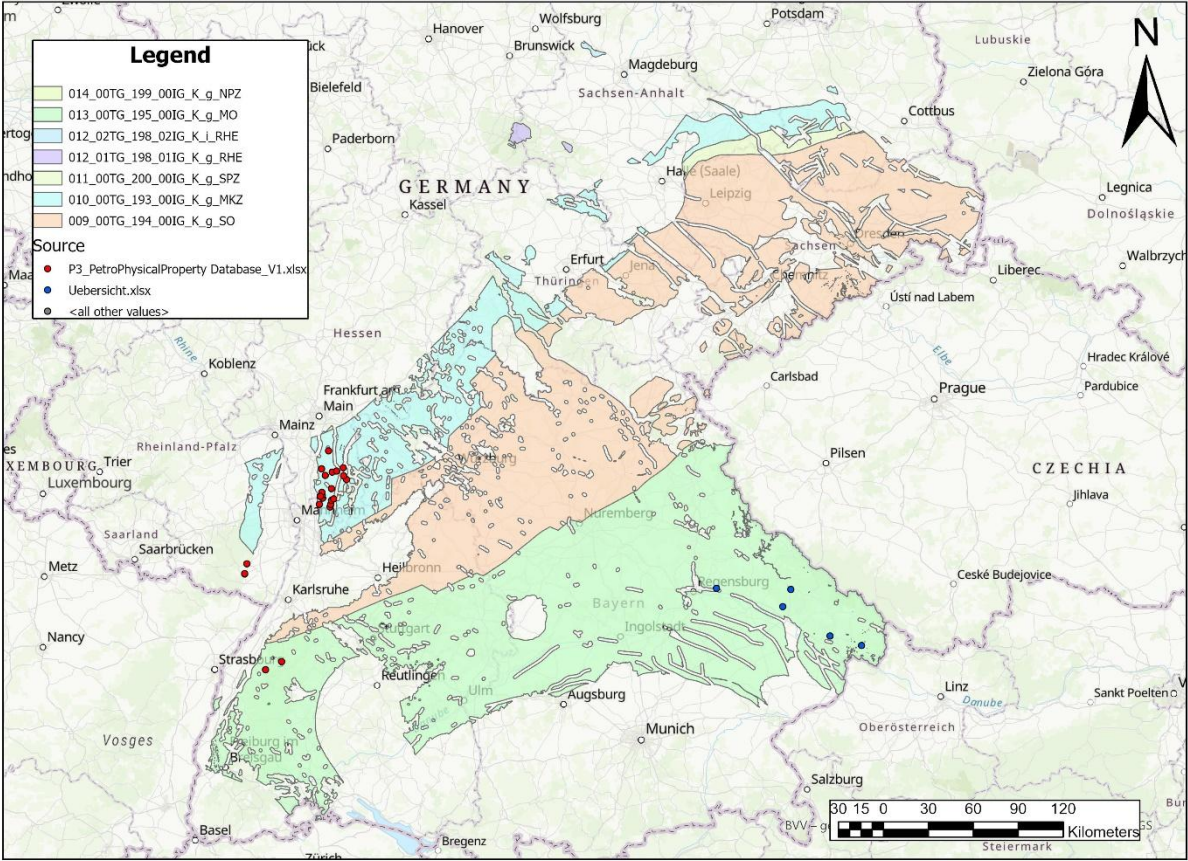


Figure 3: Overview map showing the location of Young's Moduli measurements. Points are coloured by data source.

4.1.2 Academic Databases

The PetroPhysical Property Database (styled P3 Database) is an EU-funded database of petrophysical properties collated by researchers from various German research institutions to support the exploration and development of geothermal resources. The database includes data for reservoir characterisation including temperature, geomechanical and geophysical properties. The database also includes accompanying metadata which outlines where and how data was collected.

Key properties in the P3 Database relevant to this project included UCS and both static and dynamic Young's modulus values. This was composed of 293 UCS values and 383 values of either static or dynamic Young's modulus collected across 19 unique localities in crystalline rock types. These values come primarily from two geological regions in Germany: The Upper Rhine Graben and the Odenwald in the states of Baden-Württemberg, Hesse, and Rhineland-Palatinate, and the western edge of the Bohemian Massif in eastern Bavaria.

A key caveat which must be considered alongside the data in the P3 Database is the rationale behind the data collection; most of the data included in this database was acquired to support geothermal exploration and development. A successful geothermal project will require a permeable reservoir to ensure high flow rates and associated productivity. The highest flow rates will be encountered in porous rocks and those with critically stressed fractures. Therefore, boreholes will target areas which are expected to be heavily deformed, such as fault zones. This collection bias may influence the distribution of geomechanical data in this database.

The P3 Database was accessed from:

<https://datapub.gfz-potsdam.de/download/10.5880.GFZ.4.8.2019.P3/>

4.2 Stress Magnitude Data

Stress magnitude information was derived from an open-access academic database created for Germany. The details of this database are outlined in the accompanying publication (Morawietz et al., 2020). This database draws on published sources exclusively, meaning proprietary and confidential information is not included here and but may be available in the future. This database includes 568 data points (Figure 4) which record some form of stress magnitude information (e.g. S_{Hmax} , S_{hmin} , etc.).

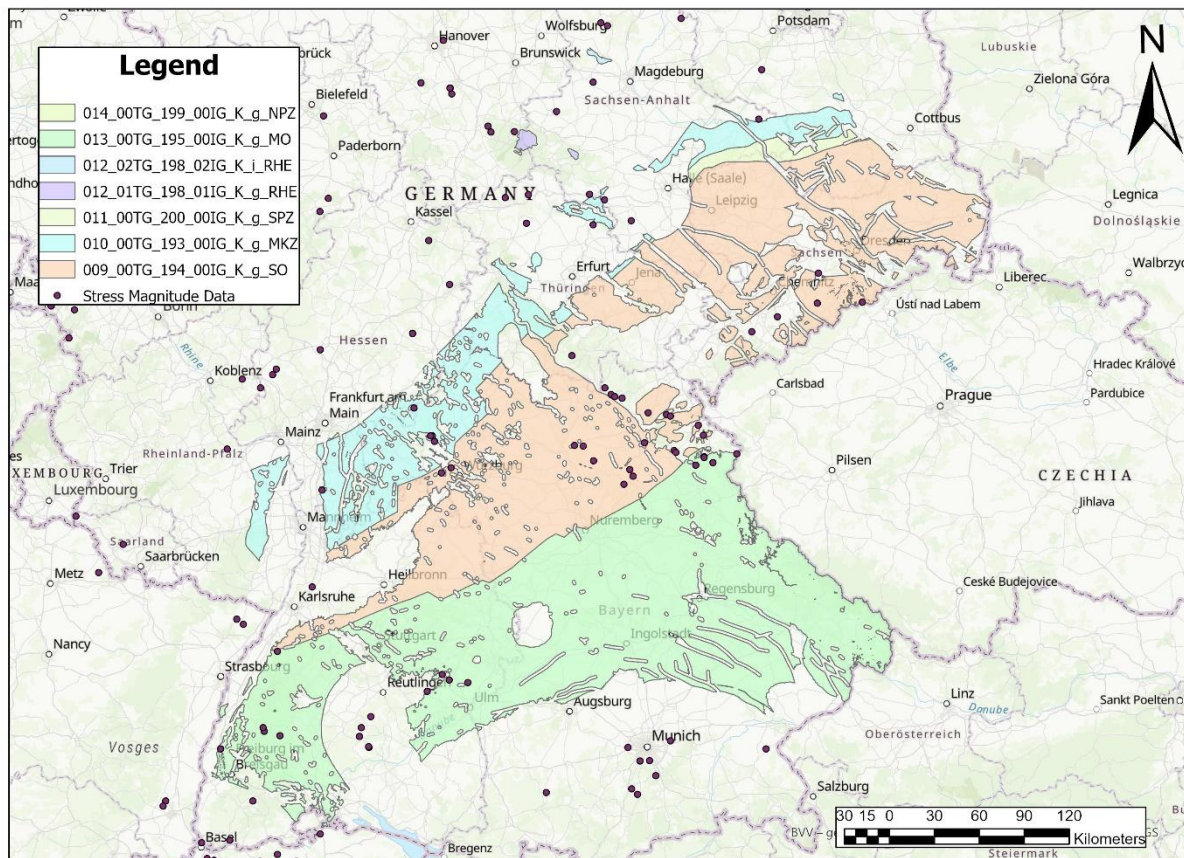


Figure 4: Overview map showing the distribution of stress magnitude data (either σ_1 - σ_3 , S_v , S_{Hmax} , or S_{hmin}).

The Open-Access Stress Magnitude Database was accessed from:

<https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-020-00178-5>

In addition to the open-access stress magnitude database, it was anticipated that some borehole data would be available from the borehole logs provided by the BGE. If a borehole contains a bulk density, a vertical stress (S_v) profile can be calculated using equation 1 (after Zoback et al., 2003):

$$S_v(z) = g \int_0^z \rho(z') dz'^1$$

Where z is depth, ρ is the bulk density and g is the acceleration due to gravity. However, there were no available boreholes with suitable bulk density logs from the areas of crystalline rock. This is not surprising given the lack of economic interest in these masses of crystalline rock.

4.3 Ice Sheet Extents

Geoscientists reconstruct ice sheet extents using a combination of methods and data sources. The data used in these reconstructions include distributions of glacial sediments, radiocarbon and cosmogenic isotope dates, and geological and geomorphological features found on the landscape. Geoscientists collate this evidence into databases and maps of potential ice margins for different phases of glaciation, and create isochrones of past ice-sheet extent. They can reconstruct past ice-sheet thickness in several ways.

Several authors have published maps showing both local and regional reconstructions of ice-sheet extents across Central Europe and Germany in particular. Two studies have been used to build up a GIS database of mapped ice-sheet extents:

- Ehlers et al. (2011) map the extent of ice-sheets across northern Germany;
- Fiebig et al. (2011) map the extent of ice-sheets derived from the Alpine glaciers and other areas in southern Germany.

These authors have reconstructed ice sheet extents for three recent glaciations (the Elsterian, Saalian, and Weichselian glaciations) for both northern and southern Germany. These were overlaid above the extents of the seven crystalline rock sub-areas to understand the potential role of both the changes to vertical stress gradients due to the loading of the ice-sheets, and the impact of glacio-isostatic readjustment on the horizontal stresses. It should be noted that the field of Quaternary science is an evolving discipline and debate over ice extent, ages of events and the impact on the terrain from palaeo glaciation is present.

5 Task 1: Geomechanical and stress analysis

Geomechanical properties are used to define the mechanical state of the rocks which make up the Earth's crust. Understanding them informs us on how rocks will behave during subsurface engineering, including the construction of a GDF. Two of the most abundant geomechanical properties in the data available for this project include uniaxial compressive strength (UCS) and Young's modulus for a variety of rock types across several localities. UCS is the maximum axial compressive stress that a rock can withstand before it fails, while the Young's modulus describes the stiffness or rigidity of a material (i.e. rock type) and ultimately how it will deform. Therefore, by analysing the maximum axial compressive stress of the various crystalline rock types and how they will deform when this stress is exceeded, we may be able to predict how these rocks might deform. By combining this with the available stress magnitude data we can also identify areas of anomalously high stress where the UCS of the crystalline rocks may have been overcome. This forms the basis of the analysis carried out in Task 1.

5.1 Analysis of geomechanical properties

Before combining the various geomechanical properties in complex analysis, simple data analysis was undertaken to identify any potential trends in the available data that could inform the site selection process. This involved analysing both the UCS and Young's modulus values against a variety of factors, including rock type, German state, and sub-area. These analyses are presented below in a series of box-and-whisker plots, which present a variety of statistical values (mean and median values, the upper and lower quartiles, and any outliers). The mean values are denoted by a cross (x), while the upper and lower quartiles are presented by the blue rectangles. The ranges are denoted by the extended lines while outliers are represented by points.

5.1.1 Uniaxial compressive strength (UCS)

UCS is a fundamental mechanical property of intact rocks. It represents the maximum axial compressive stress that a rock specimen can withstand under zero confining stress. In practical terms, UCS is crucial for designing and analysing underground excavations, tunnels, dams, and other geotechnical structures. This was also observed to be one of the most numerous rock strength values in the collated geomechanical database derived from both data supplied by the BGE and available in academic databases and publications.

The first box and whisker plot which compares UCS against rock type shows a relatively tight clustering of the data (Figure 5). The mean values across the seven igneous and metamorphic rock types lie between 140-240 MPa. The rock types with the highest UCS values are aplite and quartz-gabbros, both of which sit close to the plagioclase zone in the QAPF diagram. The metamorphic rocks (gneisses) have equally high values of UCS, although with a larger spread than both aplites and quartz-gabbros. The gneisses also have several outliers which record very low UCS values of 60 or less MPa. The mean values of diorites, granites, and granodiorites are all close to 150 MPa, with granites having the largest range of values of these three rock types.

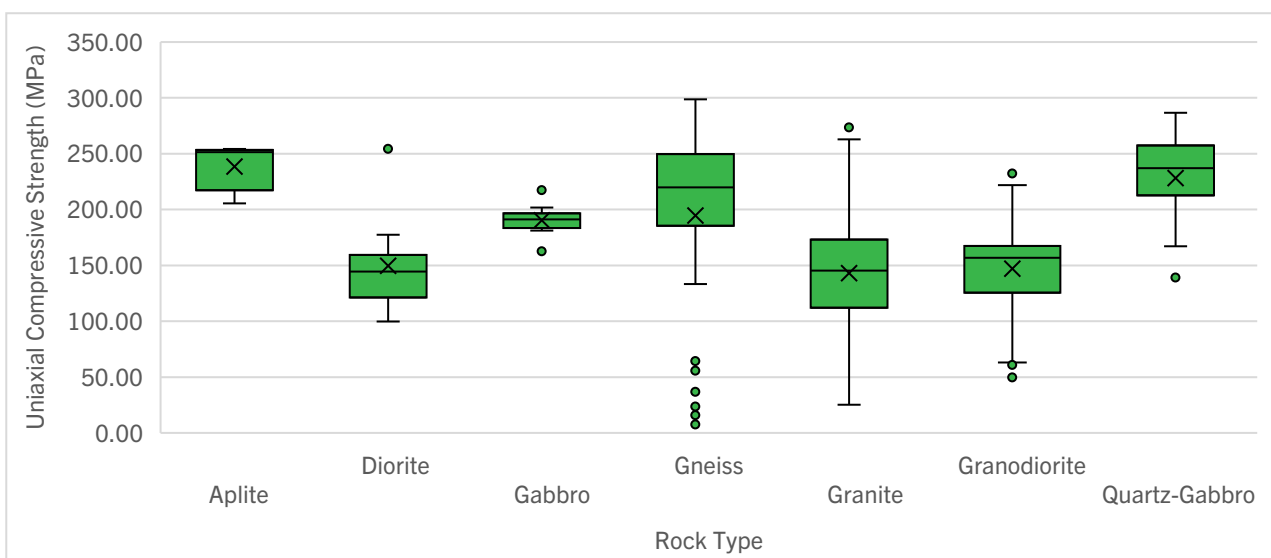


Figure 5: Box-and-whisker plot showing the distribution of UCS data across the various igneous and metamorphic rock types.

This first analysis suggests igneous rocks have reasonably high strength characteristics, although some lithologies such as granites and granodiorites have a large range of UCS values, likely due to the wide range of compositions expected in these rock types. Metamorphic rocks have equally high strength values, although several outliers with very low UCS values are also observed. These low outlier values may be due to the orientation of the foliation within the metamorphic rock relative to the principal compressive strength; these pre-existing planes of weakness within an otherwise strong rock suggest they will need further study and characterisation should these rocks be chosen to host a GDF. A key uncertainty with this data is the potential impact of chemical and physical weathering on the samples where these values were measured. The lowest UCS values (i.e. those values ≥ 50 MPa) are derived from either the Druckfestigkeiten_Stonetec.xlsx or the ING_GEOL_KENNWERTE_100M.xlsx spreadsheets, both of which lack data on the condition of the rock samples and testing procedures used to calculate these values. The remaining datasets do include sample descriptions and use primarily fresh rock samples from boreholes.

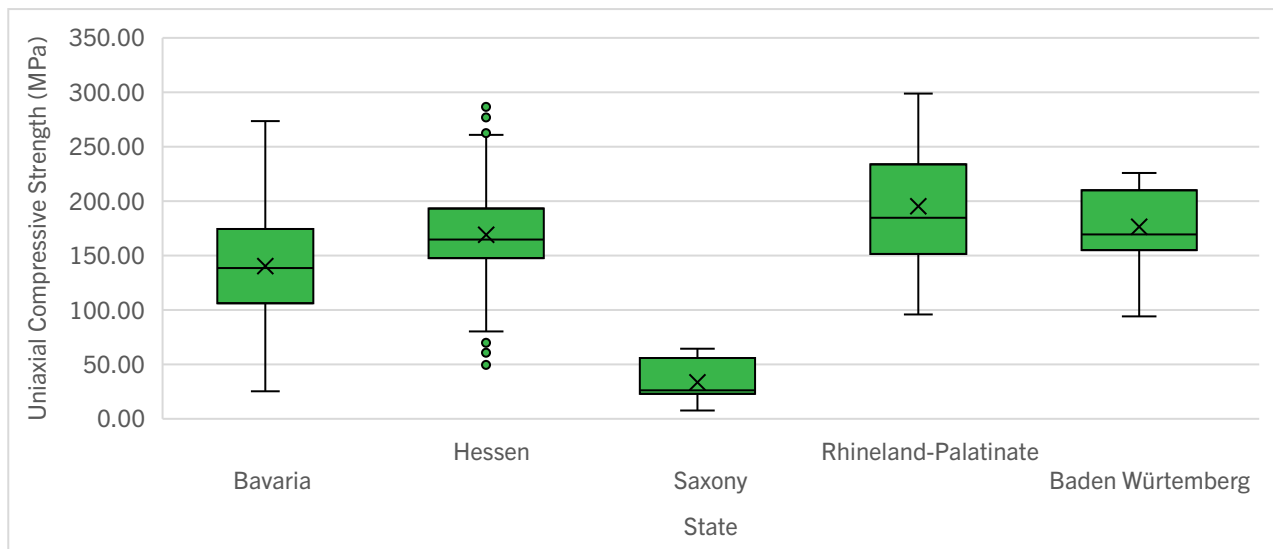


Figure 6: Box-and-whisker plot showing the distribution of UCS data across the German states containing the seven crystalline rock sub-areas.

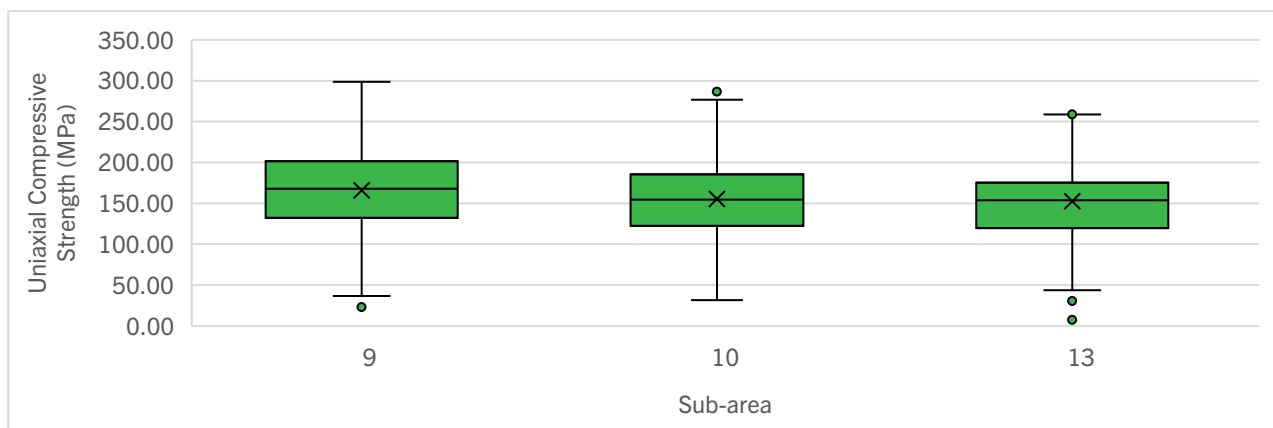


Figure 7: Box-and-whisker plot showing the distribution of UCS data across the three crystalline rock sub-areas which contain UCS data measurements.

Analysis of UCS data against spatial factors, including German states (Figure 6) and the individual crystalline rock sub-areas (Figure 7) does not reveal any clear trends; of the German states, only Saxony is significantly different with a mean UCS value less than 50 MPa while the other four states have mean UCS values within 50 MPa of each other in a range between 150-200 MPa. However, only three data points were available for the state of Saxony, while all other states had significantly more. Therefore, these low values are unlikely to be representative.

Analysis of the UCS data across the various sub-areas does not show any clear outliers or trends. The mean UCS values lie within a range between 150-200 MPa with the upper and lower quartiles being equally clustered. A key observation here is the lack of data for four of the seven crystalline rock sub-areas. This highlights the lack of geomechanical data for these rocks within Germany. This was a risk noted at the outset of the project and is being confirmed here. Nevertheless, when combined with the other datasets including the Young's modulus and stress magnitude data informative trends may be observed.

5.1.2 Young's Modulus (E)

Young's modulus, also known as the modulus of elasticity, measures a material's ability to withstand changes in length when subjected to tension or compression. In geomechanics, Young's modulus is essential for developing the geomechanical earth model. It helps characterize the stiffness of rock formations and provides critical input for fracture mapping and hydraulic stimulation designs. Young's modulus relates the longitudinal stress (applied force per unit area) to the proportional deformation (strain) along an axis, which essentially quantifies how stiff or flexible a material (i.e. rock type) is under load. A material with a high Young's modulus will be stiffer and will only change shape slightly under load, while a material with a lower Young's modulus will change its shape considerably under load.

The collated geomechanical database compiled by Amentum contains 394 values of Young's modulus across 33 unique localities. These include both static and dynamic measurements of Young's modulus; static values of Young's modulus are recorded by measuring the changes in shape of a rock sample when a known force is applied, while the dynamic values are estimated using the ultrasonic velocities of soundwaves through a rock sample. Of the 394 values of Young's modulus, 170 are static measurements while 224 are dynamic measurements.

Plotting the range of Young's modulus values against rock type provides some insight; gabbros and quartz-gabbros are noted as the stiffest rock types with the highest mean Young's modulus value of circa 90000 and 75000 MPa respectively, while meta-dolerites are the most elastic with a mean Young's modulus value of circa 35000 MPa. This lower value for meta-dolerites may be due to the low-grade metamorphism experienced by these rocks introducing some foliation which might change how the rock behaves, although gneisses, another foliated but higher-grade metamorphic rock type, has a higher mean Young's modulus value.

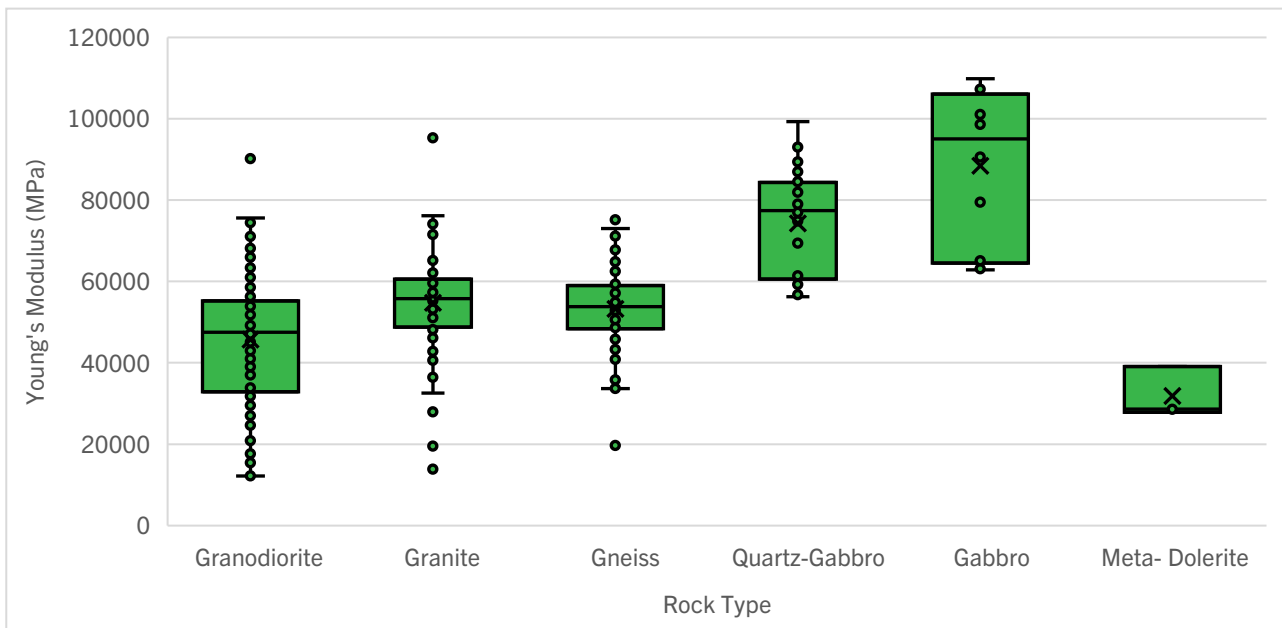


Figure 8: Box-and-whisker plot showing the distribution of Young's modulus values across the various igneous and metamorphic rock types.

When analysing both the UCS and Young's modulus data in isolation, no clear exclusionary trends are apparent. However, these two datasets will be combined using geomechanical relationships in Task 3 to apply the properties of these various crystalline rock types to attempt to predict deformation.

A key feature of the collated database is a lack of geomechanical data for four of the seven sub-areas, indicating that they cannot be characterised geomechanically with currently available data. Nevertheless, relationships between UCS and Young's modulus values will be explored in more detail in Task 3 with findings that could be extended to these sub-areas which currently lack geomechanical datasets.

5.2 Stress magnitude data

5.2.1 Stress in the subsurface

Stress in the subsurface is the complex interaction of geological, tectonic and hydraulic processes. Understanding the orientation of the stress field and the magnitude of stresses being experienced by rocks and fluids is a key consideration for any project involving engineering in the subsurface. Stress is characterised as the normals to three orthogonal planes. These are often denoted with the Greek letter sigma (σ), with the magnitudes of the three principal stresses denoted as σ_1 , σ_2 , and σ_3 , which represent the greatest, intermediate, and least principal stress respectively. In the subsurface these three principal stresses can be defined as a vertical stress (S_v) and two principal horizontal stresses, the maximum horizontal stress (S_{Hmax}) and the minimum horizontal stress (S_{Hmin}). This is called the ‘reduced stress tensor’. The main driving force for the S_v is gravity, while the motion of the Earth’s tectonic plates is the principal drive for the horizontal stresses. Other sources of stress include topographic loading caused by either large orogens (e.g. the Rockies or Himalayas) or the growth and retreat of ice sheets, alongside more local processes such as igneous intrusions and volcanic eruptions, or the movement of salt in the subsurface.

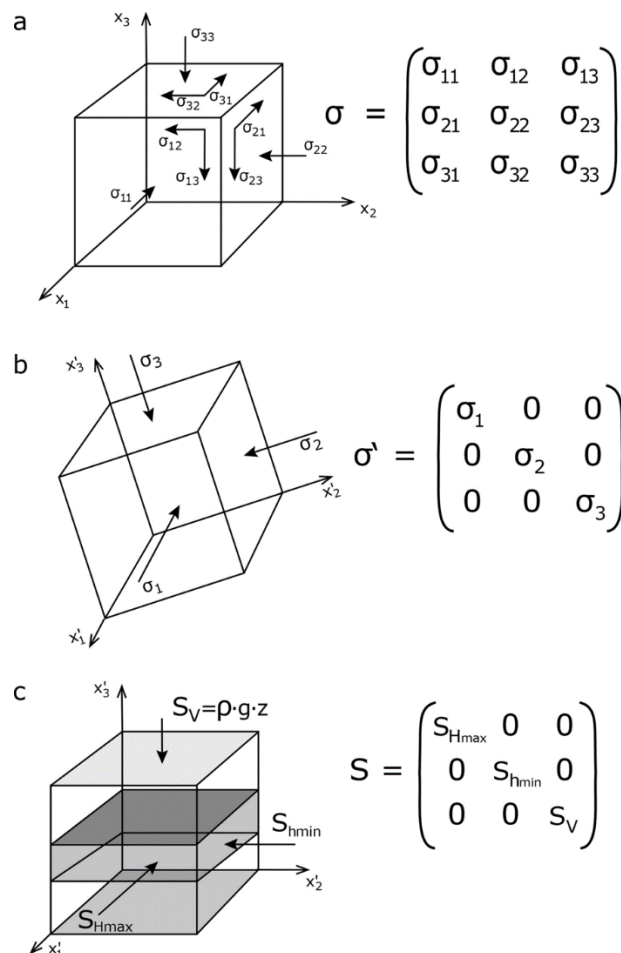


Figure 9: Explanation of the stress tensor taken from Morawietz et al. (2020). a) the nine components of the stress tensor used to describe the stress state at any point which is used to calculate the stress vector on any surface which intersects that point. b) Due to the conservation of momentum the stress tensor is symmetric, and a coordinate exists where the shear stresses along the faces are equal to zero, leaving three remaining principal stresses denoted as σ_1 , σ_2 , and σ_3 . c) If it is assumed that the vertical stress (S_v) in the Earth’s crust is a principal stress, then S_{Hmax} and S_{Hmin} should also be principal stresses. This can be fully determined with four components: the orientation of S_{Hmax} and the magnitudes of S_v , S_{Hmax} and S_{Hmin} .

Stress magnitude information is an important tool in understand the distribution of forces in the subsurface. Understanding the relationship between the vertical stress (S_v) and the maximum (S_{Hmax}) and minimum (S_{Hmin}) horizontal stresses will also reveal the principal tectonic regime active in area (i.e. extensional, compressional or strike-slip). As mentioned previously, this dataset is derived from the open-access stress magnitude database from Morawietz et al. (2020).

It is important to highlight that this stress magnitude data represents the present-day state of the forces acting upon the rock mass and does not consider the paleo stresses experienced by these rocks, including both the influences of Quaternary glaciations and older tectonic processes. Crystalline rocks, given they typically represent the oldest stratigraphic units in an area, will likely have experienced a very complicated stress history from their formation either through the intrusion of magma or regional metamorphism. Therefore, while a rock might sit in an area which at present is not experiencing notably higher stresses, they may have experienced significantly higher stresses and therefore be expected to be more heavily deformed than would be expected on the basis of stress magnitude data alone.

5.2.2 Stress magnitude relationships

Plotting vertical stress against depth for all magnitude data from Germany does not reveal many outliers, with most data lying within ± 10 MPa of a typically assumed vertical stress profile (Tingay et al., 2005). The best-fit linear trendline for this German stress magnitude data indicates a slightly higher vertical stress gradient of 24 MPa km⁻¹ compared with the typical vertical of 23 MPa km⁻¹ suggested by Tingay et al. (2005). A single major outlier is recorded from the Falkenberg Granite which is located near the KTB drilling site in Bavaria (Morawietz et al., 2020). This value is circa 35 MPa above the typical trendline, although all other values recorded from this same locality (26 values) plot on the trendline which may suggest this value is an outlier (Morawietz et al., 2020).

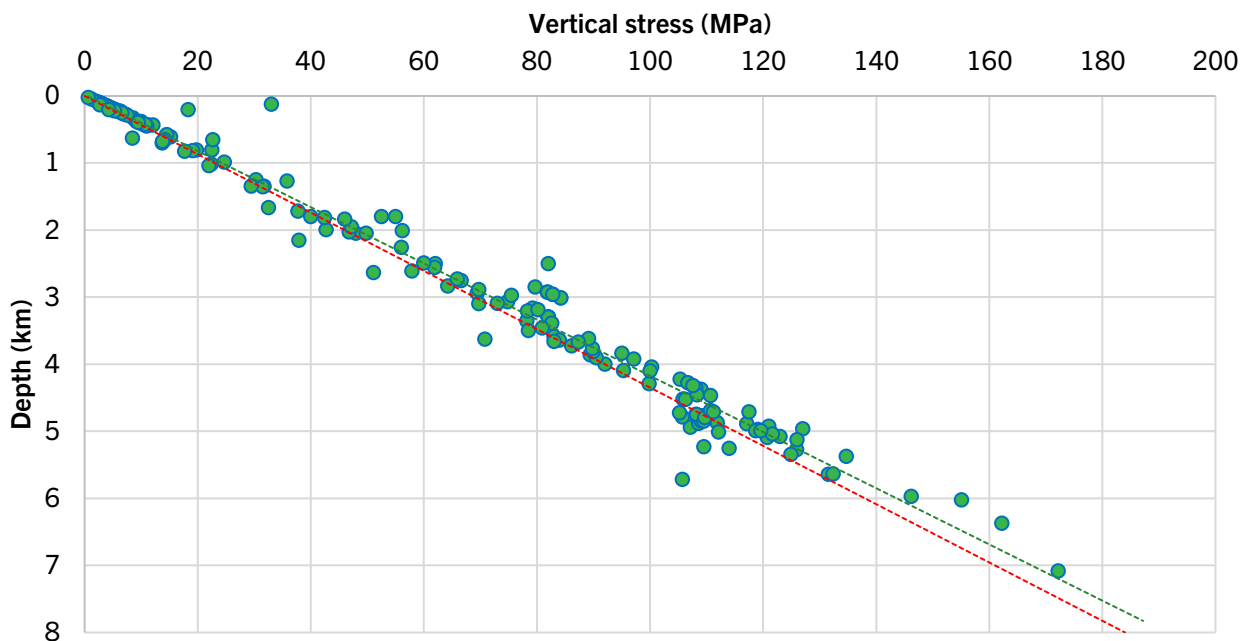


Figure 10: Vertical stress plotted against depth for values from Morawietz et al. (2020) filtered for values measurements from Germany. The predicted trendline for this data is shown as a dashed green line. A dashed red line shows the typically assumed vertical stress profile of 23 MPa km⁻¹ from Tingay et al. (2005).

With a trendline for the vertical stress gradient established for the German data a comparison can be made with the distribution of S_{Hmax} and S_{Hmin} to understand the current tectonic regime in the region. The majority of the S_{Hmax} data plots above the 24 MPa km⁻¹ vertical stress gradient derived from available S_v data in the open-access database. Only three data points plot below this vertical stress gradient trendline. One of these values comes from the Hirschentanz basalt quarry in northeastern Bavaria, while the other two values come from the Falkenberg Granite. Morawietz et al. (2020) assign the Hirschentanz measurement with a quality rank of E, which is their lowest grade on a scale from A-E, which suggests this outlier may be an unreliable data point. The majority of the Falkenberg Granite data points (21 of a total of 23 points) plot above the 24 MPa km⁻¹ vertical stress gradient which suggests the points plotting below this trendline may be unreliable. This establishes a relationship of $S_{Hmax} > S_v$.

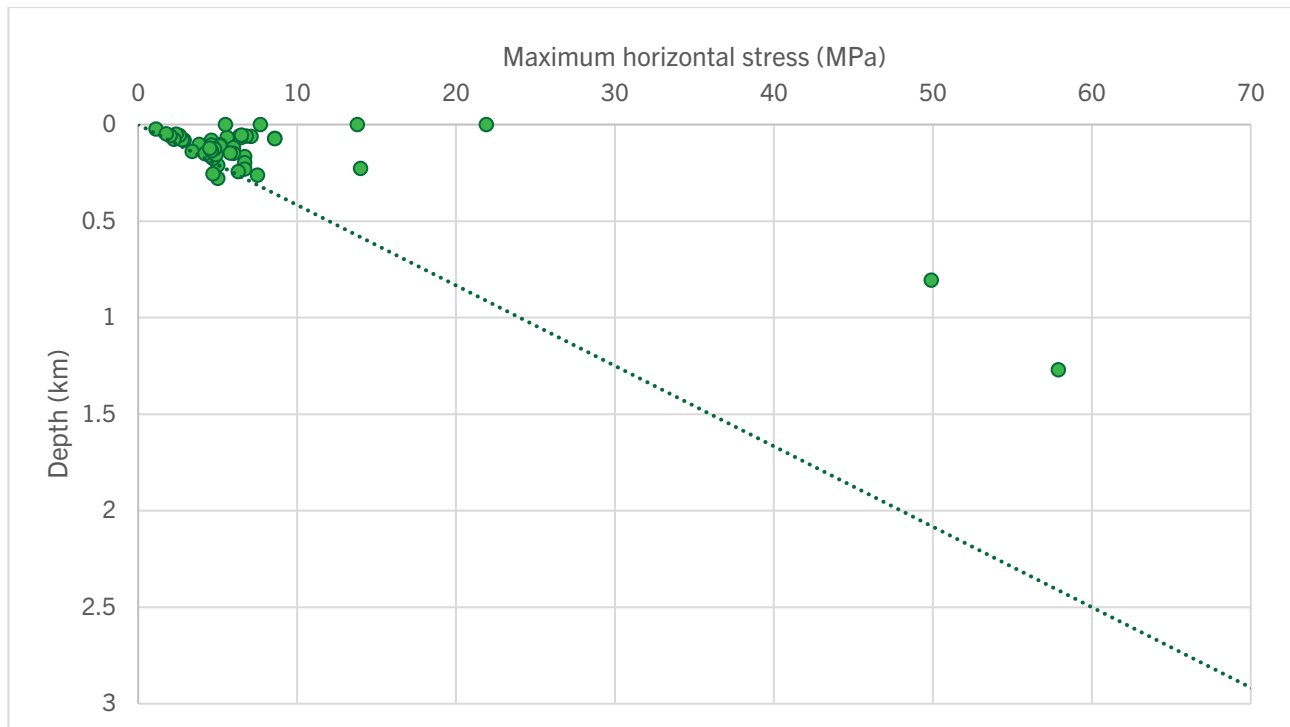


Figure 11: S_{Hmax} data plotted against depth for values from Morawietz et al. (2020) filtered for measurements taken in crystalline rock samples from Germany. The vertical stress gradient of 24 MPa km^{-1} is shown as a dashed green line.

Plotting S_{Hmin} data against depth provides a more varied relationship with the S_v trendline. 19 of the 45 S_{Hmin} data points taken from crystalline rocks within Germany plot below the 24 MPa km^{-1} vertical stress gradient, while the remainder plot above this trendline. The majority of these values which plot below the vertical stress gradient trendline come from Bavaria, including the KTB borehole and the Falkenberg Granite data (Morawietz et al., 2020).

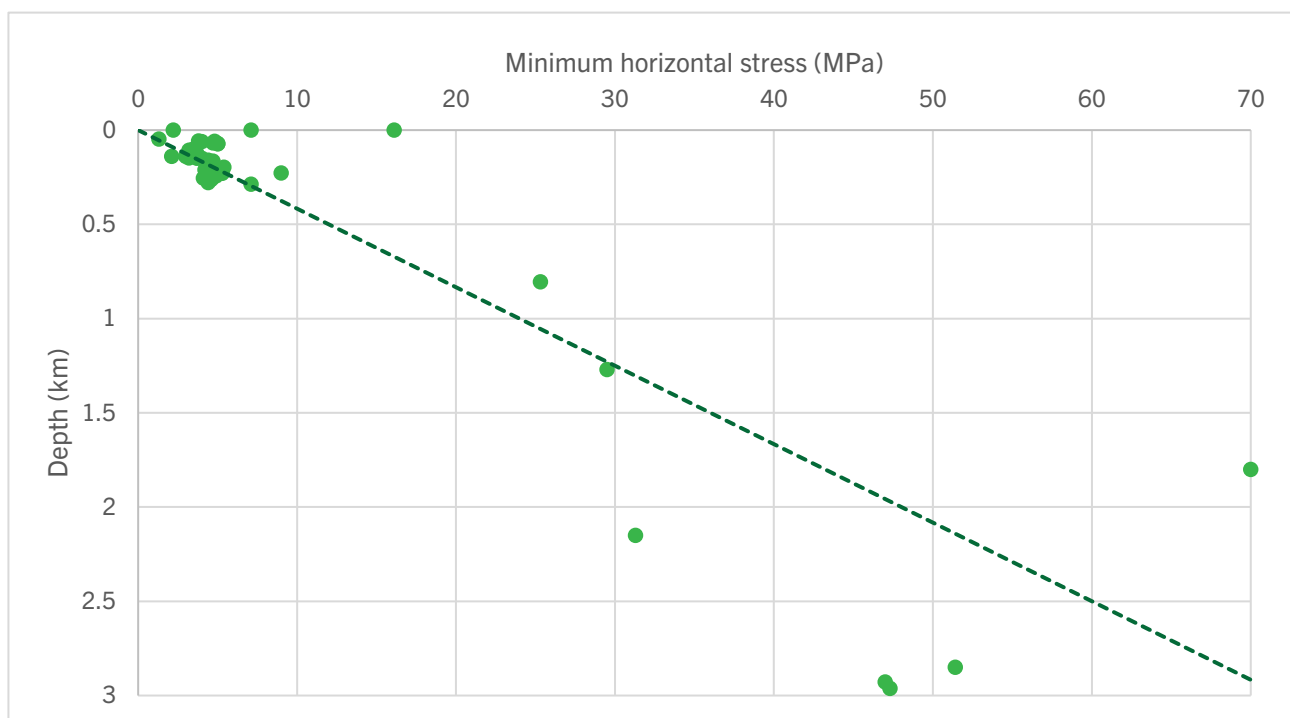


Figure 12: S_{Hmin} data plotted against depth for values from Morawietz et al. (2020) filtered for measurements taken in crystalline rock samples from Germany. The vertical stress gradient of 24 MPa km^{-1} is shown as a dashed green line

The variation in the relationship between the S_{hmin} and S_v values suggests the local tectonic stress regime varies across Germany. When combined with the S_{Hmax} data, this can indicate which tectonic regime prevails. A relationship where $S_{Hmax} > S_{hmin} > S_v$ would indicate that a compressional tectonic regime is prevailing (**Error! Reference source not found.**). This would be expected given Germany's present-day location in Central Europe, where the northwards motion of the African plate colliding with the European plate has resulted in compressional tectonics and mountain-building events. However, with some localities showing a relationship where $S_{Hmax} > S_v > S_{hmin}$, this suggests that there are areas where a strike-slip tectonic regime is prevailing (**Error! Reference source not found.**). The spread of this data suggests this is mostly located in eastern Bavaria (Morawietz et al., 2020).

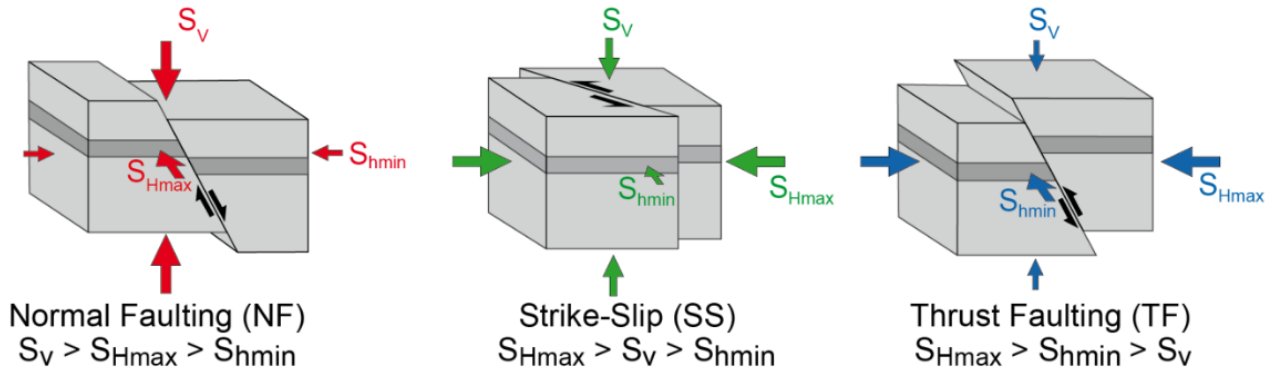


Figure 13: The relationship between the orientation of the three principal stresses axes and the prevailing tectonic regime. Taken from the World Stress Map (Heinbach et al., 2016).

This local variation is an important observation that should be considered in the siting process for the ultimate location of the German GDF. This is particularly prevalent when considering the orientation of the stress-regime relative to foliation in metamorphic rocks such as the gneisses mentioned above.

6 Task 2: Influence of Glacial processes

6.1 Overview of Quaternary glaciations in Germany

The last 2.6 Ma years, termed the Quaternary geological period, is defined by the expansion and contraction of continental scale ice-sheets. Germany, along with much of northern Europe was impacted by this ice-age cyclicality with glaciers expanding southwards from Fennoscandia and northwards from the mountainous Alpine region (Ehlers and Gibbard 2004; Ehlers et al. 2011; Fiebig et al. 2011). Terrestrial evidence for these ice-advance events is derived from litho- and bio-stratigraphic deposits laid down by the glaciers, but also from deposits left remnant in landscapes formed during ice retreat (Lowe and Walker 2014). Across Germany, such evidence exists for at least three major phases of ice advance, the Elsterian, Saalian and Weichselian glaciations. These are commonly referred to by their corresponding Marine Isotope Stage numbers (MIS) i.e., 12, 8-6, 4d-2 (Figure 14) respectively. Whilst terrestrial evidence can provide physical limits to the dimensions of ice-sheets, such evidence can be fragmentary due to erosion and overprinting of successive glacial episodes. It is probable that during glacial phases, multiple advance, retreat, and re-advance phases took place, but deciphering such complexity may be only possible with the most recent of events. Recourse to ‘far-field’ marine or ice-core oxygen-isotope records such as those recorded in Figure 14 is therefore particularly valuable, as such examples can help to illustrate the complexity of Quaternary climatic changes, and by association, the growth and decay of large-scale ice-sheets.

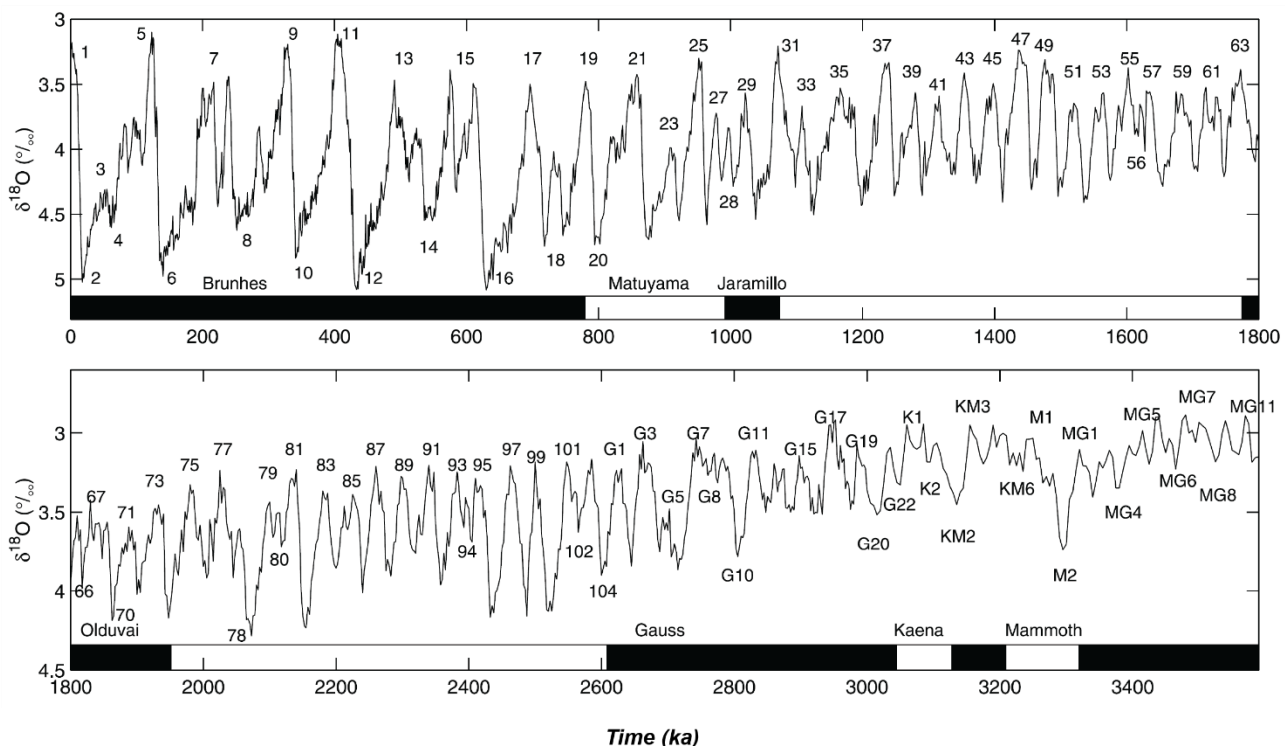


Figure 14: Stacked $\delta^{18}\text{O}$ marine core record illustrating the cyclicity of late Pliocene and Pleistocene climate change. Numbers correspond to Marine Isotope Stages (MIS) with even numbers signifying cold glacial phases and odd numbers relating to temperate interglacial phases. Note the boundary from the Pliocene to the Pleistocene (Quaternary) occurs at 2600 ka at which point the magnitude of glacial-interglacial cycles gradually increases (From Lisiecki and Raymo 2005).

6.2 Glacial extents in northern and southern Germany

Ice-sheet extent across Germany can be considered on two broad fronts, central and northern regions from the influence of glaciers originating in Fennoscandia, and a southerly front with ice emanating from the Alps. The first unequivocal evidence for glaciation in northern Germany is the Elsterian (MIS 12) (Table 3), and like elsewhere in northern Europe, the extent of ice was likely the greatest seen during the Quaternary (Ehlers and Gibbard 2004; Figure 15). Owing to this unsurpassed extent, the demarcation of a relatively well-defined ice-margin is possible, and one that is distinctly represented by the colloquially termed ‘flint-line’ of Fennoscandian erratics. This deposit, which reaches several hundred of meters above sea-level across northern and central Germany, provides both a lateral, and in some instances, vertical limit to ice extent during this period (Ehlers et al. 2011).

Approx timescale ka BP (onset of phase)	Marine oxygen isotope stage (MIS)	Northern Germany		Northern Alps	British Isles	Cold/ Temperate
11	1	Holocene				T
80	4d-2	Weichselian	Würm	Devensian		C
130	5e	Eemian	Riss-Würm	Ipswichian		T
190	6	Saalian	Warthe	Late Riss/ Penultimate glacial	Wolstonian	C
250	7		-	-		T
300	8		Drenthe	Antepenultimate glacial/ Early Riss/ Mindel		C
337	9		-	-		T
374	10		-	-		C
430	11		Holstonian	Pre-Riss	Hoxnian	T
480	12		Elsterian	Early-Late Mindel/ Donau	Anglian	C

Table 3: Quaternary stratigraphic terms for the study region and approximate correlation to terms applied in the British Isles.

The Saalian or ‘Saalian complex’ corresponds to MIS 10-6 (Table 3) and is characterised by at least two if not three glacial events of lesser magnitude and extent when compared with the previous Elsterian (Figure 15). The older sub-stages are thought to have produced glaciers of greater extent than the younger, and there seems to be a general trend to smaller and shorter-lived ice re-advances leading to the onset of the Eemian Interglacial (MIS 5).

The warm stage of the Eemian was succeeded by the most recent major glaciation – the Weichselian (MIS 4d-2). Across northern Europe and the British Isles, the cold phase was typified by multiple re-advances and retreats, however, the ice-sheets reached their maximum toward the very end of the phase, known as the Last Glacial Maximum (LGM). In northern Germany, the Weichselian ice limits were the least extensive of the late Pleistocene glaciations (Figure 15). Reasons for such limited expansion are unclear, but likely relate to internal and external climatic forcing factors as well as an element of climate preconditioning resultant from the distinctly warm Eemian interglacial (Lowe and Walker 2014). Weichselian limits across Germany are relatively well defined with a recent compilation available from Hughes et al., (2016) clearly illustrating limited expansion of the Fennoscandinavian ice-sheet no further south than the Elbe river and predominantly confined c. 200km inland to the north and east (Ehlers et al. 2011).

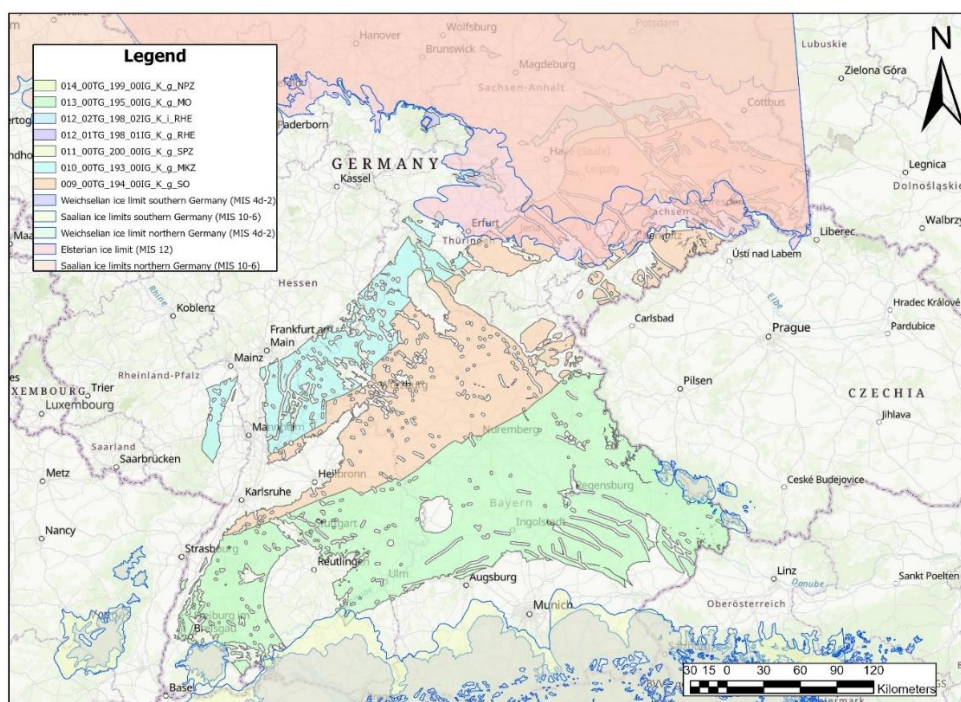


Figure 15: Extent of major glaciations across Germany during the Quaternary and interaction with the crystalline rock sub-areas. Data from Ehlers et al. (2011); Fiebig et al. (2011).

In southern Germany, the style of glaciation was markedly different to that of the north due to the mountainous Alps and the ice-cap and valley glaciers which typify such terrain. The Alpine foreland exhibits a long-established and complicated chrono-stratigraphic nomenclature (see Fiebig et al. 2011), but broad comparisons can be made to the terms discussed above (Table 3). The 'Mindel' phase equates to the Elsterian, the 'Riss' can be seen as an equivalent of the Saalian and the 'Würm' that of the Weichselian. These three cold periods, in many instances, can be further sub-divided into early and late stages, a trend which is particularly typified by the Riss which exhibits Pre-, Early- and Late-Riss substages. It is from this 'Early-Riss' stage also referred to as the 'third from last glaciation' and 'antepenultimate glaciation' that the outermost terminal moraine zone in the southern German Alpine foreland is interpreted (Fiebig et al. 2011). This would place the moraine complex as an equivalent of the northern German Drenthe (MIS 8) and mean that the Alpine glaciers reached their maximum extent, not during MIS 12 as was the case in the rest of northern Europe (e.g., Ehlers and Gibbard 2004). However, recent work elsewhere in the Alps have questioned this understanding and have instead suggested that it is more likely the most extensive Alpine glaciation does indeed date to MIS 12 (Dieleman et al. 2022). To add further complexity, within the most extensive glacial limits are younger features, which are understood to relate to the period of most recent major glaciation i.e., the LGM of the Weichselian. It is important to note, however, that the outermost series of moraines which date to the LGM may not represent the maximum extent of ice during this phase, thus it is unclear precisely how extensive this most recent glaciation was in the German Alpine lowland (Fiebig et al. 2011). Clearly more research is required to decipher the chronostratigraphic complexity in the Alpine region (Dehnert et al. 2010).

6.3 Glacioisostasy

The loading and unloading of the crust by the growth and decay of ice-sheets has had, and continues to have, a considerable impact on isostasy and seismicity in post-glaciated terrains. The basic principle of isostasy is that the lithosphere and asthenosphere are effectively 'floating' on the underlying mantle as a result of their lesser mean density compared with that of the mantle. Loading of the crust, therefore, will cause a localised depression in the lithosphere as the mass sinks down into the mantle. The amount of depression that occurs as a result of this process is determined primarily by local densities of the lithosphere/asthenosphere/ mantle, as well as the thickness of ice and distance from the thickest part – typically the centre of an ice-sheet (Benn and Evans, 1998). However, due to the inherent rigidity of the lithosphere, which can vary based on primary rock composition, geomechanical properties/competence of the various rock types, the presence and reactivation of major zones of deformation like faults and shear zones, and variation in crustal thickness, the influence of a loading ice-mass can reach well beyond the margins of an ice-sheet in an area termed 'peripheral depression'.

In addition to the negative vertical displacements as a result of glaciation, there are a degree of positive displacements. This is caused by lateral movements within the depressed mantle which is forced away from the ice-loading depocenter. This lateral displacement pushes up the overlying lithosphere and asthenosphere causing what is known as a 'glacial forebulge'. This manifests beyond the ice limits and area of peripheral depression. Distances between ice limits and the associated forebulge vary, but primarily depends on the 'flexural parameter' of the crust; a factor governed by lithospheric density, elasticity, and thickness amongst other controls (Benn and Evans, 1998). Typically, the associated uplift is approximately one hundredth of ice-sheet thickness, and as such, for the largest of the Quaternary ice-sheets, the forebulge equates to 10's m of displacement at most.

Lithospheric response to ice loading is relatively rapid, adjusting within a few thousand years. However, isostatic recovery following unloading takes considerably longer and may take in excess of ten thousand years before a new equilibrium is established (Benn and Evans, 1998). As a result of this residual uplift, many areas across the globe, including northern Europe, are still undergoing isostatic adjustment from the most recent glaciation (Figure 16), thus these crustal movements must be considered for their seismic potential, the stress field imposed on the rock and the role this may have on enhancing fracture development.

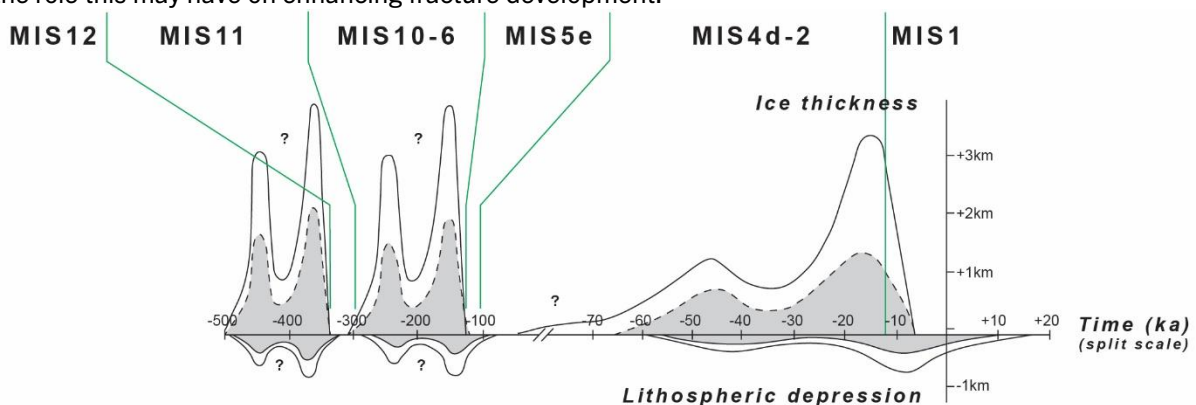


Figure 16: Conceptual model illustrating the relationship of lithospheric depression and ice loading. Note the delay in lithospheric recovery following glaciation and the projection of such into the future. Modified from Stewart et al. 2000 and Reicherter et al. 2005.

6.4 Glacio-seismotectonics

In the absence of glaciation, crustal deformation is principally controlled by tectonic plate movements. However, in regions subjected to large-scale glaciations, this prevailing tectonic stress regime is overprinted by stress derived from glacial growth and decay (Stewart et al. 2000; Figure 17). The term 'glacio-seismotectonics' refers to the seismic processes' resultant from glacio-isostatic adjustments. Beneath the centre of an ice-sheet, as well as at its margins, the crust undergoes a contraction or shortening as underlying mantle material is squeezed outward away from the area of loading. In the forebulge area, resultant from positive mantle flow, the lithospheric stress regime is opposite, manifesting as uplift and radial extension (Figure 17). Stress caused by an ice sheet a few km's thick, may equal or exceed that derived from regional tectonic processes (Figure 17), with the net stress of these opposing processes either serving to counteract one another, or work in conjunction to develop stresses of considerably greater magnitude (Figure 17).

During deglaciation, the removal of ice leads to a relatively rapid elastic rebounding of the lithosphere which is characterised by uplift, faulting and seismicity (Stewart et al. 2000). However, movement of mantle material is slower, leading to a prolonged 'recovery' period. The overall effect is a rising 'dome' characterised by radial fracturing within the former ice-sheet depocenter, and a forebulge zone that undergoes collapse via crustal contraction. The extensional stresses in the formally glaciated margins should in theory lead to normal faulting whereas in the forebulge zone tectonic stresses are expected to be compressive leading to reverse or thrust faulting. The caveat to this is that such stresses seldom operate in isolation and the influence of the enduring tectonic regime will likely be a factor in determining the dominant processes. In Germany the major controls on the stress field are the NW-SE force derived from North Atlantic ridge push and the N-S forced caused by the Alpine collision (Müller et al. 2022).

As stated in Section 5.2.1, the present-day stress field does not reflect the paleo-stresses that were acting on the rocks in the subsurface during these glaciations. The change in the vertical stress gradient (S_v) can be broadly estimated from first principles using characteristics of the ice sheets like thickness and density. It is more difficult to measure the changes in the orientation and magnitude of the horizontal stresses during these times. The SpannEnD project is actively investigating the present-day stress field across Germany using numerical modelling techniques (e.g. Ahlers et al., 2021). The results of their modelling are being across several areas, including measuring the slip-tendency (the ratio of shear to normal stresses acting on a surface, which can be used to assess the likelihood of slip on a fault surface) on faults throughout Germany. There may be potential to build on the results presented here and their on-going modelling work by numerically modelling the recent glaciations presented here to calculate changes in slip-tendency on the mapped faults across Germany. This additional work has been previously presented to the BGE and could be explored further (Jacobs, 2024).

6.5 Glacially induced faulting / fault re-activation

The release of crustal stresses as a result of ice-sheet retreat and decay can lead to the reactivation of faults across post-glacial terrains, including those areas beyond ice-margin limits. In northern Germany studies have suggested that fault reactivation can be attributed to stress-field changes associated with the demise of the Weichselian (MIS 2) ice-sheet (Brandes et al., 2012; 2015). The expansion of the Fennoscandian ice-sheet into northern Germany during the Quaternary seemingly induced a NNE-SSW stress-field. This was orientated with existing seismic structures and led to the reactivation of pre-existing Mesozoic faults (Müller et al. 2022). However, the area susceptible to such fault reactivations is not entirely clear, studies have suggested regions up to 230km south of the Weichselian (MIS 2) ice-limits may be susceptible, albeit in limited capacity (Brandes et al. 2015). It is thus reasonable to assume similar distances may be applicable to the older Quaternary ice-limits or similar events in future.

Several numerical modelling studies on fault reactivation have investigated a variety of geological factors which can influence the tendency of faults to reactivate and slip during stress changes induced by ice-sheet advance and retreat. These include the background stress state prior to ice-sheet loading, the dip of the fault, and the orientation (i.e. strike) of the fault relative to the orientation of the ice-sheet margin (e.g. Steffen et al., 2014; Steffen and Steffen, 2021)

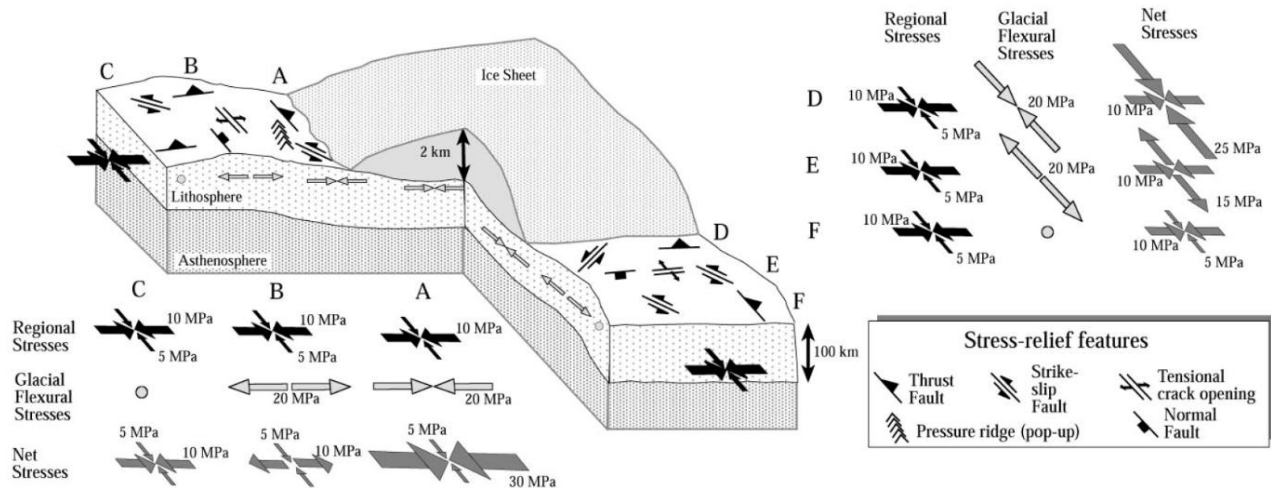


Figure 17: Conceptual model illustrating the relationship of ice loading and near surface stress. Changing glacial stresses (light grey arrows) are superimposed on a uniform regional tectonic stress field (black arrows) results in contrasting resultant stress states (dark grey) and different styles and orientations of stress-relief phenomena at the ice margin (A and D), the forebulge (B and E) and the undeformed foreland (C and F). From Stewart et al. 2000.

Directly dated evidence of fault reactivation is limited, but evidence gathered from the vicinity of the Harz Boundary Fault in northern Germany has shown neotectonic activity along the Cretaceous fault dating to younger than 15 ka (Müller et al. 2020). Similarly, along the Osning Thrust, a complex of folds and faults have been described within late Pleistocene deposits (c. <.30 ka). With the origin of such, attributed to the extension and later contraction of a glacial forebulge associated with the MIS 2 ice-sheet (Brandes et al. 2012). Thus, these and similar studies support the idea that changes to the regional stress field by the advance and then withdrawal of ice are likely responsible. Certainly, a number of palaeoseismological studies across Germany have also attributed neotectonic movements, earthquakes, surface rupturing, soft sediment deformation and displaced Quaternary sediments to glacially induced isostatic adjustments, or at the very least, acknowledged their likely contribution as a component in broader regional seismic instability (e.g., Brandes and Winsemann 2013; Brandes et al. 2015; Müller et al. 2022 and references therein).

Concerning the Alpine region, disentangling the influence of glacial processes from seismicity associated with ongoing orogenic processes is more difficult than elsewhere in Germany. Given the size and extent of the ice-sheet that covered the Alps, it is unlikely the influence of this ice mass would have the same ‘reach’ as that of the much larger Fennoscandian ice-sheets that impacted the north of Germany (Müller et al. 2022). Thus, whilst the retreat of ice from the southern German lowland likely resulted in some glacial isostatic adjustment and the potential of fault reactivation, at present it is difficult to confidently say to what extent.

The reactivation and continued slip on pre-existing faults will inevitably result in further deformation to the rock mass immediately surrounding these structures. However, earthquake modelling undertaken for both the Forsmark (Sweden) and Onkalo (Finland) sites indicates that modification of fracture networks away from large faults undergo only modest modification with slip values in the range of millimetres when subjected to large (magnitude 5-7) earthquakes (Hökmarm et al., 2019 and references therein). Slip on faults due to glacially-induced stress changes has been recorded and inferred at a range of depths. Most authors suggest these events occur in the upper 20-30 kilometres of the Earth’s crust (e.g. Steffen et al., 2016; Sandersen et al., 2021) although they note that no clear relationship can be established between the depth of fault reactivation and factors such as slip magnitude, fault orientation or timing.

6.6 Summary

Germany was repeatedly impacted by large-scale glaciation during the Quaternary. The extent of such was largely confined to northern-central regions, the Alpine lowland, and a few isolated and largely insignificant mountain glacier ice fields. The isostatic loading and unloading of the ice-sheets has and will continue to influence regional stress-fields along with the push of the Mid-Atlantic Ridge and ongoing Alpine Orogeny. Several studies have shown that stress-field changes resultant from glacial isostatic adjustment have led to a number of fault reactivations. The faults most susceptible to reactivation are those which align with former ice-margins. In the north of Germany these lie WNW-ESE, in the southern Alpine lowland this would be W-E, although the increased significance of the Alpine Orogeny may mean this relationship is less predictable. Whilst the strongest evidence exists for reactivation following the most recent (MIS2) glaciation, there is no reason why faults were not reactivated by older glaciations and why faults could not still be reactivated as isostatic adjustments continue across Germany and northern Europe.

Several studies conducted in Germany have attributed neotectonic activity, including earthquakes, surface rupturing, and soft sediment deformation/ displacement, to glacially induced isostatic adjustments. Such phenomena are seemingly not confined to areas that were glaciated but are also apparent beyond the mapped ice-limits, up to a distance of at least several hundred kilometres. As a result, large swaths of Germany are potentially impacted by glacio-isostatic adjustments and the glacio-seismotectonic and glacially induced faulting processes which accompany the crustal recovery. In citing a GDF facility it is therefore recommended to consider whether an area is subjected to isostatic movements as a result of deglaciation, whether fault reactivation in the vicinity has been noted and if not, whether such faults could be reactivated as a result of ongoing and future isostatic adjustments.

7 Task 3: Synthesis of results and developing geological siting criteria

The geomechanical data compiled in Task 1 was combined with the mapped extents and likely influences of Quaternary glaciations from Task 2 to understand the implications of these results for the seven crystalline rock sub-areas and to determine any broad trends that could be used to inform the BGE’s site selection process. To achieve this, a common risk segment (CRS) mapping exercise was used to combine the results of these two Tasks. While the method employed uses the phrase ‘risk’ in its title, our study does not seek to apply a risk matrix to the crystalline rock sub-areas but instead applies the results of Tasks 1 and 2 to produce a predictive map of deformation from known strength and stress magnitude data points combined with geomechanical principles. CRS mapping is a technique commonly used in the oil and gas industry to evaluate the prospectivity of a sedimentary basin and identify areas which may contain hydrocarbon accumulations (e.g. Fraser et al., 2010). It is also being deployed in other subsurface industries including the search for long-term disposal sites for carbon dioxide (Bump et al., 2021; Figure 18). Crucially, the CRS mapping methodology aligns with the International Atomic Energy Agency (IAEA)’s guidelines on the site selectin process for the disposal of radioactive waste.

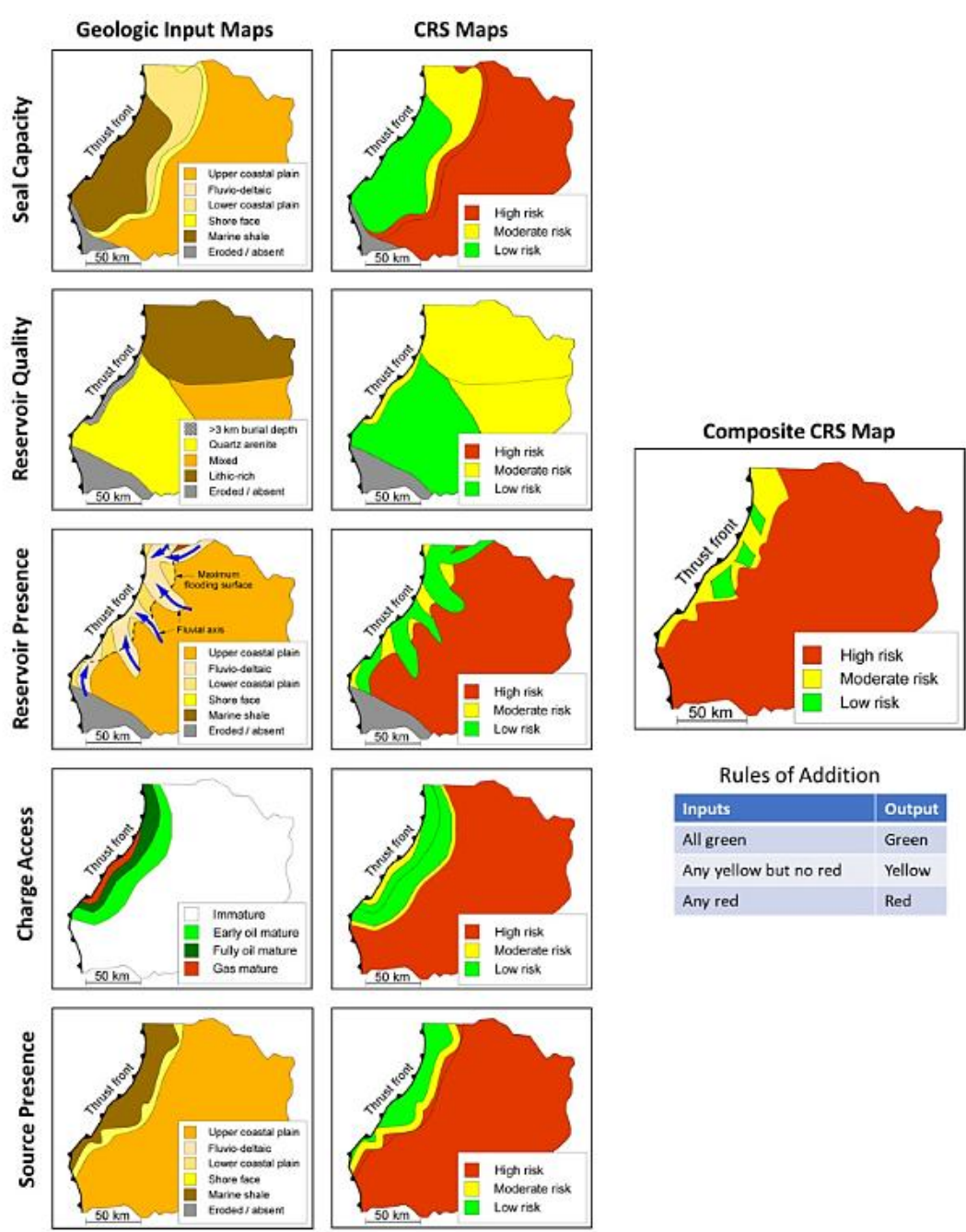


Figure 18: Example of CRS mapping taken from Bump et al., 2021.

CRS mapping involves the creation of multiple maps detailing different geological characteristics which have been converted to a ‘traffic-light’ system of desired geological outcomes (Fraser et al., 2010). In hydrocarbon and carbon dioxide disposal site exploration this includes the presence and quality of high-quality reservoir and seal rocks alongside other geological factors. Unlike the search for hydrocarbons or CO₂ storage sites, this study does not include a risk analysis which includes exclusionary criteria but rather can be used as a predictive tool to inform the BGE’s own siting criteria.

The results from Tasks 1 and 2 would be translated into three layers representing different geological factors which influence the suitability of rocks to host a GDF:

- **Rock Quality Designation (RQD):** a qualitative designation which describes how deformed a rock mass is. We have selected this as an appropriate derived parameter to represent likelihood of fracturing and of a well-developed fracture network which could have an impact on permeability and transmissivity, we describe below the methodology for deriving this value through established empirical relationships with the geomechanical parameters collected.
- **Glacial impact:** as outlined in Task 2, the key implications of glaciations on rock masses are the vertical loading caused by the thick ice-sheets on the rocks they overlie, which can reactivate pre-existing faults, and the far-field isostatic readjustment of the lithosphere beyond the ice-sheet extents which can also reactivate pre-existing faults and the fractures associated with these structures.
- **Stress magnitude:** areas of higher stress magnitude are more likely to be deformed as local stresses may overcome the strength of the rocks. While this does not account for whole stress history of the rock, it may predict areas of recent deformation.

7.1 Layer 1: Rock Quality Designation (RQD)

7.1.1 Deformation/Strength Ratio versus Fracture Frequency Methodology

Rock deformation and strength is a function of the intrinsic petrographic composition and crystallinity as well as the rock mass weathering, degree of fracturing and confining stress. Stress history also plays an important role in the behaviour and structural composition. A method adopting the intrinsic properties measured on intact specimens (Unconfined Compressive Strength (UCS), Youngs modulus (E)) is proposed to predict the rock condition (i.e. degree of fracturing) that have been subject to post-formation external factors (e.g., tecto-seismic, or post glacial isostatic adjustment). Historical deformation “memory” induced by higher stress states experienced in the past compared to the present day, may be stored within the intact rock or within fractured zones. This “memory” may be in the form of microcracks associated with pre-yield deformation that may impact the strength and deformation behaviour, particularly at lower confining stresses (Griffith, 1924; McClintock & Walsh, 1962; Walsh and Brace 1966; Hoek, 1968; Scholtz, 1968, Hoek and Deiderichs, 2006). The influence of a network of microcracks due to past loading is captured in Figure 1, which demonstrates the gradual reduction in stiffness and strength as strain is accrued.

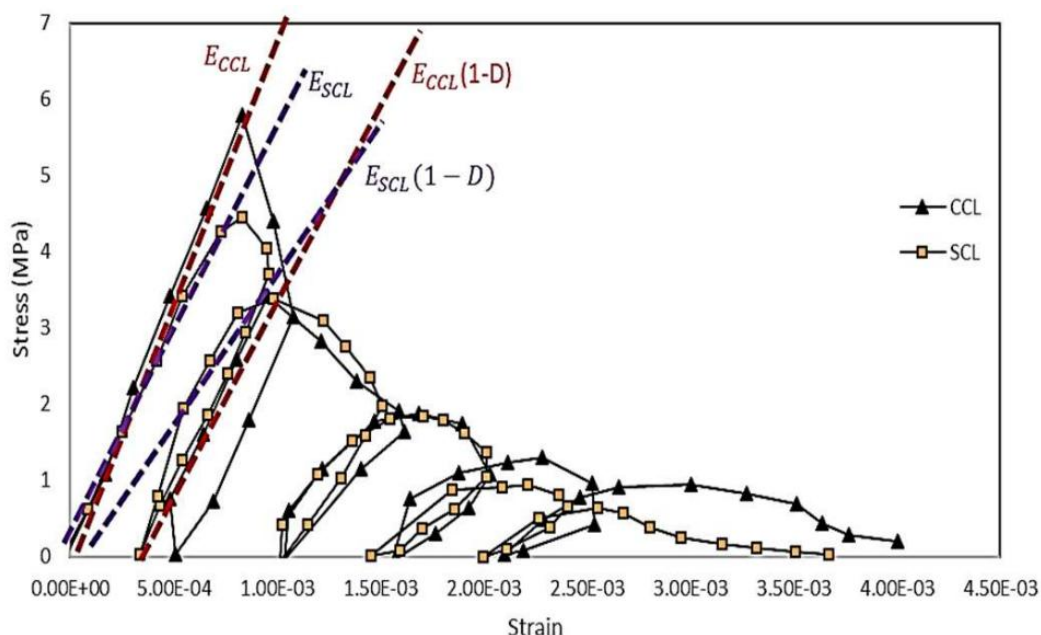


Figure 19: The effect of rock damage/ microcracking under stress cycling (After Ghamgosar, 2019; CCL- Continuous Cyclic Loading and SCL- Stepped Cyclic Loading)

Deere (1968) originally proposed the use of a modulus ratio to derive the rock mass properties for different rock types, with further modifications by Palmstrom and Singh (2001) who explored the use of relating typical modulus ratios ($MR=E/UCS$) to the measured UCS to derive the rock mass stiffness. Typical ranges for these relationships are captured through Deere-Miller plots, Figure 2. Table 1 outlines the typical values for different rock types reproduced by Hoek and Diederichs (2006). The degree of foliation and dip with respect to the direction of the major principal stress within metamorphic rocks also impact the ultimate strength, resulting in a larger range of modulus ratios compared to Volcanic, Plutonic or Hypabyssal Igneous rock types, as seen within Table 1. This has been noted in Section 5.1.1 where some of the lower UCS values recorded in the gneisses could be attributed to a combination of the orientation of paleo-stress and the planes of weakness (i.e. foliation) within these rocks. This is also discussed further in the following sections.

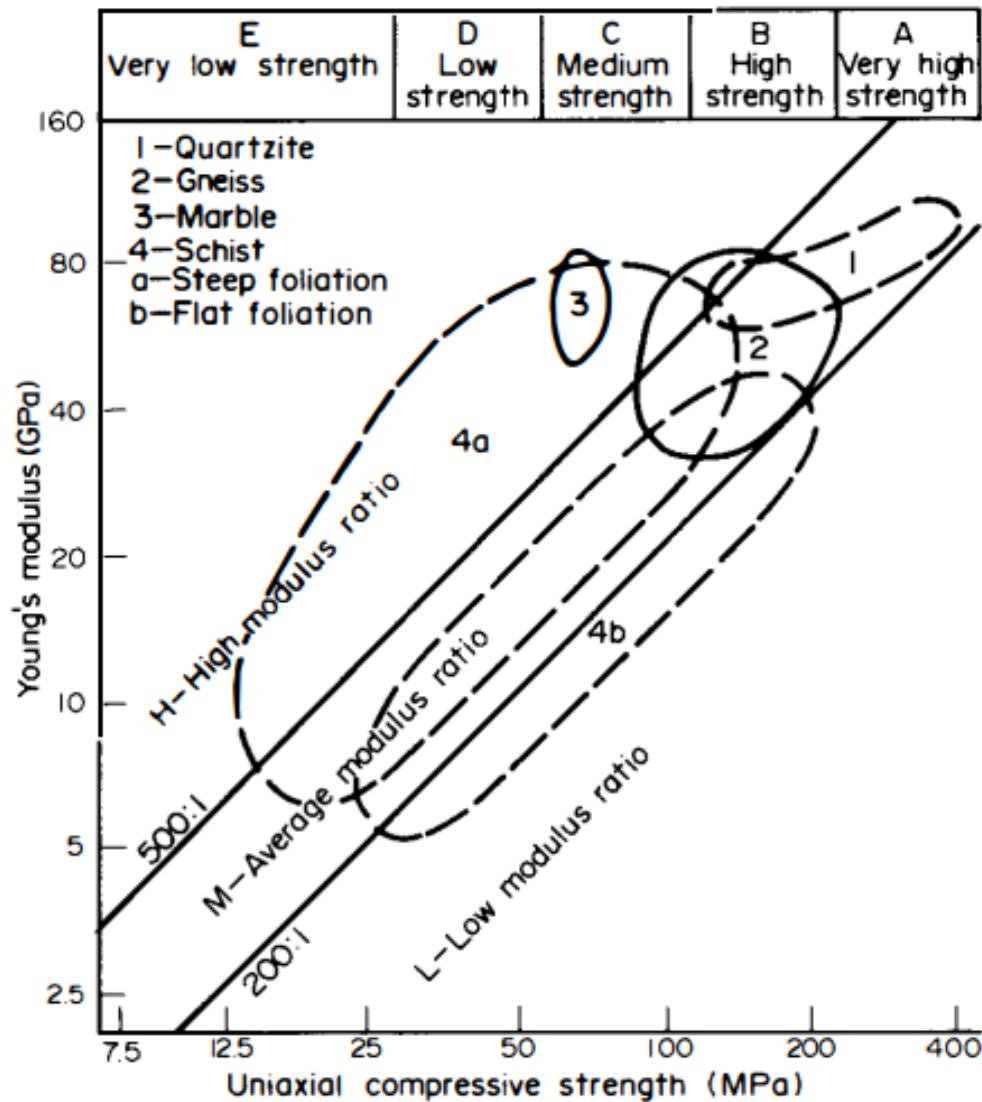


Figure 20: Deere- Miller plot (After Pells 1993)

Rock type	Class	Group	Texture			
			Coarse	Medium	Fine	Very fine
Sedimentary	Clastic		Conglomerates 300–400 Breccias 230–350	Sandstones 200–350	Siltstones 350–400 Greywackes 350	Claystones 200–300 Shales 150–250 ^a Marls 150–200
	Non-clastic	Carbonates	Crystalline limestones 400–600	Sparitic limestones 600–800	Micritic Limestones 800–1000	Dolomites 350–500
		Evaporites		Gypsum (350) ^b	Anhydrite (350) ^b	
		Organic				Chalk 1000 +
Metamorphic	Non-foliated		Marble 700–1000	Hornfels 400–700 Metasandstone 200–300	Quartzites 300–450	
	Slightly foliated		Migmatite 350–400	Amphibolites 400–500	Gneiss 300–750 ^a	
	Foliated ^a			Schists 250–1100 ^a	Phyllites/Mica Schist 300–800 ^a	Slates 400–600 ^a
Igneous	Plutonic	Light	Granite ^c 300–550 Granodiorite ^c 400–450	Diorite ^c 300–350		
		Dark	Gabbro 400–500 Norite 350–400	Dolerite 300–400		
	Hypabyssal			Porphyries (400) ^b	Diabase 300–350	Peridotite 250–300
	Volcanic	Lava		Rhyolite 300–500 Andesite 300–500	Dacite 350–450 Basalt 250–450	
		Pyroclastic	Agglomerate 400–600	Volcanic breccia (500) ^b	Tuff 200–400	

^aHighly anisotropic rocks: the value of MR will be significantly different if normal strain and/or loading occurs parallel (high MR) or perpendicular (low MR) to a weakness plane. Uniaxial test loading direction should be equivalent to field application.

^bNo data available, estimated on the basis of geological logic.

^cFelsic Granitoids: coarse grained or altered (high MR), fined grained (low MR).

Table 4: Modulus ratios for the three main rock groups (After Hoek and Diederichs, 2006).

A non-exhaustive search has been conducted into analogous data sets for HSR types that include UCS, Youngs modulus and fracture frequency. Table 2 shows the data sources used and rock types encountered (Total no. 85). The data has been compiled to establish a trend to capture the stress-deformation behaviour and likelihood of fracturing using two direct intact rock measurements, the intact UCS and Young's modulus respectively. A relationship between modulus ratio vs. fracture frequency has been developed. However, it should be noted that there is a high degree of uncertainty due to the limited data availability that captures all three parameters, it is encouraged to build upon this to establish a more rigorous method. Therefore, this is considered as a preliminary diagnostic tool to assist in determining the likelihood of fracturing for areas with no direct rock mass observations but with direct UCS and Youngs modulus measurements.

Source	Rock type	No of data points
UK NIREX investigations (1992)	Borrowdale volcanics	37
SKB Forsmark investigations (2007)	Forsmark tectonic lens, granites, and granodiorites with dykes of amphibolite and pegmatite	24
Soultz-sous-Forêts Geothermal Well (2018)	Upper Rhine Graben (URG)	9
POSIVA, POSE third niche investigations (2013)	Coarse Grained Pegmatite and Foliated Gneiss	15

Table 5: Data used to establish the preliminary relationship between intact properties and fracture frequency.

Figure 21 displays the compiled data set of the modulus ratio vs. fracture density (per metre) for the data analogue sources. An upper bound and best fit trend-line has been provided; a simple first-order approach has been established using the linear equations. These have been rearranged to back calculate an average fracture spacing (m-1) given in Equations 2 and 3 respectively. It should be noted that the Posiva data has not been included within the best fit trend data set (Equ. 3).

$$\text{Upper Bound Average fracture spacing} = \frac{MR-500}{25.282} \quad \text{Equ. 2}$$

$$\text{Best Fit Average fracture spacing} = \frac{MR-306.49}{25.282} \quad \text{Equ. 3}$$

It is recommended that the upper bound range is adopted for non-foliated to slightly foliated Metamorphic rocks with horizontal to sub-horizontal foliation dips (0°-30°). The Posiva data which encountered strongly foliated Gneiss with steep dips (≥45 degrees from the horizontal) sits within the upper range (MR=550 to 1100). It is recommended that the proposed correlation is not applied to such rock types due to significant anisotropy and inherently lower strengths due to failure along foliation planes which may result in erroneous predictions of fracture frequency.

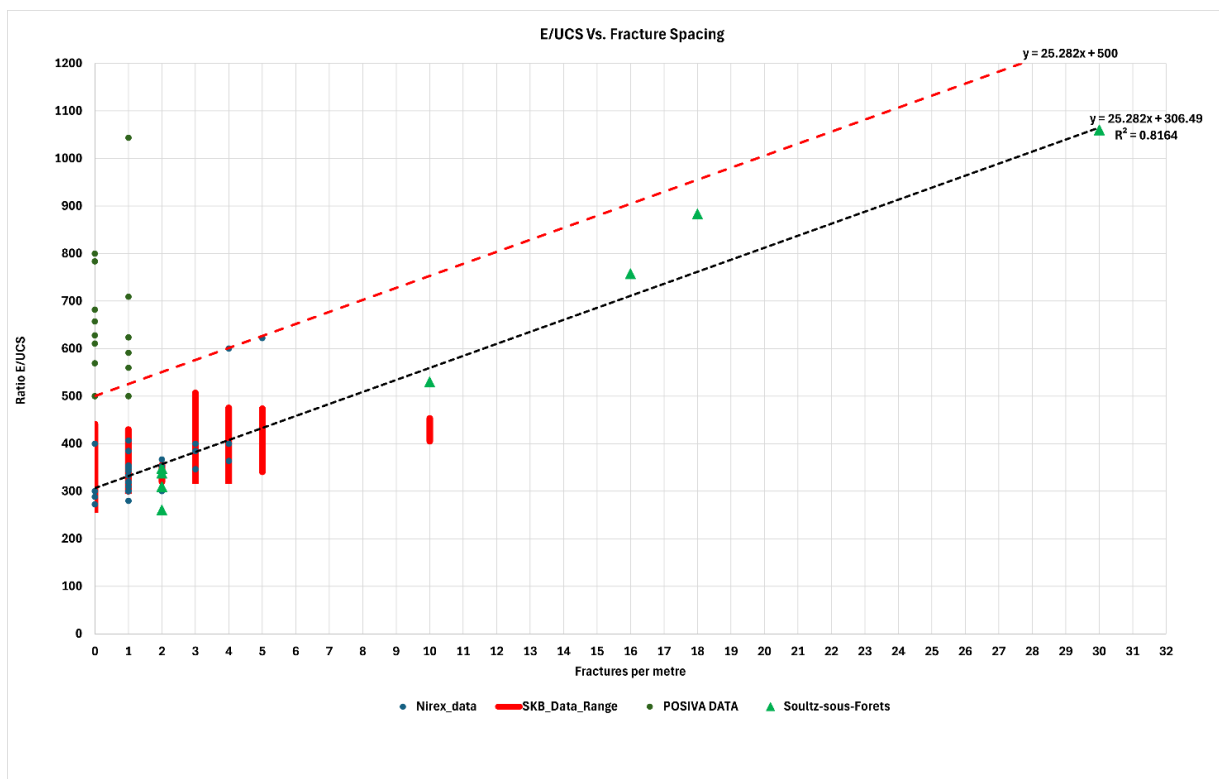


Figure 21: Modulus ratio vs. fracture spacing (per m) with upper and lower-bound limits (red and black lines).

The relationships demonstrated in Figure 21 are relevant to the seven crystalline rock sub-areas given their genetic similarity with the input data. The Soultz-sous-Forêts dataset is from crystalline rocks which are located on the French side of the Upper Rhine Graben, equivalent to sub-areas 009 and 013. The SKB dataset comes from a similar geological setting to the Variscan metamorphic terranes of Germany, and the geology of their site is composed of metamorphic rocks and granite and granodiorite intrusions. The Posovia data is suitably similar, with their GDF being located in gneisses.

7.1.2 Caveat on using the static and dynamic Young's Moduli

The available data provided by the BGE consists of static and dynamic Young's moduli. The dynamic modulus measures the intrinsic small strain modulus which is often inherently higher than the large strain static modulus. However, to capture the effects of pre-yield micro fractures and stress history, then the larger strain moduli i.e., the static Young's modulus would be more suitable (larger strains are expected to have occurred near to fracture development zones). Based on the premise that stress history/memory within the rock near to fractures comprises of a "damaged" microcrack network, then the localised area will be naturally less stiff than the intact rock mass. Meaning that the actual fracture frequency local to a pre-existing structural feature such as a fault/deformation zone will be lower due to the more ductile behaviour.

7.1.3 Method on deriving a fracture frequency and rock quality rating

Using the extrapolated fracture frequency range derived from the MR vs. fracture frequency correlation (Figure 21), a relationship was established between frequency and RQD in accordance with Bieniawski's (1989) Rock Mass Rating (RMR) methodology (Figure 4). Using the RQD ranges outlined within the table corresponding to a fracture spacing, a fracture likelihood and rock quality traffic light system was developed (Table 3) and has been applied to the local dataset examined as part of this study.

Classification parameters and their ratings (after Bieniawski, 1989)									
Parameter			Range of values						
1	Strength of intact rock	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	<1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality RQD		90%-100%	75%-90%	50%-75%	25%-50%	<25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2m	0.6-2m	200-600mm	60-200mm	<60mm		
	Rating		20	15	10	8	5		

Table 6: Excerpt from Bieniawski's (1989) RMR methodology, highlighted rows indicate the data adopted for the inferred rock quality and traffic light system

The relationship between the spacing of discontinuities (i.e. fracture density) and the RQD can then be used to provided a qualitative rank which can be applied to localities where a modulus ratio can be calculated.

Fracture frequency (m ⁻¹)	RQD range	Rank
0 to 1	90-100%	Excellent
1 to 2	75-90%	Good
2 to 4	50-75%	Fair
5+	0-50%	Poor

Table 7: Fracture risk and rock quality traffic light system.

This provides a predictive fracture frequency range that can be applied to the available data alongside a ranking of their respective RQDs which can be used to highlight areas where we could expect greater deformation and ultimately larger and more dense fractures. 22 localities have both UCS and Young's modulus data that can be used to produce a range of inferred fracture frequencies. These are outlined in the table below:

Province	Sub-area	Latitude	Longitude	Rock Type	Upper Bound Inferred Fracture Frequency	Lower Bound Inferred Fracture Frequency	Range	Grade
Hessen	10	49.795673	8.7037135	Gabbro	6	1	5	Poor
Rhineland-Palatinate	10	49.221944	8.021944	Gneiss	1	0	1	Excellent
Rhineland-Palatinate	10	49.222175	8.0222081	Gneiss	1	0	1	Excellent
Hessen	10	49.752582	8.9088806	Gneiss	1	0	1	Excellent
Baden Württemberg	13	48.586389	8.203889	Granite	1	0	1	Excellent
Baden Württemberg	13	48.637222	8.348333	Granite	1	0	1	Excellent
Bavaria	13	48.64169	13.604691	Granite	1	0	1	Excellent
Bavaria	13	48.710111	13.323656	Granite	1	0	1	Excellent
Bavaria	13	48.901374	12.910908	Granite	1	0	1	Excellent
Bavaria	13	49.001437	12.993026	Granite	1	0	1	Excellent
Bavaria	13	49.030842	12.316051	Granite	1	0	1	Excellent
Rhineland-Palatinate	10	49.160556	8.002222	Granite	2	0	2	Good
Hessen	10	49.605953	8.794533	Granite	1	0	1	Excellent
Hessen	10	49.614081	8.816294	Granite	4	1	3	Fair
Rhineland-Palatinate	10	49.161653	8.0025592	Granodiorite	1	0	1	Excellent
Hessen	10	49.581881	8.685392	Granodiorite	2	0	2	Good
Hessen	10	49.618109	8.7137448	Granodiorite	1	0	1	Excellent
Hessen	10	49.630763	8.6938764	Granodiorite	3	0	3	Fair
Hessen	10	49.637257	8.7122482	Granodiorite	1	0	1	Excellent
Hessen	10	49.654241	8.7086859	Granodiorite	3	0	3	Fair
Hessen	10	49.675644	8.7950126	Granodiorite	1	0	1	Excellent
Hessen	10	49.782408	8.8444664	Quartz-Gabbro	1	0	1	Excellent

Table 8: Overview of the 22 localities where a range of inferred fracture frequency could be calculated and their corresponding RQD rank.

Of the 22 localities, 16 have an inferred fracture frequency range of 1 or less per metre, which results in an RQD designation of excellent. The rocks in these localities would be expected to have very few fractures, indicating that they would have poor permeability and possibly transmissivity. These excellent ranks are also spread across multiple rock types, including quartz-gabbros, granites, granodiorites and gneisses, indicating that at least at particular localities all of these rock types can be expected to be found intact with few fractures.

Plotting these 22 localities on a map overlying the crystalline rock sub-areas highlights the scarcity of suitable geomechanical data (Figure 22). The 22 localities only cover two of the seven crystalline rock sub-areas, indicating a significant portion of the potential area is not accounted for. Additionally, the variability observed in the data from the Upper Rhine Graben region highlights the lateral variability that would be expected across these areas of crystalline rock, with fracture density expected to increase near fault zones and other major structures as is likely the case in the actively extending Upper Rhine Graben rift system. Nevertheless, this dataset forms the first layer in the common risk segment map.

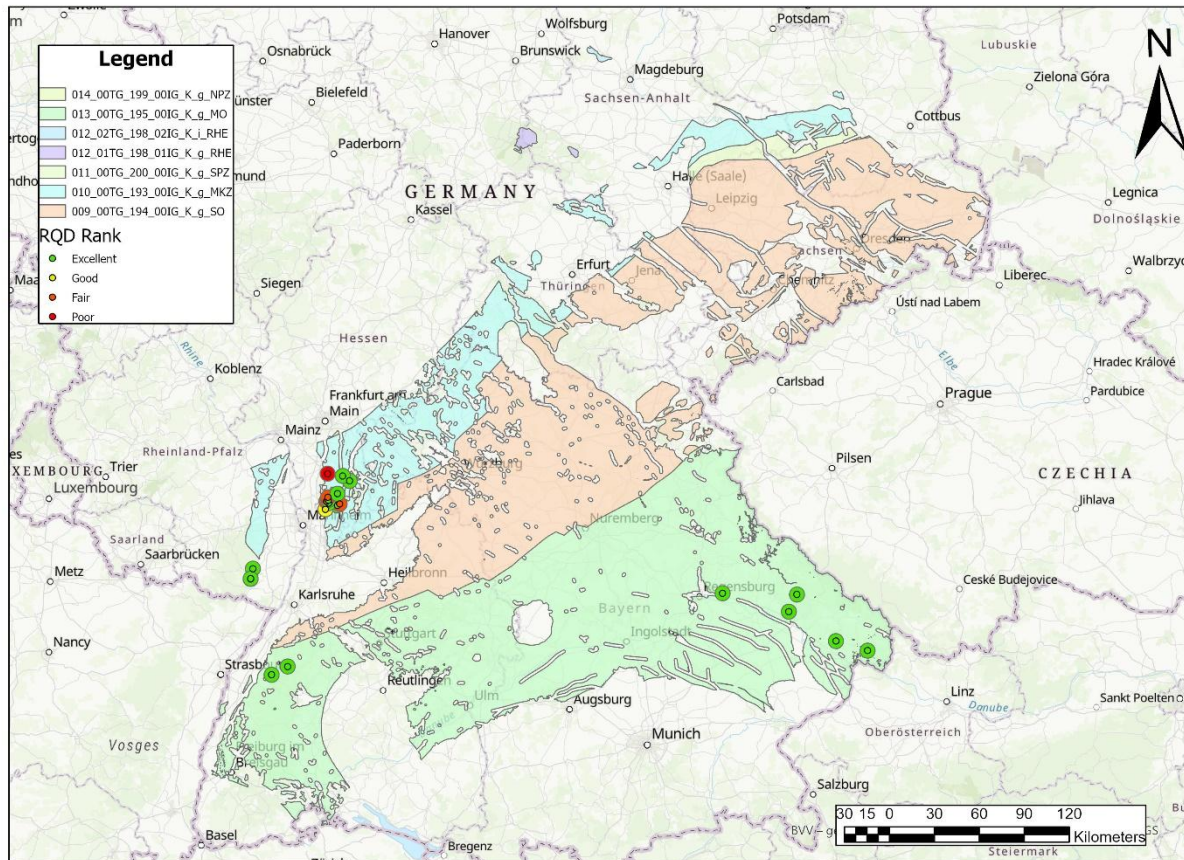


Figure 22: Overview map showing the location of the crystalline rock sub-areas and the 22 localities with sufficient data to provide a predictive RQD rank. A five kilometre buffer has been added to highlight these localities.

While beyond the scope of this study, further work could be done to incorporate the mapped faults and magnetic datasets which were included in the database provided by the BGE to map out currently unmapped faults within the crystalline rock sub-areas. Some of these fault zones have been accounted for in Step 1 Phase 1 of the BGE's siting process, but there are likely several unmapped faults, particularly within large crystalline rock bodies, which would also represent zones where we would expect greater deformation.

7.2 Layer 2: Glacial extents and impacts

The extent of three glaciations were mapped in Task 2. It was observed that certain sub-areas were covered by ice-sheets; the northern German extents of the Elsterian and Saalian ice sheets covered sub-area 012_02 in totality alongside portions of sub-areas 009, 010, 012_01 and 014 (Figure 15). The southern Saalian and Weichselian ice-sheets extending from the Alps interact with the southern fringes of sub-area 013. There are also small ice-sheets formed on the mountains of the Bavarian Forest region in eastern Bavaria. However, these small ice-sheets are unlikely to have enough mass to cause significant isostatic adjustment in the lithosphere.

When considering a ranking schema similar to that devised for the geomechanical data, it should be noted that the presence and thickness of ice-sheets should not rule out a location as a suitable host for a GDF. Both the Swedish and Finnish GDFs have been sited in crystalline bedrock which has experienced repeated glaciations and interglacial periods, albeit with the caveat of local geological variations such as sedimentary cover and crustal thickness which differ from the setting of the crystalline rocks of Germany. Therefore, a ranking scheme considering the impact of glaciation will not have an excellent-poor grade scheme. Instead, the ranking scheme was based on the type of glacially-induced processes expected:

- Crystalline rocks which have been covered by a significantly thick ice-sheet will have experienced increased vertical stresses in the recent geological past. This increase in stress can have a variety of implications. These rocks will also experience the glacio-isostatic readjustment following the retreat of the ice-sheet, resulting in fault reactivation and glacially-induced fault movement and accompanying seismicity. These areas will be affected by a twofold process and therefore have a lower rank relative to areas which will only be impacted by glacio-isostatic readjustments.

- Areas not covered by ice during Quaternary glaciations will not have experienced the associated additional vertical stresses caused by ice-sheet loading. However, there will be influence from the glacio-isostatic readjustment of the lithosphere following both ice-sheet build-up and advance and also the retreat of the ice-sheet. The glacially-influenced process most likely to be experienced by these crystalline rocks is fault reactivation due to the changes in horizontal stresses. Minor modification of fractures, with slip values on the millimetre-scale, would also be expected in these areas due to these same changes in the horizontal stresses.

This results in two layers, one made up of the combined ice-sheet extents mapped in Task 2 and the remaining portion of the study area not covered by these Quaternary glaciations (Figure 23). Sub-area 012_02 is the only sub-area completely covered by Quaternary glaciations, while sub-area 011 is the only area which has not been covered by any Quaternary glaciation. The remaining five sub-areas were all partially covered by Quaternary glaciations.

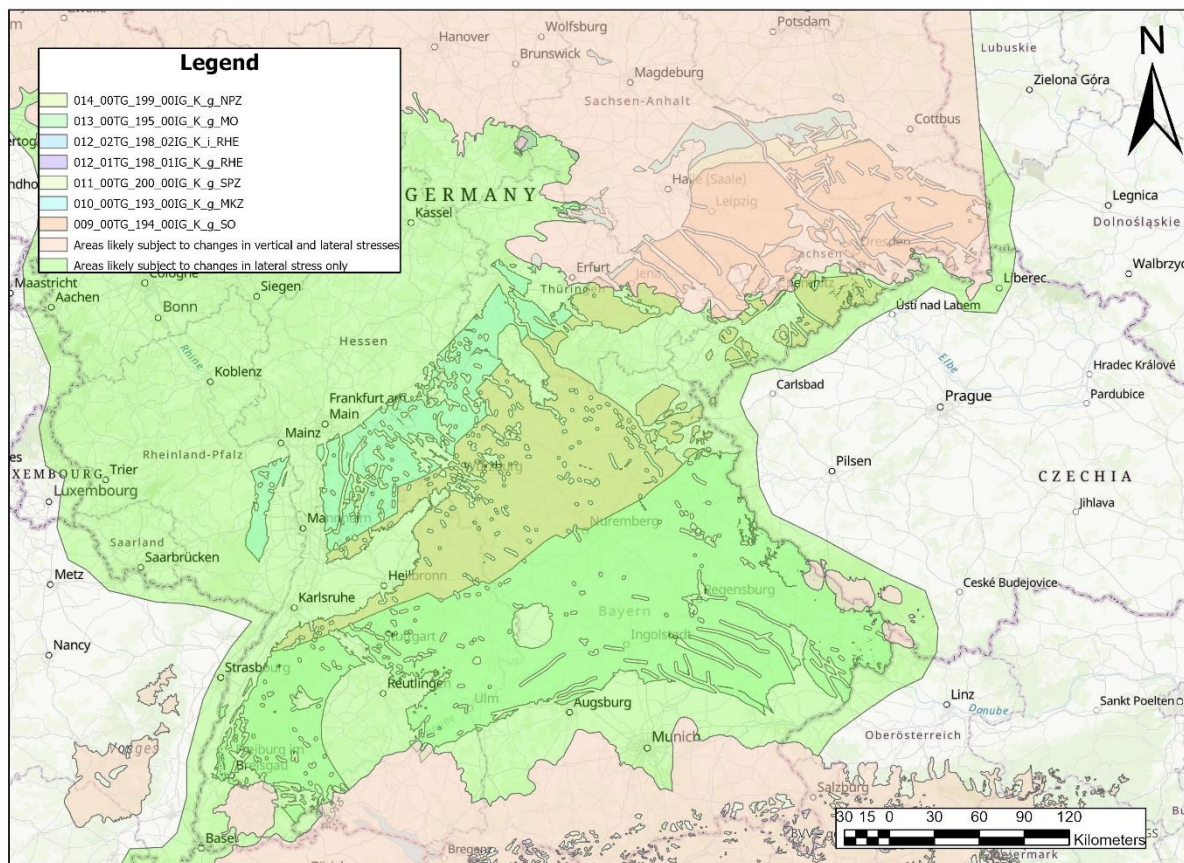


Figure 23: Overview map showing the crystalline rock sub-areas and the two areas likely impacted by different glacially induced processes.

As noted in Section 6.4, the results of Task 2 and the resultant map shown in Figure 23 could be further developed through incorporation with third-party datasets, principally the numerical stress mapping being carried out by the SpannEnD project team. Should the influence of glaciations be incorporated into their modelling workflow, as previously suggested by Jacobs (2024), the slip tendency of faults in the crystalline rock sub-areas could be modelled which would provide another geological characteristic that could inform the BGE's siting process. It is likely that faults with certain strikes (i.e. orientations) will have a greater tendency to reactive and slip, causing both fracture modification in the rocks immediately surrounding the fault, and accompanying seismicity. This modelling could identify those faults and further refine the map presented in Figure 23.

7.3 Layer 3: Stress magnitude

It was noted in Task 1 that there are few areas with exceptional stress magnitudes. The plot of Sv did not show any outliers, with most data plotting within $\pm 10\text{MPa}$ of a typically assumed vertical stress profile (Tingay et al., 2005) with only one exception from a locality where all other data points did follow the trend, suggesting it may be an outlier. It is therefore difficult to build a ranking scheme for this stress axis which is to be expected as Sv is primarily derived from the loading of the overburden.

There is more variability with in both the SHmax and Shmin datasets. This is not surprising giving the variety of processes in the subsurface that can cause variations in lateral stresses. While it was noted that there were no large outliers in the SHmax dataset, this lateral stress magnitude does tend to increase with depth broadly correlating with the Sv gradient. It is therefore possible to highlight areas of higher SHmax values by measuring the difference between the measured SHmax values and the expected Sv gradient at the same depth. There are 62 SHmax values across 16 unique localities which are composed of crystalline rock. Across these 16 localities, only two have SHmax magnitude values which are greater than 40 MPa above the predict Sv using the 24 MPakm⁻¹ derived in Task 1 from German Sv data. This is not necessarily a significant deviation but represents the three highest values. Similar deviations have been observed in stress magnitude data from other countries (e.g. the UK – Fellgett et al., 2018). Nevertheless, this can be used to provide a ranking system for the stress magnitude data, although the higher ranks may not necessarily rule out a locality for further study in the GDF siting process.

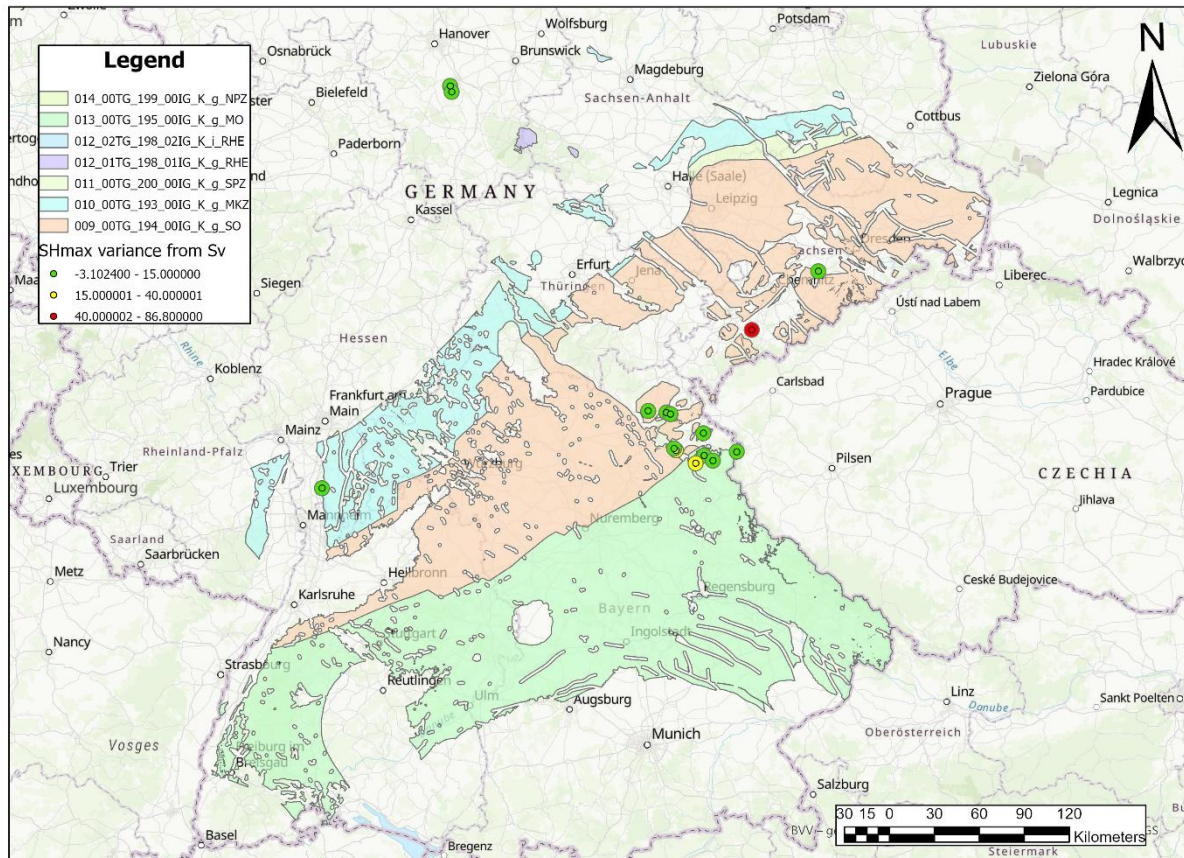


Figure 24: Overview map showing the crystalline rock sub-areas and the location of stress magnitude measurements in crystalline rock coloured by the difference between SHmax and the Sv gradient.

The data presented here is caveated with the knowledge that these in-site stress magnitude measurements represent the present-day stress field and do not record the complex stress history the various crystalline rock sub-areas likely experienced during their formation and geological evolution. As stated in previous sections, numerical modelling of the recent paleo-stresses caused by ice-sheet loading could be achieved, but a full reconstruction from their formation in the Variscan Orogeny and subsequent evolution through the Mesozoic and Cenozoic is likely to involve too much uncertainty.

7.4 Composite map

Combining the layers of RQD, glacially influenced process (including estimated palaeo stress field extent), and current stress magnitude values results in a composite map containing all the usable data available to this study. Given the relative scarcity of the data available for this study, it is not surprising that there is almost no overlap between RQD and stress magnitude data points. Only by extending a five-kilometre buffer around the data points do the two datasets interact across two data points from the eastern flank of the Upper Rhine Graben. All the data points for both RQD and stress magnitude which occur within the seven crystalline rock sub-areas also fall within the area which has not been covered by Quaternary ice-sheets and is therefore expected to be mainly subject to changes in lateral stresses as a result of glacial advance and retreat.

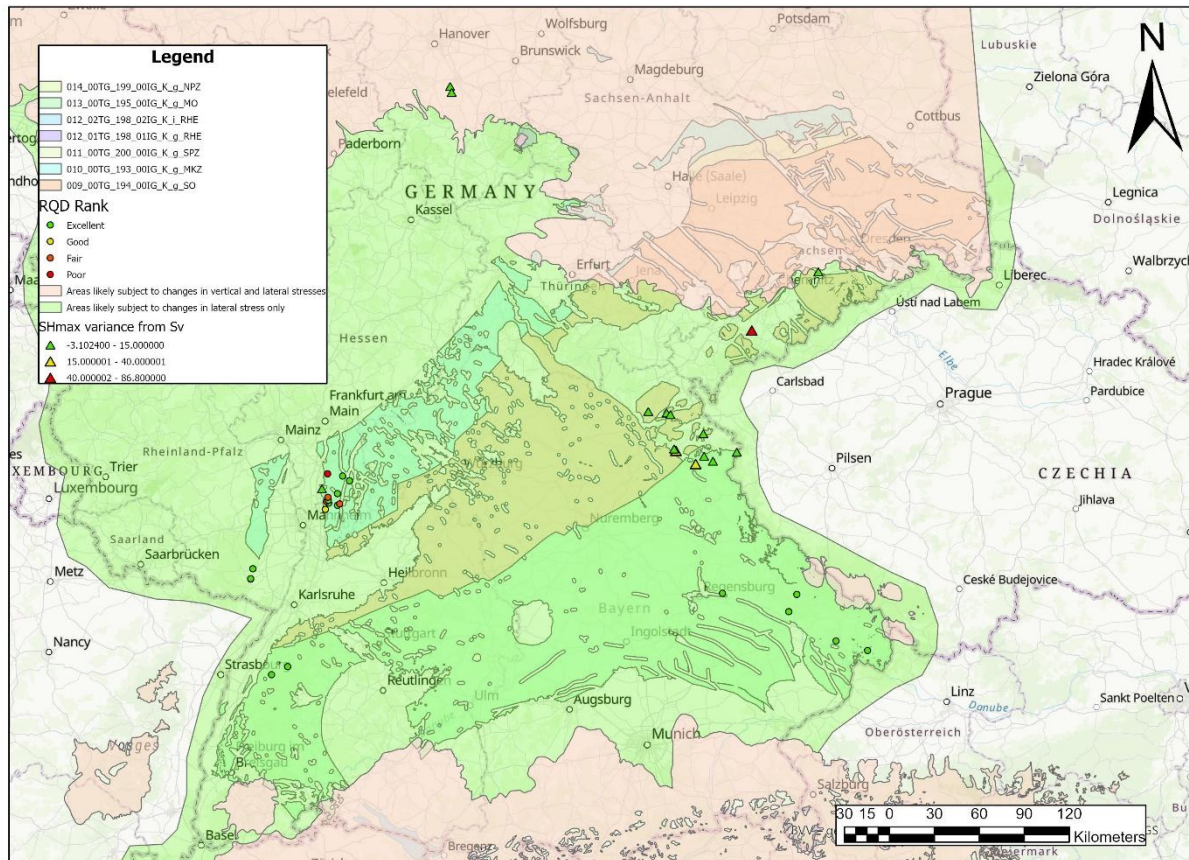


Figure 25: Composite map of the seven crystalline rock sub-areas overlain with the resultant layers of Task 3.

Figure 25 suggests that the crystalline rocks in sub-area 013 (the Moldanubian Zone) have the highest proportion of RQD rankings of the seven crystalline rock sub-areas. There is more variability in the RQD rank of the crystalline rocks in sub-area 010 (the Mid-German Crystalline Zone), with the only poor RQD ranking in the Upper Rhine Graben region. The remaining five crystalline rock sub-areas do not have any geomechanical data available. The highest variance from the typical stress magnitude curve is observed in sub-area 009 (the Saxothuringian Zone), although is located in a section of this zone which has already been excluded from the GDF siting process.

These results do highlight the lack of data available to characterise the seven crystalline rock sub-areas and create criteria with which to rank them for suitability for further study in the GDF siting process. This could be supplemented by targeted data collection across the sub-areas which currently have no suitable geomechanical or stress magnitude data. However, this study has demonstrated that all the rock types included in the available data have been predicted to not be heavily deformed at certain localities. Furthermore, the methodology employed in this study has highlighted high-level findings which can further inform the BGE's site selection process beyond the results discussed above:

- **Crystalline rock types:** As noted above, all the igneous and metamorphic rock types which have geomechanical data available have strength and elasticity characteristics that would indicate high-quality, intact rock masses at certain localities. Other crystalline rock types which may be weaker or more likely to deform have already been excluded from the site selection process by the BGE, such as schists, slates and fine-grained igneous rocks.
- **Stress magnitude:** the stress magnitude data has not highlighted any localities with anomalously high values. The available data supports the generally accepted model that Germany is experiencing a broad, compressive tectonic regime driven by the on-going collision of the African and Eurasian tectonic plates.
- **Varying tectonic regime:** some of the stress magnitude data suggests that there may be local variations in the active tectonic regime being experienced by the crystalline rock sub-areas, namely an anomalous strike-slip regime in an area which is experiencing a broadly compressive regime. While these data points may be of poor quality or due to faulty measurements, they warrant further investigation with implications for rock stability (e.g. considering foliation in metamorphic rocks) and fault slip-tendency.

- Impact of glaciations: Quaternary glaciations have played a significant role in the recent geological history of Germany. The advance and retreat of glaciers has caused the stresses active in the crust to vary over time, resulting in the reactivation of faults, both during glaciations and following their retreat as the crust readjusts to the removal of the ice-sheet load. Both processes have clear implications for GDF siting and warrant further research.

Amentum have already provided the BGE with suggestions for further work to expand the results of Task 2 (Jacobs, 2024) which include expanding our collaboration with the SpannEnD team and explore the variety of glacial geohazards that may impact a GDF. As noted above, the variation in the prevailing tectonic stress regime also warrants further study to understand the forces influencing this variation and how it could impact both fracture formation and growth, fault slip tendency and the design parameters of a final GDF. This could be achieved through further work with the researchers of the SpannEnD team, or by Amentum constructing local site-scale models for these areas and using the wide range of industry standard kinematic modelling tools to map the stress state onto faults to understand how they might behave over geological time.

8 Conclusions

This study has demonstrated a valid methodology to combine a geomechanical and stress magnitude database with the mapped extents of Quaternary glaciations to produce a composite map to inform a site selection process for a GDF. However, the study area in question has a significantly restricted database which limits the ability of this methodology to be applied across all seven crystalline rock sub-areas under investigation. Geomechanical and stress data was only available for three of the seven crystalline rock sub-areas which left four sub-areas outside the bounds of the study. Given the significant rock mass which has not been studied due to a lack of available data, it is difficult to justify the significance of the results for a comprehensive GDF siting study. Really don't like this negative statement. Nevertheless, high-level findings which can inform future data collections efforts and ultimate siting criteria applied to the seven crystalline rock sub-areas can be highlighted:

- All rock types investigated in this study have geomechanical measurements that would predict very little deformation (i.e. fracture intensity) across several localities.
- The available present-day stress magnitude database does not highlight any areas of exceedingly high in-situ stresses.
- The stress magnitude data does reveal some local variability in the present-day tectonic stress regime, with most localities experiencing a compressional tectonic regime with some outliers experiencing a strike-slip tectonic regime. The local variability in the orientation of the stress field and the resultant tectonic regime is important in any GDF site selection process and the driving factors behind this variability warrants further study.
- Glaciation has played an important role in the evolution of the Quaternary geology of Germany. They have also overlain areas of crystalline rock, likely causing increased stresses to both the loading of the ice-sheets and the adjustments of the lithosphere caused by the advance and retreat of the ice-sheets.
- Glacio-isostatic adjustment as a result of ice-sheet advance and retreat has a much wider area of influence beyond the mapped extents of ice-sheets. This has important implications for the reactivation of faults and resultant seismicity this may cause across all German territory, alongside the potential for fracture modification and growth in the rocks around these faults. It also appears to an area of research that has received relatively little attention and warrants further research in support of GDF siting.

Ultimately, Amentum have applied a defensible methodology which incorporates all geomechanical and stress magnitude data that was available with knowledge and research of Quaternary glaciations to produce a model which predicts the distribution of deformation across the seven crystalline rock sub-areas. While this is a valid technique, it has also highlighted the severe lack of data across these seven sub-areas and highlighted the challenge facing the BGE to rank them for further study in their GDF siting process. Nevertheless, high-level findings that can help to inform this process and has pushed our understanding of these crystalline rocks significantly further than that available at the project outset.

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Appendix A. List of data provided by BGE

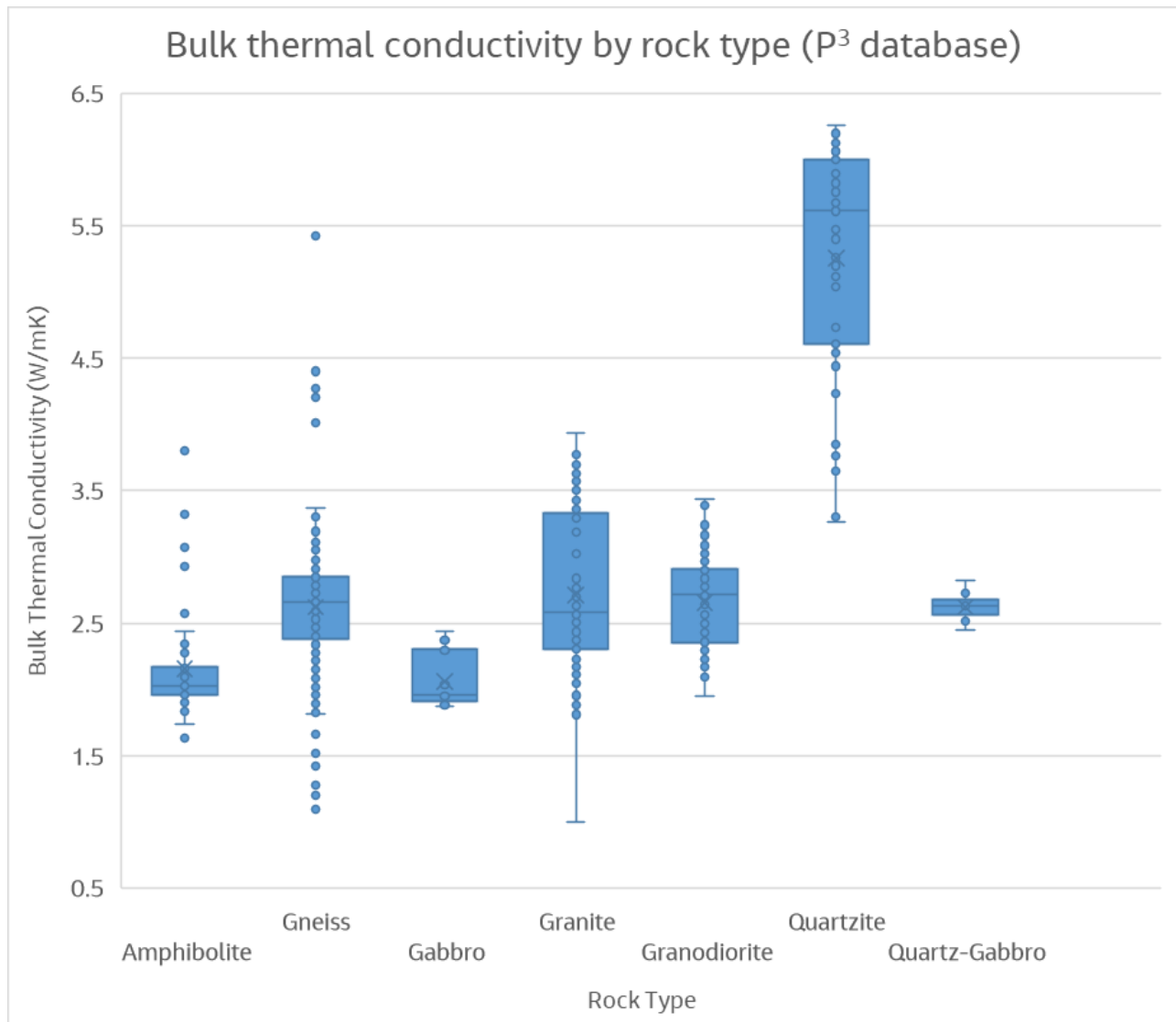
A list of the data provided by the BGE is included below. File descriptions were translated from German and may contain some errors or mistranslations.

DOKID	Description	Location file
11973787	Detailed landscape data on the Elbe Valley/Eastern Ore Mountains region, including maps of hydrogeological characteristics	DokID_11973787_02/
Komposit	Database compilation of drill master data, drill paths, petrology, stratigraphy, drilling documents	funki_exp_2024_01_18_16_10_17.7z
11973787	Geopackage with layers on erosion, contaminated sites, consequential mining damage, etc.	DokID_11973787_03/Ausgewaehlte_Layer_Elbtal_Ostergelbige.7z
11973322	shapefiles on raw material deposits along with explanations	DokID_11973322.7z
11926950	Geological 3D model from Skua/GOCAD	DokID_11926950.7z
11839700	Shapes of mining activities of the State Mining Authority	DokID_11839700.7z
12020789	Report with strata lists, petrographic descriptions, X-ray and grain size analyses	DokID_12020789.7z
11975975	for a few selected locations: permeability, magnetic susceptibility, P- and S-wave velocity -> dyn. elast. Module, dyn. Transverse strain number, dyn. Shear modulus, thermal and thermal conductivity -> spec. Heat capacity, XRD, XRF, ICP-MS, thin sections, tensile strength, uniaxial compressive strength -> Stat. elast. Module, stat. Transverse strain coefficient, compression modulus, shear modulus, triaxial compressive strength -> cohesion, friction angle.	DokID_11975975.7z
11974535	Shapes of raw materials	DokID_11974535.7z
11973335	Geothermal Atlas	DokID_11973335_Geothermie.7z
11973335	Raw Material Shapes	DokID_11973335_Rohstoffe.7z
11992976	Raw Material Shapes	DokID_11992976.7z
11954745	Geological and tectonic maps, groundwater levels	DokID_11954745_rekompiliert.7z
11954715	Reports and Measurement Data (csv) Aeromagnetism	DokID_11954715.7z
11965212	Excerpt (Excel conversion (moderately good)) from the Saxon drilling database system UHYDRO for all boreholes up to 100 m including petrochemical	DokID_11965212.7z
11876520	Faults, geomechanics, thermal properties, deep hydrochemistry	DokID_11876520.7z
11854451	Tectonic faults from suborsion and glaciation	DokID_11854451.7z
11839476	3D surface of the quaternary base in GOCAD .ts format	DokID_11839476.7z
11839344	3D models VES, Mueg, NW_Sachs, Elbe zone, Elbe valley, Lower Lusatia, Rohsa	DokID_11839344_01.7z
11839344	3D models Rohsa (3.1), NBS, ZwGe, ATC, Sadisdorf, TransgeoTerm	DokID_11839344_02.7z
11839344	3D models TransGeo Therm, Zittau Basin, Zittau, Berzdorf, Oderwitz, Annaberg, Aue, Freiberg	DokID_11839344_03.7z
11839344	Geological map scale 1:25,000	DokID_11839344_04.7z
11839344	Geological map scale 1:50,000	DokID_11839344_04_2.7z
11839344	Geological map scale 1:100,000	DokID_11839344_05_01.7z
11839344	Geological map scale 1:200,000	DokID_11839344_05_02.7z
11839344	Geological overview map scale 1:400000	DokID_11839344_05_03.7z
11839344	Map of the granite surface	DokID_11839344_05_04.7z
11839344	Book publication on the geology of Saxony	DokID_11839344_05_05.7z
11839344	Hydrogeological map on a scale of 1:50000 incl. faults	DokID_11839344_06_01.7z
11839344	Collection of official statements, e.g. on geothermal energy, partly with useful characteristic values	DokID_11839344_06_02.7z
11885584	ArcGIS project with active disturbances in Saxony	DokID_11885584.7z

11971514	Seismicity Auersberg: Shape with epicenters and disturbances	DokID_11971514.7z
12032251	Digital Elevation Model with 1 m tile width; crs=25832	DGM_Sachsen.7z
11956678	Geomagnetics Brandenburg (and some Saxony)	DokID_11956678.7z
11938730	Nationwide gravimetry and magnetics (coarse)	DokID_11938730.7z
12024644	SEGy data on the seismic surveys Dekorp and GRANU	DokID_12024644.7z
12018142	Seismic scans in Saxony from the TLUBN archive	DokID_12018142.7z
11971835	Gravimetry and Geomagnetics Thuringia (and some Saxony)	DokID_11971835.7z
11987734	Gravimetry and Geomagnetics Saxony	DokID_11987734.7z
12010226	Gravimetry and Geomagnetics Thuringia (and some Saxony) interpreted	DokID_12010226/
12024644	2D and 3D SEGy data, .kml files on the position of the lines	DokID_12024644_Seismik_2D_3D_DEKORP_ GRANU
11842369	GIS Project on Geological Maps with Symbolization	02_GIS_Projekt
11842369	N/A	03_Grunddatensatz Bayern
11977425	Original Well Database as provided by bavarian geological survey	DokID_11977425_BYorig_DB_Bohrungen\DokID_11977425\04_2022\1.1 Bohrungen\Bohrungen.accdb
11879793	Data partly refer to boreholes whose master data and ids come from the database [Pkg_ID=4]	DokID_11879793_Hydrochem_Geomech_Temp\
11879793	N/A	DokID_11879793_Hydrochem_Geomech_Temp\p\DokID_11879793\Temperaturverträglichkeit\ Porosität_und_Dichte\Porosität_Dichte_Bohrung_7448BG015093.xlsx
N/A	Master data, petrology, stratigraphy, LAS/LIS/DLIS, drilling paths from the BGE's internal drilling database	wells_BGE\
N/A	Bavarian Forest / Bedrock Bavaria - Geometry Investigation Area of Data Delivery	study_area.gpkg
11842665	N/A	DokID_11842665_Bayern_Störungszonen_seis _aktivität
11873386	Version 2019, update in clarification	DokID_11873386_dGK25
11898794	Tailored to Bavaria	DokID_11898794_Aktive_stoerungen_bundesg ebiet
11938730	N/A	DokID_11938730_GravMag_Data_Germany
11881514	Extract of the hydrocarbon database as a port to sqlite format. Reference tables in KWDB_ref_port.sqlite	DOKID_11881514_KWDB_excerpt
11977425	Project report "Integrated geophysical-structural-geological-kinematic analysis of the fault inventory in Northern Bavaria"	DokID_11977425_FAU_Projekt_Stoerungen_N ordbayern
12028355	DGM (DEM) 1 of the Bavarian Forest as 1x1km tiles in .tif format; EPSG=25832	DokID_12028355_DGM1
11977425	Usually grain size proportions and derived param: elasticity, pore proportions, etc.	DokID_11977425_geomech_Kennwerte
11977425	Various hydrogeol. Information: Pumping tests, hydrochemistry	DokID_11977425_GW_Erkundungen
11977425	Data from pumping tests	DokID_11977425_Pumpversuche
11977425	Results of tracer tests in groundwater	DokID_11977425_Markierungsversuche
11977425	Detailed report on the tectonic situation in the target area	DokID_11977425_stoerungsanalyse
11842665	GIS project and geodatabase with tectonic features	DokID_11842665_aktive_Stoerungszonen
11842665	GIS project and geodatabase on seismic activity	DokID_11842665_Erdbebenkatalog
11842601	GDB's on Tectonic Fault Zones and Elevation Rate	DokID_11842601_atek_Stoerungszonen_Hebu ngsraten_Bayern

Appendix B. Note on thermal conductivity of crystalline rocks

As noted in the review undertaken by SKB (see Appendix C: Third-party peer review comments) the thermal conductivity of rocks play an important role in deciding their suitability to host a GDF. Rocks with a low thermal conductivity will not dissipate the decay heat generated by radwaste which could lead to unacceptable heat build-up resulting in failure of the GDF seal. Therefore rocks with higher thermal conductivities are favoured over those with lower thermal conductivities as host rocks. While beyond the scope of the original project, a short analysis of thermal conductivity values for various crystalline rock types was undertaken for the data available in the P3 database. This provides a high-level overview of the range of bulk thermal conductivity values that could be expected for the various crystalline rock types within Germany.



As noted by the reviewer from SKB, gabbro has the lowest mean bulk thermal conductivity at 2 W/mK. There were not bulk thermal conductivity measurements of diorite in the P3 database. Amphibolite, a rock type not considered during the geomechanical study due to a lack of data, also has a low mean bulk thermal conductivity of 2.15 W/mK. Gneiss, granite, granodiorite and quartz-gabbro all have higher mean bulk thermal conductivity between 2.5-3 W/mK. Gneiss and granite both have a wide spread in data which is likely due to the variety of mineral compositions sampled throughout the P3 database. Quartzite, another rock type not sampled during the geomechanical study due to a lack of data, has the highest mean bulk thermal density by a significant margin at 5.26 W/mK.

Appendix C. Third-party peer review comments

The review document produced by the SKB in review of this report is included below. Formatting errors result from the original document.

Type:	Report	Review date: 2007-06-10	Revision #:0.1	Revision date:
Author(s):	Conor O'Sullivan; Rhys Timms; Chris Davies; Kevin Burbidge			
Document:	Performance specifications of concept design for quantitative methods in crystalline rocks			
Reviewer(s):	Assen Simeonov			

I have used the 'Performance specifications of concept design for quantitative methods in crystalline rocks, Draft version' document for this review, sent e-mail by Sean Humphreys on June 04, 2024.

Background

BGE are in a siting process of selecting a location to host a geological disposal for final storage of high and medium level nuclear waste. The work is planned to be achieved in three phases:

- 1 Desk-top study to identify candidate sites for investigations on the ground-surface.
- 2 Ground-surface investigations → 2D-modelling.
- 3 Investigations by drilling → 3D-modelling.

This report is presenting a concept developed by Jacobs, for screening areas (phase #1) with crystalline bedrock with possibly suitable properties (low fracture frequency). The concept is a desktop study based on data from public and private sources.

- The geomechanical properties of the crystalline rocks, which would be used to characterise their strength and how they might deform.
- The present-day, in-situ stress magnitude data which could reveal areas of particularly high stress, which may represent areas where more intense deformation and fracturing might be observed.
- The extent of recent glaciations, which have been observed in other countries to modify existing fracture networks and reactivate faults which can lead to seismicity.

The work is divided in three tasks:

- Task 1 collation and data analysis of all available geomechanical and stress magnitude data.
- Task 2 mapping the extents and thicknesses of Quaternary glaciations in Germany
- Task 3 combination the results above to produce a composite map which would aim to predict the degree of deformation across the crystalline rock sub-areas.

General comments

This is a carefully and clearly written, well-structured and focussed report. The majority of comments in my review relate to points of clarification.

I appreciated the detailed descriptions of the data and of the various processes which are then used to create syntheses. Processes (orogenic and glaciation related) that have affected, and some still affect, the bedrock create a complexity that is always a challenge to interpret. Extra challenging is that no field visits have been done during this work. In my view, assumptions based on data and literature studies are mostly well supported and clearly described.

I also appreciated very much the work done including the CRS mapping in Task 3, Chapter 7. The method is very suitable to make a synthesis of the complicated combination of data and conceptual assumptions made in previous chapters.

In view of the above, I thought that the authors had displayed clearly the audit trail from primary data through interpretation to conceptual model.

In addition to producing a well-documented and thorough description of the 3D geology of the proposed repository site, the authors have also addressed the difficult problem of how best to sub-divide a block of rock as structurally complex and lithologically variable as the Forsmark area. Having established the basic lithological divisions and major structures it became apparent that in order to effectively model the region, particularly from a thermal point of view, it would be very useful to attempt to define 'rock domains' i.e. rock volumes that show similar composition, grain size, degree of homogeneity etc. The authors have not suggested abandoning the standard geological description of the area but have argued that the rock domain model can be used to compliment the standard model. The correlation between the different domains of fracturing and the rock domains is impressive and has helped justify and validate the rock domain approach.

To be filled in by the Reviewer					To be filled in by the Author
ID	Page	Section	Content	Comment/Question	Revision
					Correction/Explanation
1	ii		Glaciation has played an important role in the evolution of the Quaternary geology of Germany. They have also overlain areas of crystalline rock, likely causing increased stresses to both the loading of the ice-sheets and the adjustments of the lithosphere caused by the advance and retreat of the ice-sheets. The loading of these ice-sheets can cause an increase in fracture size and intensity.	During the complete site investigation at Laxemar, Simpevarp and Forsmark, we do not have obvious evidence to draw the conclusion that the loading of the ice-sheets during glaciation in that part of Sweden has caused increased fracture size or fracture frequency at depth in the bedrock volume. However, there is an extensive fracturing of the bedrock close to the surface due to stress relief after the ice-sheet withdrawal. Typically, those fractures horizontal and are lacking fracture minerals or may have a faint mineral coating, in contrast with the old fractures which were formed and reactivated multiple times during the geological evolution. Typically, different generations of fracture fillings are present and also host rock alteration (oxidation). We had a situation during the modelling work, when fractures without mineral filling were discovered in the database both at Laxemar and at Forsmark. That could mean that the non-mineralised fractures may have been formed recently. Not a good property for a site for spent nuclear fuel. A study was initiated to clarify this issue, and it was found that no significant formation of new fractures could be ascertained. See SKB TR-11-02 and also SKB TR-08-05	The reference to fracture modification as a result of glaciation has been removed.
2	1	1	The present-day, in-situ stress magnitude data which could reveal areas of particularly high stress, which may represent areas where more intense deformation and fracturing might be observed.	Is this assumption correct? High stress → no stress relief → low fracture frequency !?!	Having explored this with the SKB, this section has been reworded to come across more clearly. Areas with high present-day stress may be more likely to fail due to increased stresses which may accompany future glaciations. As noted in the SKB's comments, areas of high stress will not have undergone deformation to relieve stress through processes like fracturing or faulting. Nevertheless, areas of present-day in-situ stress values warrant further study as these elevated stress levels have important implications for any subsurface infrastructure development in these rocks, including a GDF.

To be filled in by the Reviewer					To be filled in by the Author
ID	Page	Section	Content	Comment/Question	Revision
					Correction/Explanation
3	3		The BGE use the term 'crystalline rock' to describe both igneous plutonic rocks such as granites, diorites and gabbros,	Thermal properties of a rock suitable for geological repository is important. Rock with low thermal conductivity are not suitable, because of the thermal load in the bedrock leading to after deposition of the spent nuclear fuel. Especially gabbro but also diorite have low thermal conductivity.	While beyond the scope of this study, we have included an appendix which provides a short analysis of bulk thermal conductivity data available within the P ³ database to provide a high-level overview of the distribution of thermal conductivity for various crystalline rock types in Germany.
4	3	3	... and high-grade regional metamorphic rocks such as gneisses and granulites.	Metamorphic rocks, gneisses – if they are of sedimentary origin (paragneiss), they may be very heterogenous in composition and structure (foliation, banding, etc..). Not always suitable for a repository.	Unfortunately most of the data sources used in this study did not distinguish the protolith of the gneisses, leaving some ambiguity here.
5	15	5.2.1	Stress in the subsurface is the complex interaction of geological, tectonic and fluid processes.	Consider: Stress in the subsurface is the complex interaction of geological, tectonic and hydraulic processes.	Text updated as suggested.
6	20	6.1	These are commonly referred to by their corresponding Marine Isotope Stage numbers (MIS) <i>i.e.</i> , 12, 8-6, 4d-2 (Error! Reference source not found.) respectively. Recourse to 'far-field' marine or ice-core oxygen-isotope records such as those the record in Error! Reference source not found.	Figure Reference missing	Figure reference updated.
7	23	6.3	However, due to the inherent rigidity of the lithosphere, which can vary based on primary rock composition and other factors , the influence of a loading ice-mass can reach well beyond the margins of an ice-sheet in an area termed 'peripheral depression'	Elaborate this statement – difference in competence of different rock types, as well as grade of reactivation of major deformation zones, variation of crust thickness etc..	The text has been updated to include these additional factors which can influence the crustal response to ice-loading.
8	23	6.4	(Stewart et al. 2000; Error! Reference source not found.). lithospheric stress regime is opposite, manifesting as uplift and radial extension (Error! Reference source not found.) equal or exceed that derived from regional tectonic processes (Error! Reference source not found.), with the net stress of these opposing processes either serving to counteract one another, or work in conjunction to develop stresses of considerably greater magnitude (Error! Reference source not found.).	Figure and reference - Reference missing	Figure reference updated.

To be filled in by the Reviewer					To be filled in by the Author
ID	Page	Section	Content	Comment/Question	Revision
					Correction/Explanation
9	25	6.5	The reactivation and continued slip on pre-existing faults will inevitably result in further deformation to the rock mass surrounding these structures. Pre-existing fractures in the vicinity of reactivated faults are likely to grow in length and may become more connected through this growth. Research suggests that the damage associated with this fault reactivation due to glaciations is up to 100 metres either side of the structure (e.g. Rosengren and Stephansson, 1990). These authors have also demonstrated using numerical models that pre-existing fractures tend to accommodate a large portion of the additional stress during the loading and unloading of the crust by Quaternary glaciations. This implies that pre-existing fracture networks, including those which are not spatially associated with large fault zones, will be impacted by glaciations, and increases in both fracture sizes and intensities will likely be observed. This highlights the importance of understanding these glacial processes when siting a GDF.	This study is old, the simulation technique (UDEC) and the assumptions and conclusions are outdated. Please see TR-19-19 for more details and conclusions regarding possible propagation of fractures/fracture zones. . .	The text has been updated to reflect the findings of the TR-19-19 authors and include their work as more contemporary reference.
10	32		Two distinct zones are defined that differentiate between Igneous (Blue shaded box) and Metamorphic sedimentary rocks (Orange shaded box).	Two distinct zones are defined that differentiate between Metamorphic Igneous (Blue shaded box) and metamorphic sedimentary (are those rocks para-gneisses or ortho-gneisses or mixture of both? Please clarify) rocks (Orange shaded box). See also comment ID4	This original distinction was confusing and has been removed to avoid confusion.
11	33	7.1.3	Using the extrapolated fracture frequency range derived from the MR vs. fracture frequency correlation (Figure 3),	Using the extrapolated fracture frequency range derived from the MR vs. fracture frequency correlation (Figure 21),	Text updated as suggested.

To be filled in by the Reviewer					To be filled in by the Author
ID	Page	Section	Content	Comment/Question	Revision
					Correction/Explanation
12	35		While beyond the scope of this study, further work could be done to incorporate the mapped faults and magnetic datasets which were included in the database provided by the BGE to map out currently unmapped faults within the crystalline rock sub-areas. Some of these fault zones have been accounted for in Step 1 Phase 1 of the BGE's siting process, but there are likely several unmapped faults, particularly within large crystalline rock bodies, which would also represent zones where we would expect greater deformation.	A very good point	
13	35	7.2	Both the Swedish and Finnish GDFs have been sited in crystalline bedrock which has experienced repeated glaciations and interglacial periods.	There are some differences between the German situation and that in Sweden and Finland, where the bedrock belongs to the Baltic shield and the crust thickness is 38 – 40 km. Any idea of the crust thickness in Germany? A thick crust composed with metamorphic crystalline rocks makes obviously difference concerning the stiffness.	A statement caveating the varying geology of both Scandinavian GDF sites and the crystalline rocks of Germany has been included to indicate that while an apt comparison, they are not a perfect analogy for the focus of this study and the subtleties of German geology must be considered going forward.
14	36		However, there will be influenced the glacio-isostatic readjustment of the lithosphere following ice-sheet retreat.	However, there will be influenced the glacio-isostatic readjustment of the lithosphere following both build-up of the ice-sheet and also retreat. The fore-bulge is created and also moving forward during the building-up of the ice-sheet.	Text updated as suggested.
15	37		It is likely that faults with certain strikes (i.e. orientations) will have a greater tendency to reactive and slip, causing both fracture modification and seismicity. This modelling could identify those faults and further refine the map presented in Error! Reference source not found..	A very good point	

To be filled in by the Reviewer					To be filled in by the Author
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16	38		Jacobs have already provided the BGE with suggestions for further work to expand the results of Task 2 (Jacobs, 2024) which include expanding our collaboration with the SpannEnD team and explore the variety of glacial geohazards that may impact a GDF. As noted above, the variation in the prevailing tectonic stress regime also warrants further study to understand the forces influencing this variation and how it could impact both fracture formation and growth, fault slip tendency and the design parameters of a final GDF. This could be achieved through further work with the researchers of the SpannEnD team, or by Jacobs constructing local site-scale models for these areas and using the wide range of industry standard kinematic modelling tools to map the stress state onto faults to understand how they might behave over geological time.	I only browsed some of the work done by researchers of the SpannEnD team, so cooperation between Jacobs and the team could be fruitful...	
17	41	8	Given the significant rock mass being excluded for the study on the basis of available data, it is difficult to justify the significance of the results for a comprehensive GDF siting study.	Given the significant rock mass being excluded for the study on the basis of available data, it is difficult to justify the significance of the results for a comprehensive GDF siting study.	Text updated as suggested.