



Crystalline Rock Study: 2D Mechanical Modelling to Quantify the Range and Impact of Ice-Sheet Loading

Client: Bundes-Gesellschaft Fur Endlagerung Mbh (BGE)

Client reference: STAUvg03-23-05-JB

Document number: DEPGSC02-TR-004

Amentum Clean Energy Limited

HQ Building, Thomson Avenue, Harwell
Campus, Didcot, OX11 0GD, United Kingdom.

Crystalline Rock Study: 2D Mechanical Modelling to Quantify the Range and Impact of Ice-Sheet Loading

Client name:	Bundes-Gesellschaft Für Endlagerung Mbh (BGE)				
Project name:	Preliminary studies of crystalline rock in support of site selection				
Client reference:	STAUVg03-23-05-JB	Project no:	DEPGSC02		
Document no:	DEPGSC02-TR-004	Project manager:	Sean Humphreys		
Revision:	001	Prepared by:	Conor O'Sullivan, Simon Emsley, Tanu Singh, Rhys Timms, Adam Paxton		
Date:	5 September 2024	File name:	BGE_2D_Modelling_Report.docx		

Document history and status

Revision	Date	Description	Author	Checked	Reviewed	Approved
001	05/09/24	Draft issued for client review	COS; SJE; TS; RT; AP	NJ	NJ	CC

Distribution of copies

Revision	Issue approved	Date issued	Issued to	Comments

Amentum

HQ Building
Thomson Avenue
Harwell Campus
Didcot OX11 0GD
United Kingdom

T +44 (0)

www.amentum.com

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Executive Summary

Amentum have been supporting the BGE in exploring aspects of the geomechanical properties of crystalline rock to assist the BGE's search for a site for the disposal of high-level radioactive waste. The impact of Quaternary glaciations was noted in the previous phase of this project. Mapping the extents of Quaternary glaciations in the previous phase of this project had placed the seven crystalline rock sub-areas in this zone of potential impact. This work also indicated that there was a particular knowledge gap identified in the quantification of stress change and resultant potential for deformation in the areas adjacent to the mapped extents of Quaternary ice-sheets (Jacobs, 2024). Therefore, Amentum were commissioned to undertake this follow-up study where 2D cross-sections of the Earth's crust underneath Germany would be constructed in a numerical modelling software package. The load of an ice-sheet would be simulated to explore stress change and potential deformation in areas adjacent to ice-sheets.

FLAC3D was chosen as the numerical modelling package for this project due to project scope and in-house expertise. Amentum carried out initial sensitivity testing on a variety of parameters including ice-sheet thickness, ice density profile, ice-sheet shape and varying geomechanical parameters of the rock layers on a simplified 2D cross-section of the Earth's crust and shallow mantle. A four-layer approach was taken, which included the following layers:

- Sedimentary rock
- Crystalline rock
- Deep crust
- Mantle

This model was 600 km long and 40 km deep with a grid cell size of 1 km³. Given the scale of the model, it was decided that a uniform ice-load 2000 metres thick and with a density of 0.917 g/cm³ or 917 kg/m³ would be appropriate, informed both by available literature on natural examples and the results of the sensitivity testing.

The location of four cross-sections were chosen in consultation with the BGE. Two sections were oriented NE-SW, with a further two sections that were oriented N-S and NW-SE respectively. These sections were extended to run the length of German territory, and all sections included three principal geological features; the North German Basin, the Mid German Crystalline Rise, and the Molasse Basin. The geometry for these models was supplied to Amentum by the SpannEnD research group whose research has been incorporated into previous aspects of the BGE's work. Some of the required geomechanical properties for these rock layers were also taken from SpannEnD publications.

The results were relatively similar across the four cross-sections. The area beneath the ice-sheets experienced the greatest stress and associated deformation with the largest shape and volume change experienced in the grid-cells in that area. An area of potential tensile failure was observed in the area adjacent to/in front of the ice-sheet margin which is of greatest interest as it occurs above the Mid German Crystalline Rise where the majority of the crystalline rock sub-areas are located.

The model results, however, have to be caveated with the limitations of the modelling approach taken. In particular, the key process of glacioisostasy is not captured by the FLAC3D model as presented here. Indeed, the present model simplifies the problem by generally treating all lithospheric layers as solid rock, with a zero-velocity boundary condition at the base of the mantle layer. While the upper three layers (sedimentary rock, crystalline rock and deep crust) are suitably represented as solids, the mantle is typically described as a non-Newtonian fluid and not as a solid. While the compressional load of an ice sheet does lead to deformation of the crust following the physics of solid mechanics (as

is modelled here), significant displacement will also occur due to the sinking of the crust into the mantle as caused by the weight of ice on top. Following the principle that a buoyant object displaces its own weight in liquid, and taking the density of the mantle to be approximately four times the density of ice, it follows that a loading 2,000m of ice should cause approximately 500m of vertical displacement. This is a significant displacement effect which in turn would induce flexural forces on the crust, influencing the stress field.

To address these effects, future work, to expand these results, should treat the mantle appropriately as a non-Newtonian fluid. This may involve either a multiphysics modelling approach whereby the mantle is explicitly modelled, or implementation of a custom lower boundary condition in FLAC3D to simulate the isostatic equilibrium state. The proposed way forward to expand on these results has been discussed with the BGE team and a high-level methodological approach has been developed and presented in this report.

Ultimately, the results of this numerical modelling project demonstrate the far-field impact of ice-sheet loading on the areas adjacent to their margins, as well as the potential for modelling these processes in FLAC3D. This is an area of research that has seemingly been overlooked in the available academic literature. However, given the caveats and assumptions of the current modelling approach, the results of this study should only be used in a qualitative manner when applying them to the understanding of the stress change and deformation in crystalline rocks in response to ice-sheet loading. With further work, a refined, quantifiable relationship between ice-sheet size and distance from the ice-sheet margin could be established to aid in ranking crystalline rock sub-areas, as well as being applicable to the understanding of stress change and deformation within other rock types like mudstones/mudrocks and salt.

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Acronyms and abbreviations

BGE	Bundes-Gesellschaft für Endlagerung MbH
BP	Before Present
DEM	Digital Elevation Model
EISC	Eurasian Ice-Sheet Complex
Firn	Crystalline or granular snow on the upper part of a glacier which has not yet compressed into ice
FIS	Fennoscandian Ice-Sheet
FISH	FLAC-ish, the coding language developed for FLAC3D
FLAC3D	Fast Lagrangian Analysis of Continua in 3 Dimensions
GDF	Geological Disposal Facility
ka	Thousand years
LGM	Last Glacial Maximum
Ma	Million years
NWMO	Nuclear Waste Management Organisation
SKB	Svensk Kärnbränslehantering Aktiebolag

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 intermediate-level nuclear waste on German territory. They are currently undertaking Phase 1 of their three-Phase approach to site selection, which involves various desk-based studies which aim to shortlist sites for Phase 2 of the GDF search process. Phase 2 involves on-site surface geological mapping of the sites shortlisted in Phase 1. The BGE have employed Amentum to assist in the desk-based study of crystalline rock sub-areas which have been identified in earlier parts of Phase 1 study as having potential for further research.

Amentum have completed two studies investigating aspects of crystalline rock when considering the siting of a GDF. The first was a high-level feasibility study which analysed how other national nuclear waste disposal agencies had approached applying scientific methods to rank crystalline rock areas for suitability to host a GDF. One of the findings of that study was that fractures represent the main geological risk to GDFs located in crystalline rock masses. Fractures introduce secondary porosity and permeability into rocks, as a result of damage or by weathering or fluid enhancement, which are typically otherwise impermeable and have very little porosity (Jacobs, 2023). The feasibility study also identified the challenges that other national nuclear waste organisations have faced when trying to develop and apply technical ranking criteria to various areas of crystalline rocks within their respective countries. The study investigated approaches taken by the SKB in Sweden and the NWMO in Canada, both of whom ultimately relied on social license, community volunteering, and by soliciting offers to communities to focus geological investigation, rather than technical rankings (Jacobs, 2023).

Nevertheless, Amentum identified three aspects of crystalline rocks which could be investigated further using existing data, where available:

1. The geomechanical properties of the crystalline rocks which could be used to characterise the strength of the crystalline rocks and how they might deform.
2. The present-day stress data measured in-situ which could be used to understand the current stress regime acting on the crystalline rock masses, which will influence how fractures might form.
3. The extent of Quaternary glaciations which had been noted in other countries to reactivate faults leading to associated seismicity due to the loading of these ice-sheets on the crust and the resultant adjustment of the crust to these loads.

To address the first point above Amentum incorporated published academic databases and proprietary data provided by the individual state geological surveys across Germany through the BGE. The geomechanical aspect of the study resulted in the development of a model that allowed the reasonable prediction of fracture intensity (quantified as fractures per metre) using available uniaxial compressive strength and Young's modulus data alongside analogue fracture intensity data from infrastructure development projects developed in other areas of crystalline rock, including the SKB's GDF site in Forsmark, Posiva's GDF site in Onkalo, and a geothermal plant in eastern France. When applied to available data for crystalline rocks in Germany it predicted that very little deformation (i.e. low fracture density) would be encountered across several localities for various crystalline rock types. Analysis of in-situ stress magnitude measurements revealed that while most of Germany was experiencing a mild compressive tectonic regime present-day, some areas were experiencing a strike-slip tectonic regime.

Amentum also noted, third point above, the potential impact of the Quaternary geological history on the crystalline rocks of Germany, whereby the loading of ice-sheets on the crust has resulted in isostatic imbalances/adjustment from which the crust of northwestern Europe is still rebounding at present. Review of published literature also indicated that the impact of this isostatic adjustment extended beyond the mapped limits of the ice-sheets and influenced rocks up to 230 kilometres away from ice-sheet margins. However, there has been limited work to quantify this phenomenon and hence there may be scope to explore this process through geomechanical modelling. Therefore, Amentum proposed to model ice-sheet loading using a suitable geomechanical software package to examine potential stress changes and associated deformation in the area below and in front of the ice-sheets.

2. Literature Review

A literature review was conducted focusing on the ice sheet thicknesses and ice density, and determining the geomechanical properties required to populate the FLAC3D model.

2.1. Ice-sheet thickness

Through the Quaternary Period (last 2.6 Ma), northern Europe was repeatedly glaciated. Large ice-sheets developed over modern day Scandinavia, Russia and the British Isles. Forming as independent ice masses, these centres merged into an area of ice termed the Eurasian ice-sheet complex (EISC). During the Weichselian Last Glacial Maximum (LGM), the EISC was the third largest ice-sheet, after those in North America and Antarctica, and likely possessed a volume three times as large as the contemporary Greenland ice sheet (Hughes et al. 2016).

The maximum extent of the EISC was time-transgressive with different sectors reaching their furthest limits at different times, but broadly within the period spanning 33-19 ka BP (Patton et al., 2016). The Fennoscandian Ice Sheet (FIS) which occupied much of modern-day Scandinavia, the Baltic region and ultimately northern parts of mainland Europe including Denmark, Germany and Poland has been relatively well reconstructed in terms of spatial parameters and retreat chronology (e.g. Ehlers et al., 2011a; Hughes et al., 2016). The southerly and easterly limits of FIS, i.e. over mainland Europe, seem at least in part to have been controlled by the dominance of dry continental conditions, a product resultant from the rain-shadow effect of the EISC itself (Patton et al. 2016). Ice therefore reached southerly limits across Germany relatively late and was likely in retreat by 21-20 ka BP, although such ages can be seen to be uncertain owing to the asynchronous behaviour of the wider EISC and FIS.

The thickness of ice characterising the FIS has proven less clear when compared to lateral extent. Constraints on the verticality of glaciers can typically be ascertained through cosmogenic-nuclide dating of exposed erratic boulders and bedrock, recording the position of trimlines thought to mark the upper limits of a glacier surface and by examining the rate and magnitude of isostatic rebound (e.g. Lambeck et al. 2010).

An alternative approach is to produce ice sheet reconstructions based on computational parameters and fed or guided by lines of empirical information and governed by key glaciological principles. Figure 1 illustrates the differences in a number of reconstructions derived from models of the FIS over central Scandinavia. A clear spread of results can be observed, as data from Siegert and Dowdeswell (2004) depicts a comparatively low profiled ice cover, whilst the output of Peltier (2004) and Peltier et al. (2015) suggest a much more extensive ice thickness of up to c.2500m inland and 1200m at the margins. Such estimates are not atypical and thicknesses, particularly over higher ground, of c.3400m have been suggested by Lambeck et al. (2010). Results from Patton et al. (2016) present a more moderate estimate with an optimal mean thickness in the region of 1300m and ice marginal thicknesses of 200-300m. In lowland areas beyond mappable trimlines, establishing ice thicknesses can be more challenging owing to the lack of verticality in remnant geomorphology. Estimates have typically been derived from glaciological principles (e.g. Benn and Hulton 2010) and complied modelling efforts as above. In models previously developed and applied over Germany for the purposes of understanding salt structure response to ice loading, ice thicknesses of between 300-1000m have been applied (Lang et al., 2014; Lang and Hampel, 2023), whilst Piotrowski and Tulaczyk (1999) suggested maximum ice thickness limits over Germany of 280m during the Weichselian. These estimates are all in broad agreement with those modelled for the ice-margins in Scandinavia and are

within theoretical parameters expected for an ice marginal environment (see Benn and Hulton 2010). This is supported by a database on global ice thickness observations (Gärtner-Roer et al., 2014).

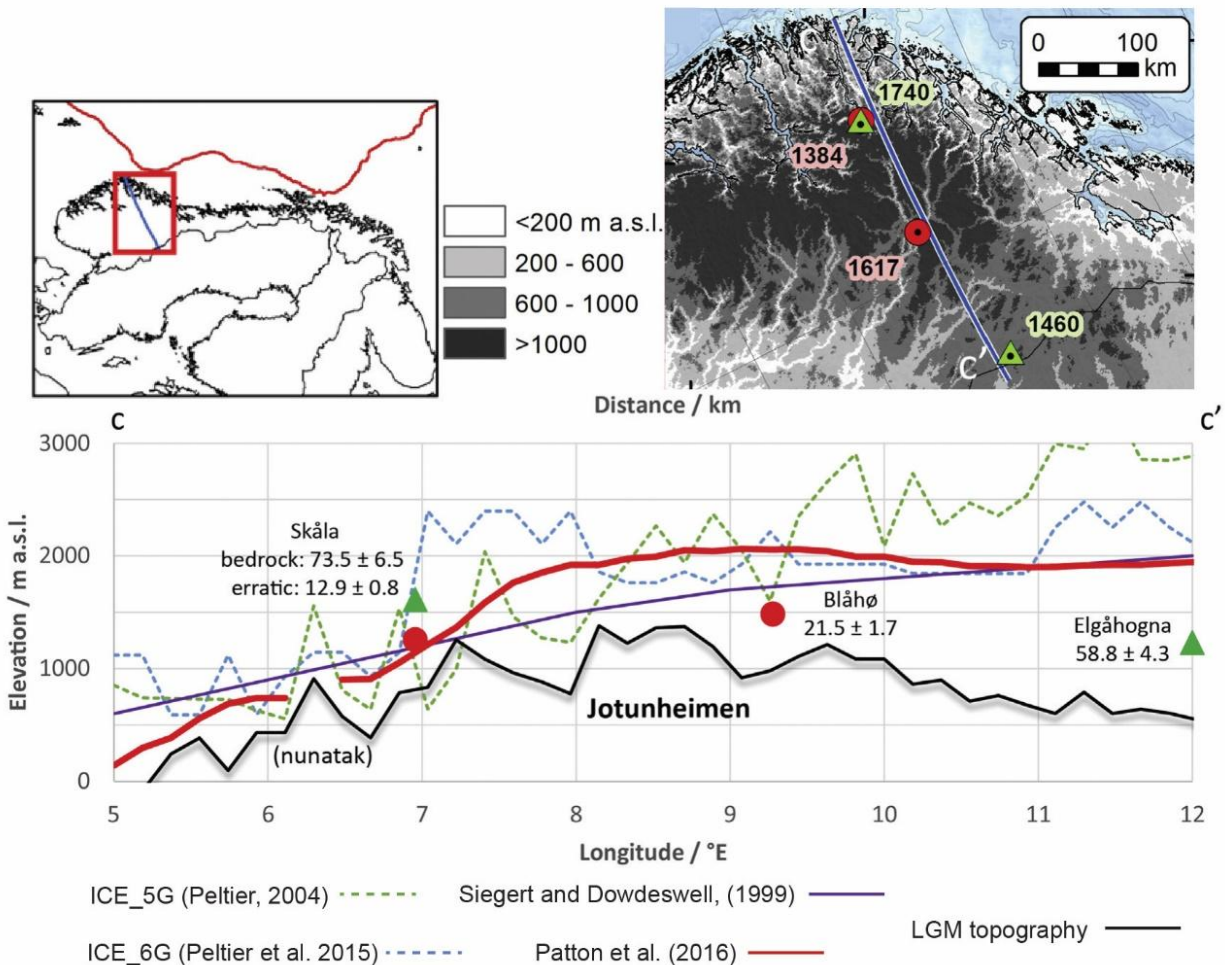


Figure 1: Compilation of modelling estimates for ice sheet thickness over Scandinavia during the Weichselian. Ice margin thicknesses are in agreement with those estimated over Germany at this time. From Patton et al. (2016).

In southern Germany, beyond the direct impacts of the FIS, the area would have been under greater influence from ice emanating from the Alpine region. Estimates for the ice sheet capping the Alps are as varied as those characterising the FIS. Empirical reconstructions of ice thickness and extent are constrained by glacial geomorphology, trimlines, moraines glacial erratics etc. (e.g. Ehlers et al., 2011b) which, as with the case of the EISC, serve both as input and validation for computed ice-sheet reconstructions. Mey et al. (2016) model a minimum and a maximum ice thicknesses of 415 and 2445m, respectively, across the Alpine region with estimates of 2000m coming from Kelly et al. (2004). As noted above, however, uncertainties and inherent mismatches in data and methodological approach indicates that reconstructions from models and empirical measurements may differ by several hundred metres regarding the total thickness of ice covering this region (Višnjevic et al., 2020).

These estimated differences in maximum thickness range from 500-800m and have been ascribed to difficulties in assessing the elevation of the ice surface away from mapped limits as well as decisions regarding spatial resolution, and various parameters governing the behaviour of an ice sheet, both from a geological and climatological perspective. It is probable that in southern Germany the thickness of the Alpine glaciers at their margins would have been an order of magnitude less than those characterising northern Germany and more akin to modern day valley glaciers which reach tens to a few hundred metres in thickness.

Whilst not all of these model outputs honour mapped limits and dated evidence, they do serve to illustrate the uncertainty behind computed and empirical reconstructions, which must be considered when considering ice thicknesses for modelling purposes. With more sophisticated models and a gradual amassing of empirical data, estimations of ice-thickness across the EISC and Alpine region are in progressive refinement and testing.

As a result, and to reflect this uncertainty and evolution, a series of plausible ice-thickness values were utilised in the sensitivity testing of the FLAC3D model employed as part of this study. This approach is further justified by the fact that the reported values noted above relate to the most recent phase of major glaciation i.e. the Weichselian, but earlier glaciations in the Quaternary, the Saalian and particularly the Elsterian were typified by larger more voluminous ice sheets and thus likely possessed thicker ice margins (Sirocko et al., 2008).

The values employed in this study were: 1800 metres during testing and 2000 and 3600 metres during the modelling runs.

2.2. Ice density

As fresh layers of snow are precipitated onto the glacial mass and transform to ice, deeper layers compact resulting the general relationship where ice density increases with ice-sheet thickness. Although seemingly simple, the generation of the ice is temperature dependent, whilst this may be obvious it is more complex than may appear. Snow turns to firn and then to glacier ice, increasing in density through the process [Table 1].

Table 1: Typical Densities of Snow and Ice [kg m⁻³] from Cuffey and Paterson [2010].

New snow (immediately after falling, calm conditions)	50-70
Damp new snow	100-200
Settled snow	200-300
Wind-packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-923

In temperate regions firn turns to ice in a short period of time of the order of 3 – 5 years and at shallow depths of the order of 15 metres. As the temperature decreases the depth of the transformation increases as does the time required for the transformation. Examples from Antarctica indicate depth of the transformation of approximately 95 metres and the time required increases to 2500 years.

Although, typically, in such areas the transformation of firn to ice takes 100 - 300 years and at a depth of the order 50 – 80 m (Davies et al., 2020). The factors; temperature and time are of importance that should not be overlooked by the BGE going forward and into post closure considerations are both the temperature and the length of time for development of the glaciers.

The density of pure glacier ice is usually taken as 0.917 g cm^{-3} . Shumskiy (1960) derived a power-law function quantifying the relationship between ice sheet density and thickness. Through this method it was demonstrated that ice density tends towards 0.917 g cm^{-3} or 917 kg m^{-3} when ice thickness exceeds roughly 200 metres (Figure 2), although it was noted that the function and the resultant values did not account for the impact of horizontal ice movement which is a common feature of ice-sheet advance and retreat (Shumskiy, 1960). Strictly this density is only true at 0°C and in the upper layers of ice sheets and mountain glaciers. The density may be greater at mid-depth ranges in polar ice sheets, where there are no bubbles and temperatures are -20°C to 40°C . It is reported that below 4 km of ice, such as at the centre of the East Antarctic Ice Sheet, the pressure would increase the density to 921 kg m^{-3} (Davies, 2020).

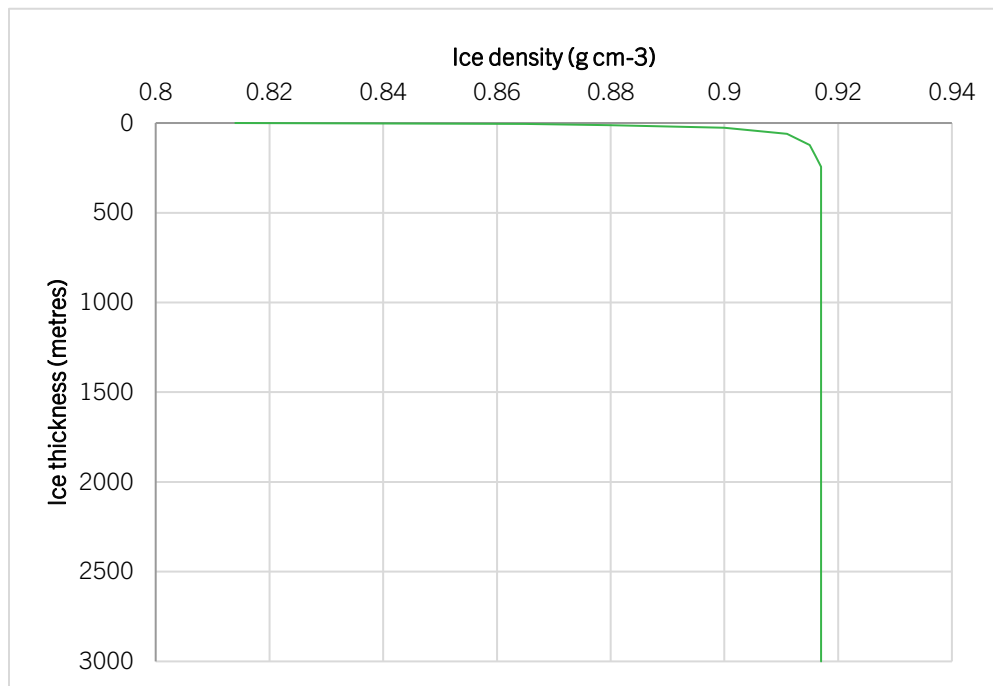


Figure 2: Graph demonstrating the relationship between ice density and thickness. Note ice density tending towards 0.917 g cm^{-3} with increasing ice thickness.

The depth dependent variation in the density of the ice is one of the parameters that was considered in this modelling and is discussed later in this report. Having said that a value of 917 kg m^{-3} was used in the modelling.

2.3. Geomechanical Properties

FLAC3D offers a variety of constitutive models which describe how the materials will respond to the forces applied to them. Two constitutive models were tested for this project: an elastic continuum constitutive model and a Mohr-Coulomb constitutive model. The latter was ultimately chosen as the

best representation of the processes being modelled. The following parameters were required for this constitutive model:

- Density
- Young's modulus
- Poisson's ratio
- Bulk modulus
- Cohesion
- Friction angle
- Tension – tensile strength
- Dilation

These are required for each of the four layers within the model (see section 3.1). The majority of the values were taken from two publications from the SpannEnD research group, who have experience in modelling the geomechanical properties of the crust across Germany (Ahlers et al., 2021; Ahlers et al., 2022). The geomechanical properties for each layer are shown below in Table 2.

Table 2: Geomechanical properties of each layer.

Layer/ Parameters	Thickness (km)	Constitutive model	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio [-]	Friction angle [°]	Cohesion (MPa)	Tension (MPa)	Dilation angle [°]
Sedimentary	2	Mohr-Coulomb	2300	30	0.25	38	10	5	7
Crystalline rock	8	Mohr-Coulomb	2750	70	0.25	55	25	5	8.6
Deep crust	20	Mohr-Coulomb	3000	80	0.25	40	30	5	5
Mantle	10	Mohr-Coulomb	3300	130	0.28	40	0	5	1

Some of the parameters were not included in the papers by Ahlers et al., 2021; 2022), Bulk modulus for the layers were calculated from the established relationship between Young's Modulus and Poisson's Ratio. Dilation angle was obtained from work conducted for SKB.

3. Modelling

Modelling was carried out using the FLAC3D 7.0 software developed by Itasca Consultants. FLAC3D is a three-dimensional (3D) geomechanical modelling package that is used across a variety of industries including oil and gas, mining, and nuclear waste storage. Whilst modelling was done in FLAC3D, a 3D modelling tool, the geological cross-sections used were constrained in the Y direction such that they provide a pseudo-2D plane approximation. The modelling approach was therefore a plane-strain method where the out-of-plane deformation was assumed to be zero. This approach was adopted given the short project timeframe while ensuring that the model inputs, testing and results could provide the foundation for a more detailed 3D model in the future. The Fennoscandian ice-sheet extended into northern Germany from the north, with the mapped margins of this ice-sheet forming an approximately ENE-WSW oriented boundary across Germany. Therefore a plane strain approach was considered appropriate for this initial phase of modelling.

3.1. Model sections

Modelling was carried out in two phases; the first involved creating a simplified layer-cake model of the Earth's surface which was used to understand the impact of the ice-sheets in the absence of any complex geology, followed by a second phase which used geological cross-sections from Germany. The simple model used idealised thicknesses (e.g. Allen and Allen, 2013) for each component layer of typical continental crust and included a thin mantle layer:

Table 3: Thicknesses of each layer for the simplified layer-cake model.

Layer	Thickness (km)
Sedimentary Rock	2
Crystalline Rock	8
Deep Crust	20
Mantle	10

This simple layer-cake model was used for initial sensitivity testing of various factors including ice-sheet thicknesses and geomechanical parameters the four geological layers. The model was constructed using grid cells with a dimension of 1km^3 resulting in a model dimension of 600km in the X axis and 40km in the Z axis. Ice-loading was applied to the top surface of the model (i.e. top of the Sedimentary Rock layer) from 0-300km from the left-hand post of the model. A visualisation of the simple layer-cake model is shown below:

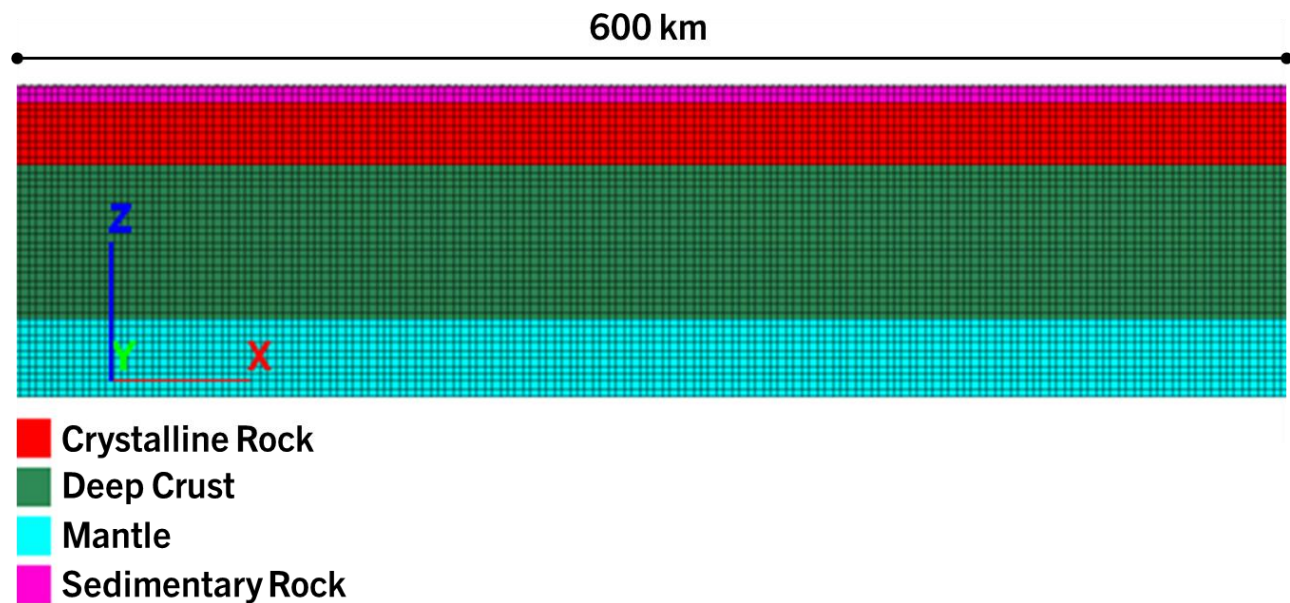


Figure 3: Visualisation of the simplified layer-cake model in FLAC3D. Model dimensions are 600km in the X axis and 40 km in the Z axis.

The complex cross sections were generated from surfaces provided to Amentum by the SpannEnD research group which have previously been published in academic journals (e.g. Ahlers et al., 2021). These surfaces were compiled from a wide array of sources outlined in their publication. These surfaces align with the four-components used in the simple model (i.e. Sedimentary Rock, Crystalline Rock, Deep Crust, and Mantle) with the top of crystalline basement and top of the lower crust being equivalent to Crystalline Rock and Deep Crust, while the Mohorovičić discontinuity is commonly used to represent the top of the Mantle. Maps showing the extent and depths of these surfaces are shown in Figure 4. Surface topography was modelled using a digital surface elevation model (DEM) for the whole of Germany derived from the shuttle radar topography mission (SRTM). The German DEM is available from the OpenDEM project at:

https://www.opendem.info/download_srtm.html

Four sections were chosen in consultation with the BGE. These sections were chosen to intersect the main crystalline rock sub-areas and cross the margin of the northern German ice-sheet. Two sections were oriented NE-SW to be perpendicular to the broadly WNW-ESE margins of the northern German ice-sheets advancing southwards from Fennoscandia (Figure 5). A third section was oriented NW-SE to perpendicularly intersect the Variscan structures which subdivide the various crystalline rock sub-areas. The final section was oriented N-S to intersect the Alps along the southern border of Germany. While the alpine ice-sheets have been noted to have been significantly smaller than the northern ice-sheets, the impact of the Alps was of interest and therefore modelled using this section. XYZ points for all four surfaces were extracted along the section traces (the map view line showing the trace of the cross-sections) in ArcGIS Pro using the Extract Value to Points geospatial tool. The extracted Z values contained some irregularities and spikes and required some smoothing to ensure successful gridding in FLAC3D.

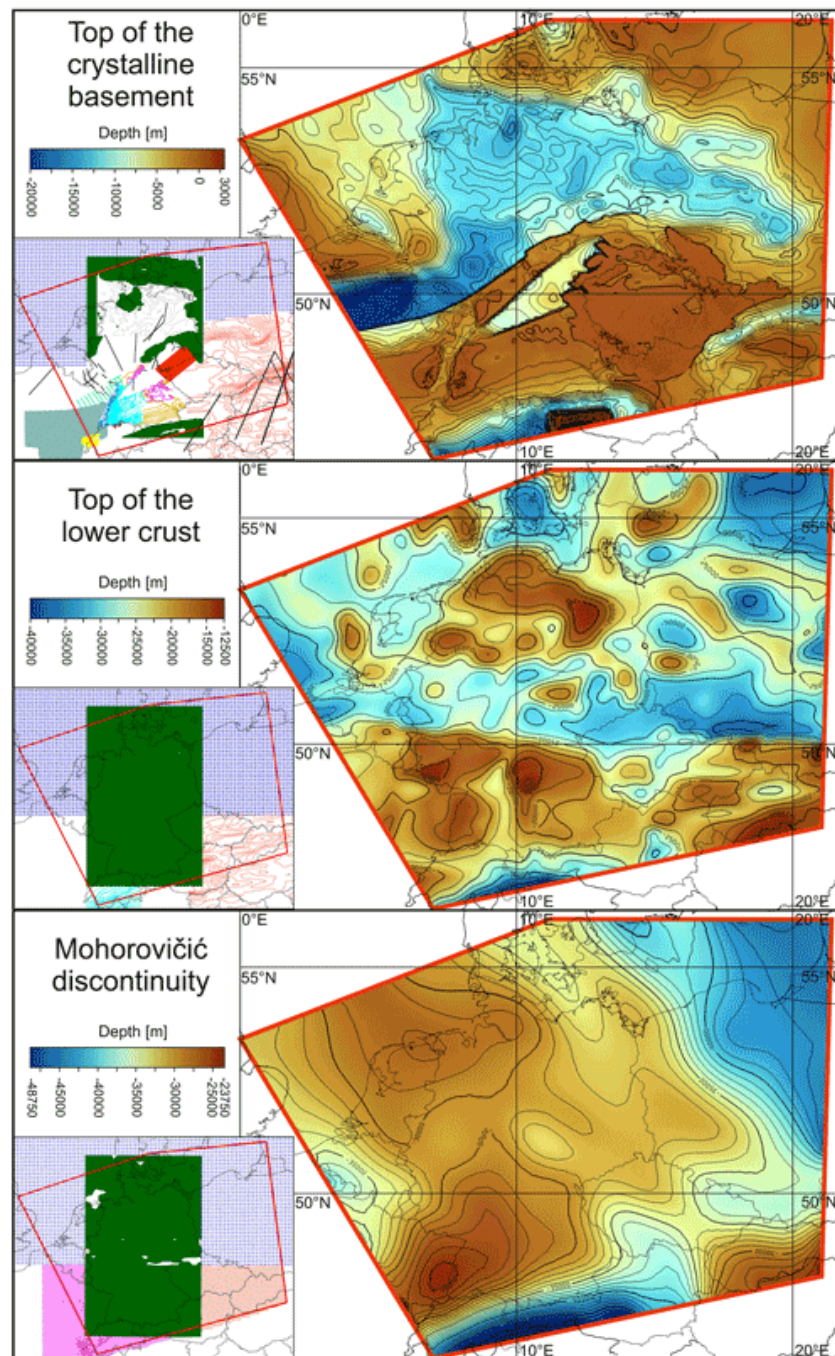


Figure 4: Depth maps for three surfaces provided by SpannEnD to Amentum.



Figure 5: Map showing the locations of the seven crystalline rock sub-areas, the locations of the four cross-sections and the maximum known extents of the various Quaternary ice-sheets. Please refer to Jacobs, 2024 for more details on ice-sheet extents and ages. Ice sheet data from Ehlers et al. (2011) and Fiebig et al. (2011). There are several geological features captured across the four cross-sections and the thick sedimentary section of the North German Basin is apparent on the northern side of each of the four

sections (Figure 6). These sediments thin onto the Mid-German Crystalline Rise, which is the location of most of the seven crystalline rock sub-areas, while the sediments in the Molasse Basin in the Alpine foreland are present on the southern margin of most sections.

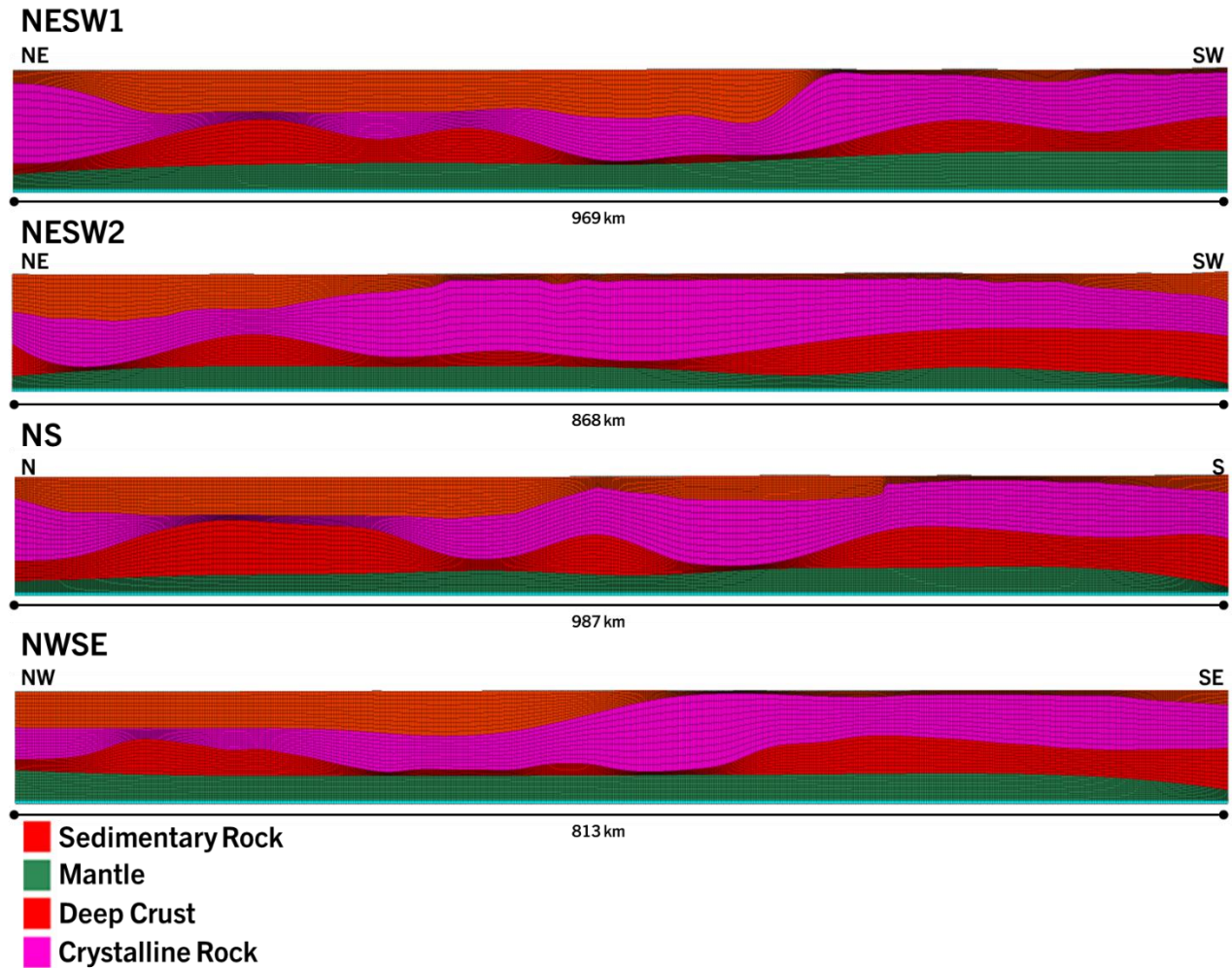


Figure 6: Cross sections showing the shape of the four layer model for each of the sections. Section length shown at base of each section. See Figure 5 for cross section locations.

3.2. Modelling ice loading

The ice load was applied to the model once the initial model state had reached equilibrium (with a model solve ratio set to 1e-6). In FLAC3D, the model solve ratio is a measure of the ratio of unbalanced force magnitude to the applied force magnitude across all cells within the model and is used to determine the convergence of a model during the solving process.

The ice load was calculated using the following equation:

$$\text{ice load} = \text{ice thickness} * \text{ice density} * \text{acceleration due to gravity}$$

Sensitivity analyses were conducted for the shape of the ice and also to look at whether the variation of density with depth would have an impact on the results.

There was ambiguity regarding the shape of the ice-sheet front during modelling. In nature, ice-sheets tend to have relatively consistent thicknesses in the core area, which rapidly tapers to zero thickness at the ice-sheet margins (e.g. Boulton et al., 2001; Schoof and Hewitt, 2013). Therefore, two end-member shapes were tested with the simple layer-cake model to understand the impact of changing ice-sheet shape on the resultant stress change (Figure 7):

- A uniform ice load 300km long.
- A trapezoidal ice load tapering from 3000m (3km) to 0m thickness (in the Z axis) from 0-300km along the X axis of the model.

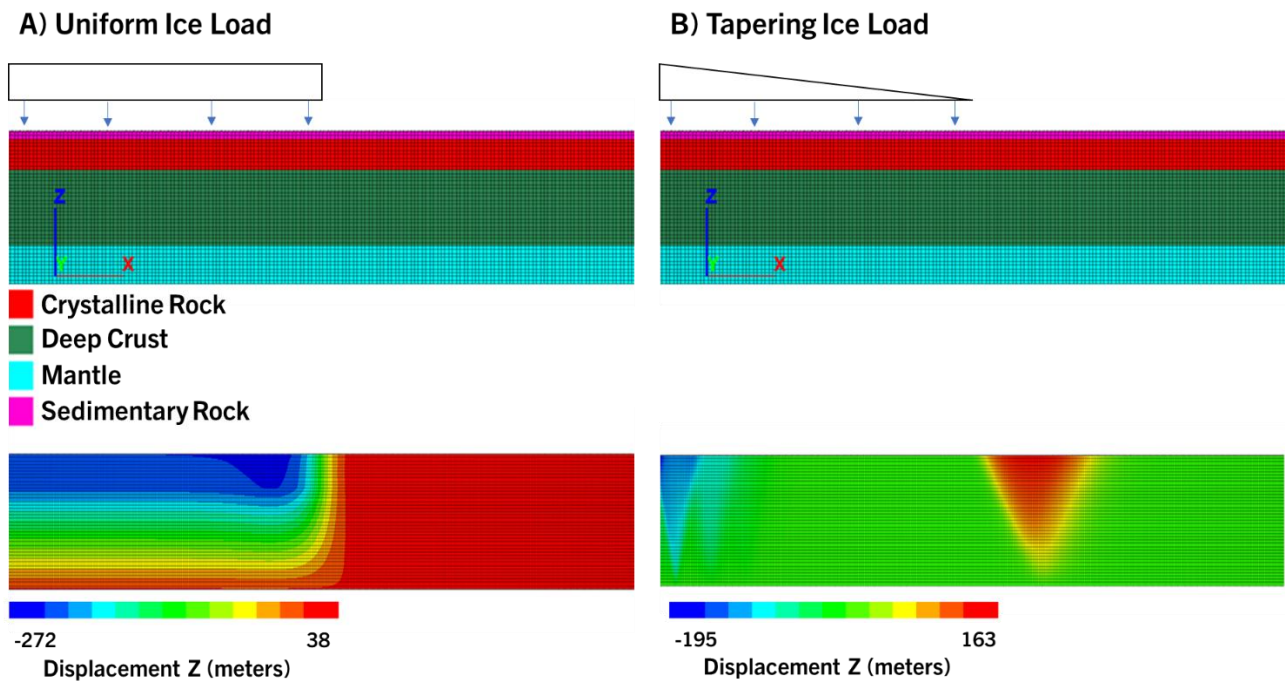


Figure 7: Schematic diagram demonstrating the shape of the ice load being applied for each of the uniform and tapering ice loads. Note the ice is illustrated schematically and not to scale. FLAC3D does not visualise the load itself, only the resultant change in the rock. Results show comparison of vertical displacement (Z displacement) for the simple layer-cake model when A) a uniform ice load is applied, and B) a tapering ice load is applied.

Figure 7 shows the variation in deformation when either a uniform or tapering ice load is applied. The uniform ice load results in a uniform negative displacement in the Z axis beneath the ice load on the left side of the model alongside a modest positive uplift in the Z axis in the area in front of the ice-sheet load on the right side of the model. There is a relatively narrow area of transition from depression to uplift circa 40km wide in the centre of the model. Conversely, the areas of maximum depression and uplift are more confined with the tapering ice load; depression is focused on a 35km wide area on the left margin of the model, with there likely being some impact from the model boundaries, while maximum uplift occurs in a triangular shape, 90km-wide at in the shallow Sedimentary Rock layer to

the right of the model centre. It was determined that the uniform ice load was a better representation of the natural processes (e.g. Figure 8) given the scale of the model and the 1km³ grid cell size.

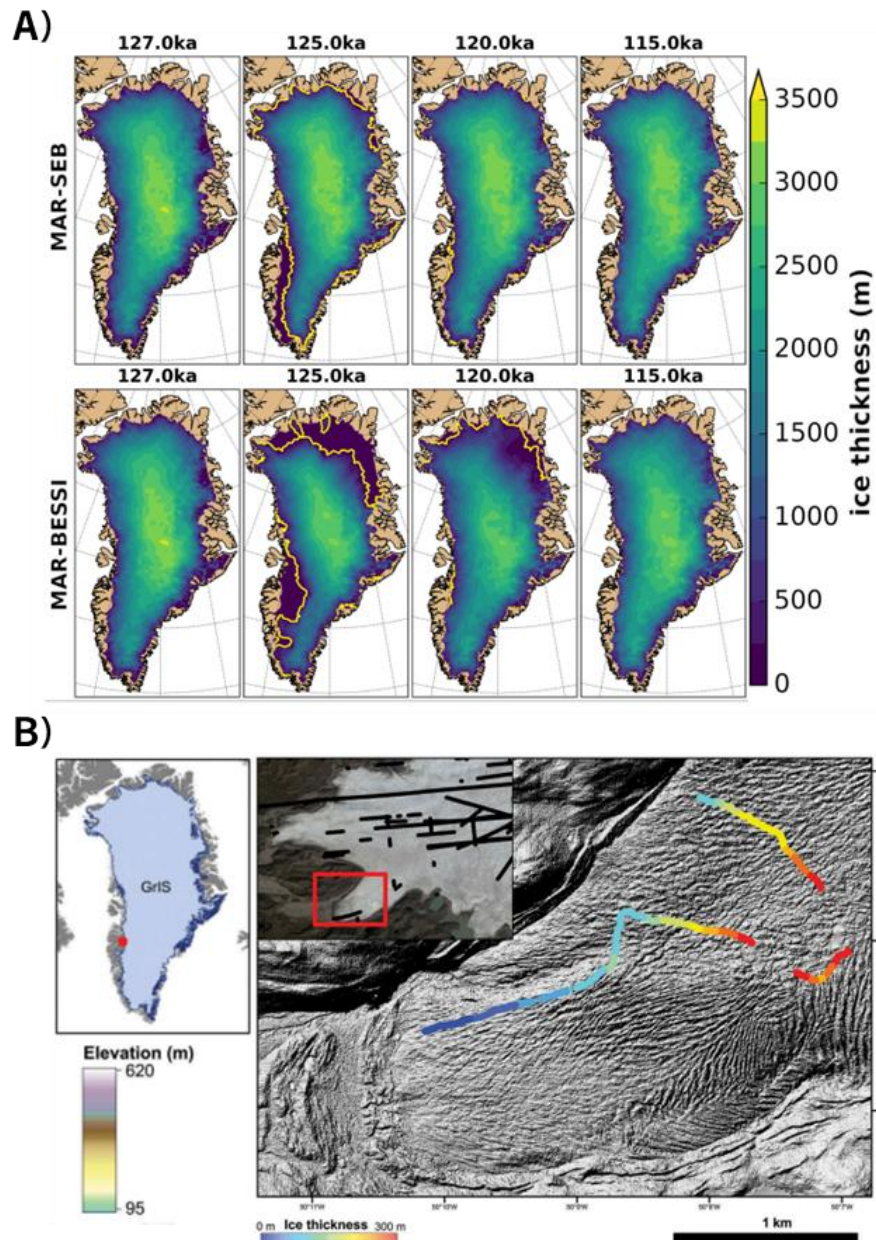


Figure 8: A) Ice sheet thickness for Greenland at indicated time steps. From Plach et al. (2018). B) Depth profiles acquired using Ground Penetrating Radar (GPR) over a section of the Leverett Glacier in Greenland. Modified from Ross et al. (2018).

The modelling of the ice load used two different ice thicknesses; these were 2000 metres and 3600 metres. These thicknesses were selected based on information derived from a world wide database

on glacier thicknesses. It is also noted that during the initial testing an ice thickness of 1800 metres was used.

During the modelling it was noted that the deformation caused by the ice did appear to be of the anticipated magnitude. Intuitively it was considered that deformation magnitudes reflect those resulting from the FIS, however, the modelling showed lower magnitudes of deformation. It became apparent that this appeared to be the result of two factors/processes:

- FLAC3D is not modelling the isostatic component of the mantle – discussed in Section 4.
- That the deformation, both downwarp and uplift, is controlled and dependent on the Mantle thickness. The models were initially run with a thin 20 km mantle. Looking at the thickness of the mantle in the Scandinavian area it is much greater than the equivalent thickness beneath Germany. Subsequent model runs included a much thicker more representative mantle thickness at approximately 60 km.

4. Results

Results for each of the four geological cross sections are shown below followed by a general discussion of trends and insights observed across the model. These are the results of the model run using a uniform ice thickness of 2000m. Additional model runs including those with thickened mantle and varying ice thickness are included in the FLAC3D files accompanying this report. The geological sections are displayed with four characteristics:

- The strength-stress ratio: used in FLAC3D as a local indicator of the model's current stress state and its proximity to failure. FLAC3D uses a default range of 1-10, where a value of 1 represents shear failure.
- The state of each zone: provides the current plasticity state for each zone (i.e. grid cell) in the model and captures if the zone experienced elastic deformation or underwent permanent plastic deformation, and notes if this was shear or tensile failure.
- The volumetric strain increment (trace of Epsilon): measures the volumetric change of each grid cell within the model. Positive values indicate cells which have increased in volume, while negative values indicate cells have decreased in volume.
- von Mises equivalent strain increment: measures the shape change (i.e. distortion) of grid cells without volumetric change. Larger values of von Mises equivalent strain increment indicate significant shape change in the grid cell, while smaller values indicate the grid cell has maintained its shape.

These visualisations were requested by the BGE. The following sections are shown with a 2X vertical exaggeration to make the results more easily visible.

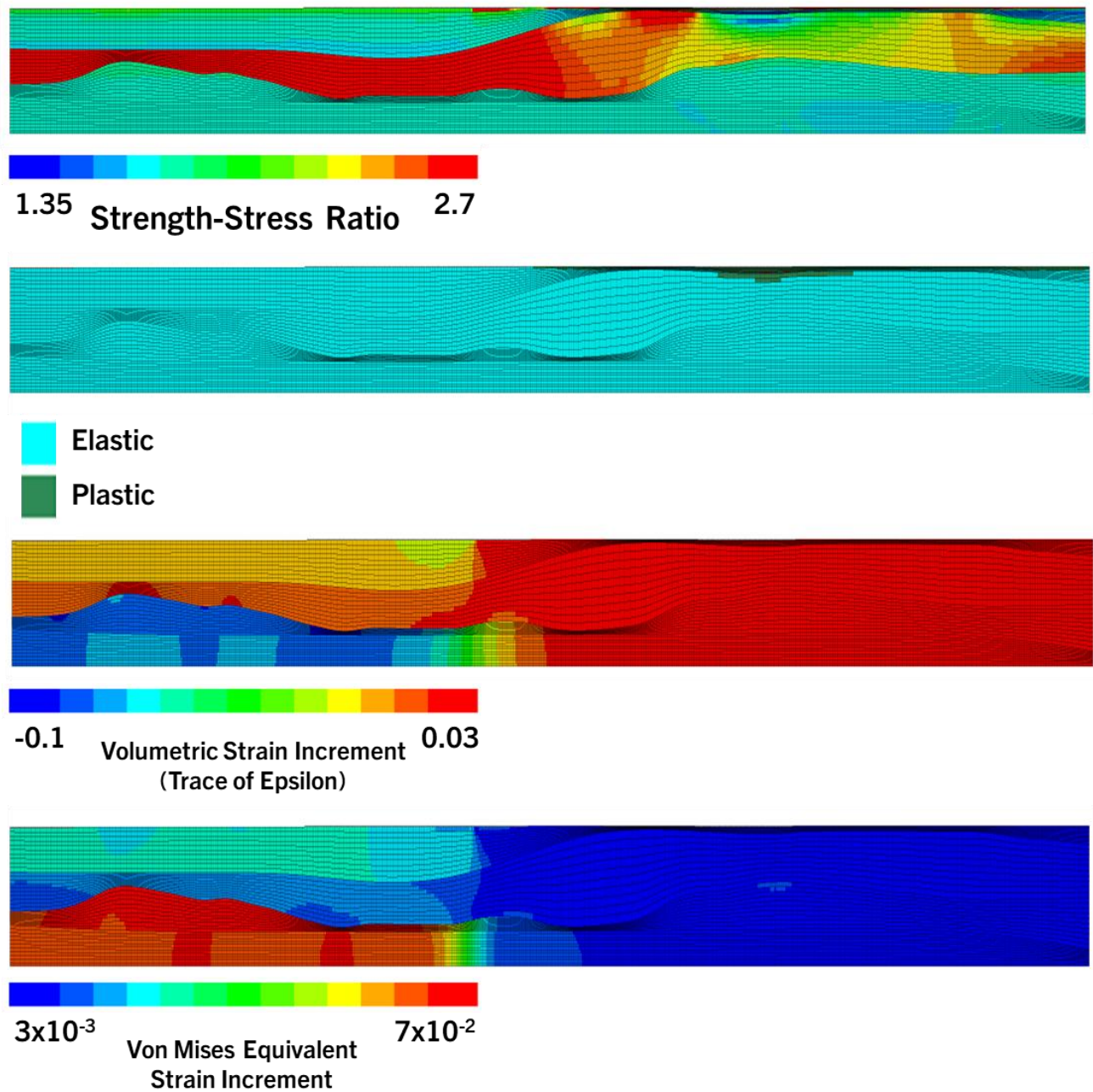


Figure 9: Results for the NESW1 section. See Figure 5 for line location.

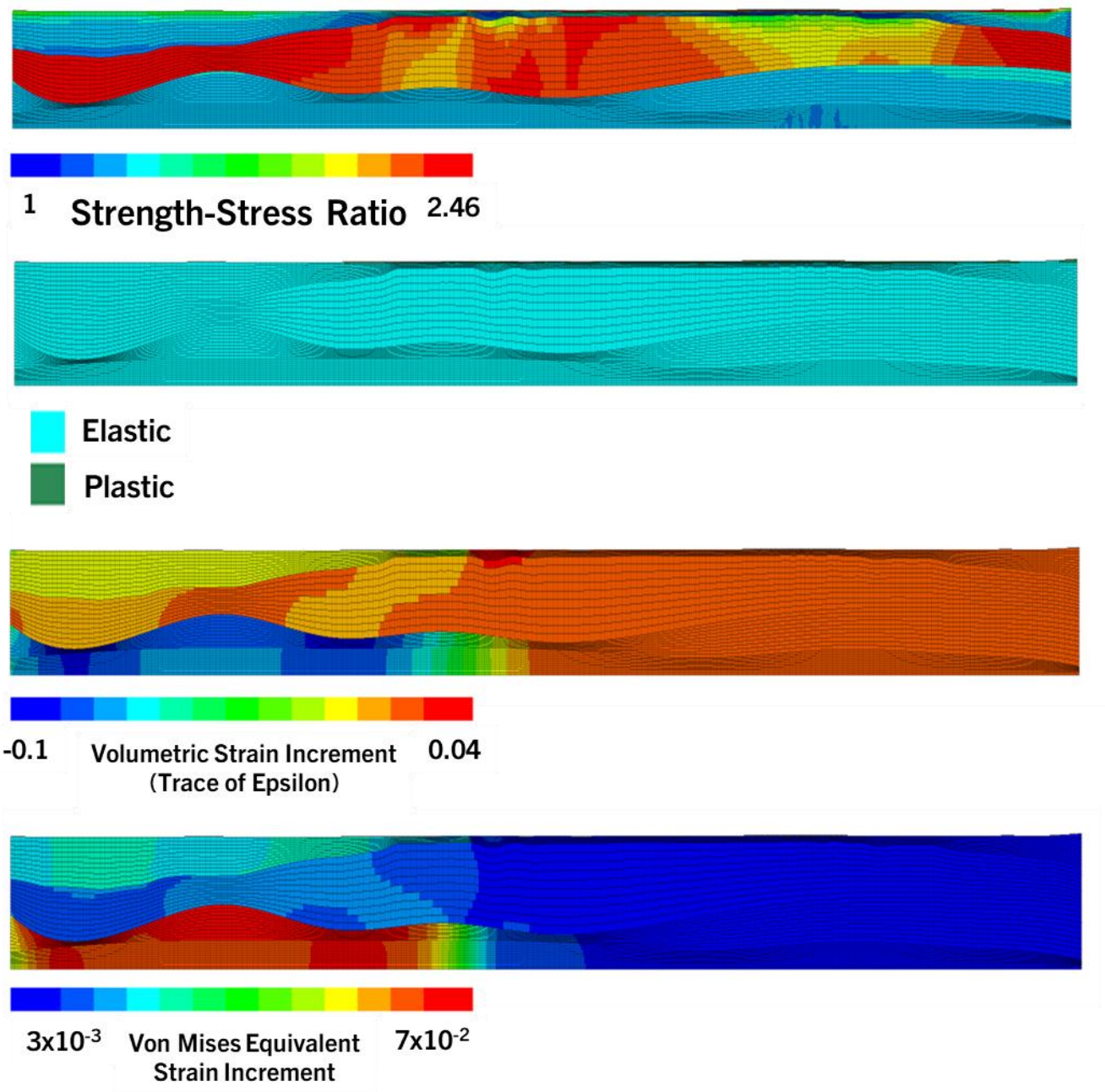


Figure 10: Results for the NS section. See Figure 5 for line location.

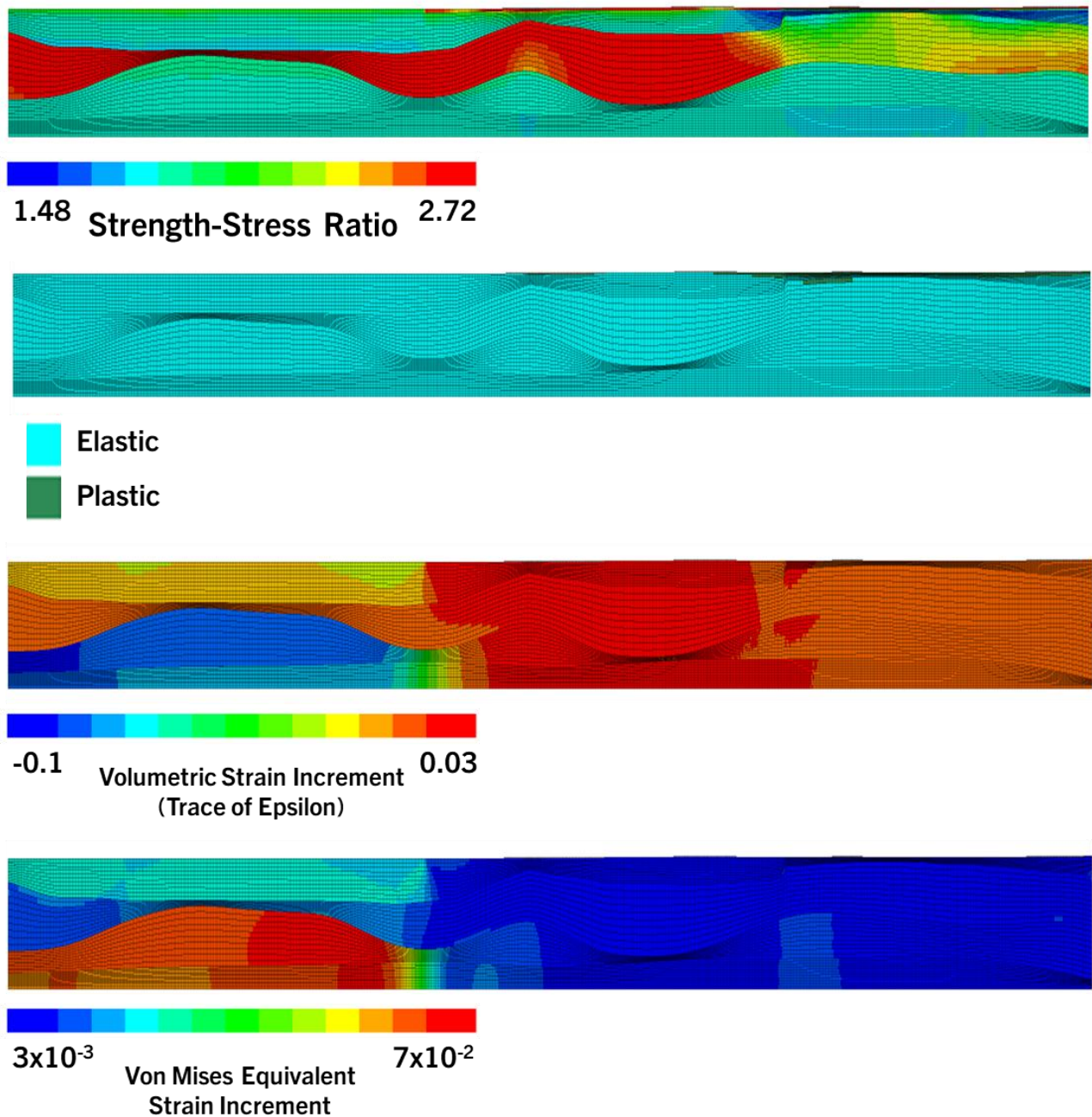


Figure 11: Results for the NESW2 section. See Figure 5 for line location.

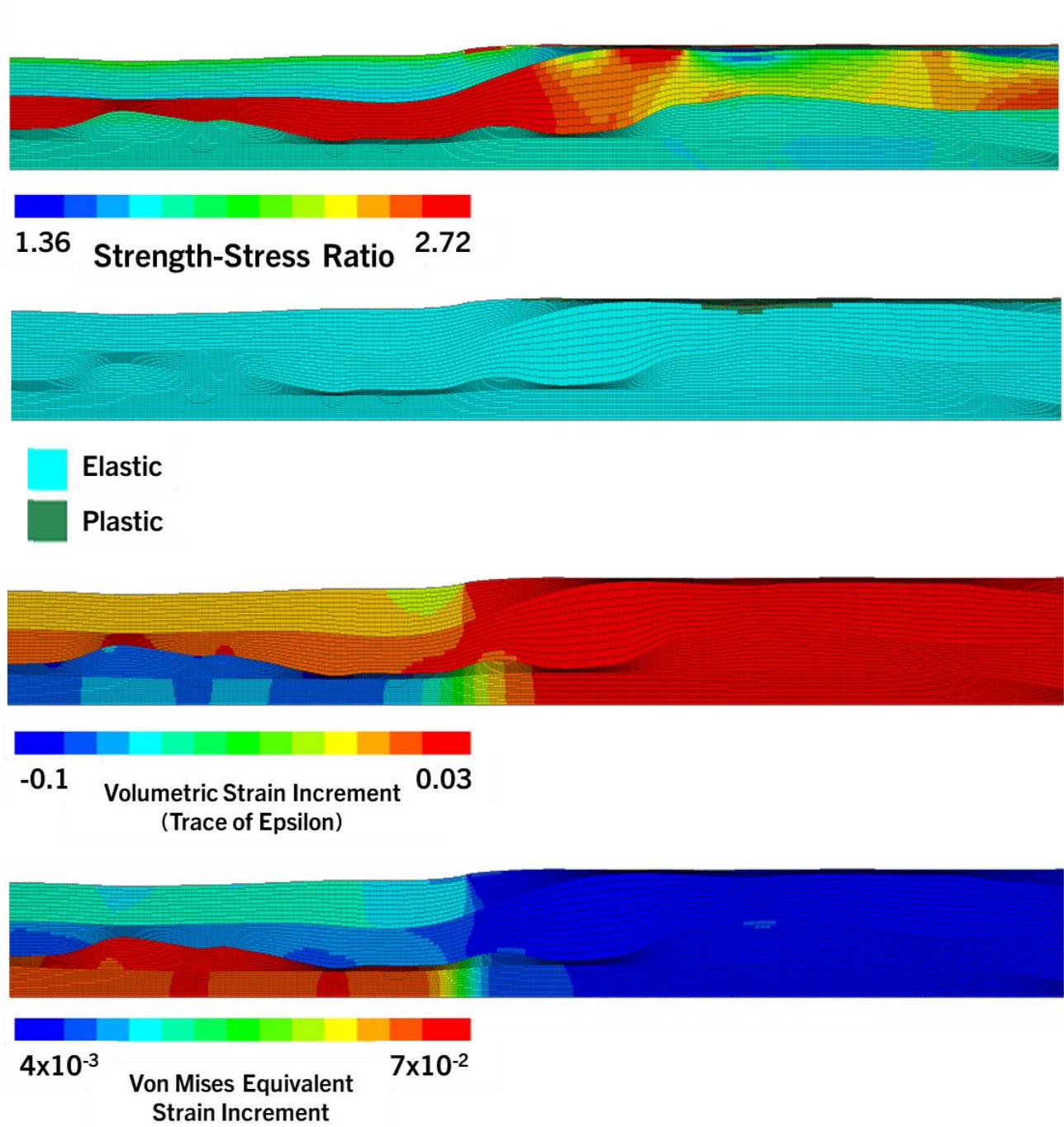


Figure 12: Results for the NWSE section. See Figure 5 for line location.

4.1. Discussion of results

The results for all four sections are relatively similar, given they transect the same geological features of Germany, namely the North German Basin, Mid German Crystalline Rise and the Molasse Basin. All

models indicate some tensile failure has occurred in the shallow area of crystalline rock in the Mid German Crystalline Rise (the upper 1-3 kilometres of the model).

Volumetric strain shows that grid cells in the deep crust and the mantle largely underwent volume decrease beneath the area loaded by the ice-sheets. This would be expected given the compression expected beneath an area experiencing increased loads due to ice-sheets. The grid cells on the right hand side of all the models (i.e. the south of Germany) experienced a minor volumetric increase. While not directly reflecting the exact process of mantle isostasy and glaciostatic uplift (see section 4.6), this does partly reflect what has been observed occurring in the areas adjacent to ice-sheet margins by various Quaternary scientists (e.g. Stewart et al., 2000).

The von Mises strain equivalent follows a similar pattern to the volumetric strain increment, with the greatest shape change occurring in the deep crust and mantle beneath the area where the ice-sheet load is applied, while smaller shape changes occur in other parts of the model. There is also a noted zone of shape change in the sedimentary section beneath the ice-sheet load which is not reflected in the underlying crystalline rock. This is likely due to the lower Young's modulus of the sedimentary layer (30) relative to the higher Young's modulus of the deeper layers (70-130).

These results broadly reflect the observations of the natural geological processes being modelled. However, the limitations of FLAC3D in reflecting the full extent of these processes has to be acknowledged before they are applied to any further technical assessment of rock suitability. With this caveat in mind, it was chosen not to use the results of these 2D sections to generate gradational lines that could be applied to the impact of glaciation and common-risk segment maps produced during the earlier phase of the crystalline rock study (Jacobs, 2024). This has been discussed with the BGE during project update calls and is explored in detail in section 5.

4.2. Limitations of modelling approach

Some key aspects of the natural systems of the Earth's crust and its response to ice-sheet loading were not captured in the modelling approach taken using FLAC3D. These are explored in the following sections.

4.2.1. Modelling of the mantle

FLAC3D only models the response of solids to applied forces and does not model fluids. This is appropriate for the sedimentary rock, crystalline rock and deep crust layers. However, the mantle is typically understood to be a non-Newtonian fluid, which means its viscosity changes depending on the stress and strain rate being applied to the fluid. These behave like a solid when rapid stress is applied (e.g. an earthquake) and a viscous fluid when slower and prolonged stresses are applied (e.g. the advance and retreat of an ice-sheet). The FLAC3D model presented here does not consider this effect, and potential methods to include it are discussed in detail in section 5.

4.2.2. Modelling ice-sheet advance

The ice load was applied instantaneously in this project. Real ice-sheets advance at a rate of 10s to 100s of metres per year and this advance will have an associated impact on the distribution and change of stress in the subsurface (e.g. Robin, 1955; Batchelor and Christie, 2023). This is not captured in the models due to the time constraints of the project. Future modelling work should therefore address this aspect of ice-sheet development by adapting the approach into a transient study rather than the steady-state approach taken at present.

4.2.3. Further grid refinement

For the simple model considered here with constant layer thicknesses, a uniformly spaced rectangular grid was employed for each layer. For the variable thickness model, a grid mapping approach was deployed to map a regularly spaced grid onto the variable thickness layers, such that at each individual position along the surface the grid cells were regularly spaced. Future work may wish to consider alternative gridding methods, and to refine the grid further in the upper 1km of the model which is most relevant to GDF siting.

5. Future work and model refinement

As noted in previous sections, there are limitations with the current modelling approach. The key process missing from the modelling approach is the modelling of the mantle as a non-Newtonian fluid rather than as a solid.

One potential option to represent the liquid mantle may be to modify the lower boundary condition in FLAC3D, so that normal velocity is defined as proportional to the difference between normal stress in the crust and mantle pressure, where mantle pressure is defined as for a hydrostatic liquid. This would not physically represent the mantle dynamics, however, it would ensure that an equilibrium solution would exhibit the expected balance between normal stress and hydrostatic pressure. This option was explored during the project, however, it was determined that this boundary condition could not be specified using the pre-existing FLAC3D command language (personal correspondence with FLAC3D technical support). It may still be possible to implement such a boundary condition either using FISH scripting within FLAC3D, or using a custom time-stepping scheme whereby the boundary condition is altered dynamically (e.g. running FLAC3D iteratively through an external script), however, it was identified that this may present convergence challenges, and there was not time to attempt such a custom implementation within the short timescales of the work.

A full treatment of the problem including the mantle dynamics would require the application of coupled modelling, so that fluid dynamics for a non-Newtonian mantle is coupled together with solid mechanics for a solid crust. It is appreciated that the identification of a two-dimensional interface between solid crust and liquid mantle would itself be an imperfect description of reality, however, this may be considered a reasonable approximation for a next stage of modelling.

It may still be possible to utilise FLAC3D within a coupled modelling approach, by calling the code iteratively via an external script which alters the lower boundary condition dynamically in conjunction with an independent simulator for mantle physics.

In addition to this, other options for coupled modelling have been discussed with the BGE and a high-level roadmap for follow-up steps are outlined below. Two software packages were identified that could provide coupled modelling functionality for future work:

- COMSOL Multiphysics, a commercial multiphysics software.
- OpenGeoSys, an open-source and community developed multiphysics software.

Each of these offers different benefits to the study of crystalline rock and its response to ice-sheet loading. COMSOL is a well-established commercial multiphysics software that is used in a variety of industries. Amentum have extensive experience using this software in the nuclear industry and also have a strong relationship with the development and support team at COMSOL. There are also published examples of academic research which has modelled the Earth's crust and mantle, with the mantle represented as a non-Newtonian viscoelastic fluid (Lee and So, 2019).

Conversely, OpenGeoSys is an open-source software project that is developed by the UFZ Leipzig with support from several German universities. The BGE have indicated that there is strong links between the operators of the OpenGeoSys project and members of the BGE team. This would facilitate the potential for refined software solutions which could address the shortcomings of the current modelling approach.

One approach would be to carry out modelling in both software suites to benchmark results. A high-level methodology for use in COMSOL is outlined below:

- Choosing suitable model physics:
 - Sedimentary rocks, Crystalline Rocks and Deep Crust can be treated as in FLAC3D.
 - The Mantle can be modelled in three ways, dependent on desired physics:
 - A Newtonian fluid with adapted viscosity, density and other parameters (simplest approach).
 - An inelastic non-Newtonian fluid with a non-linear relationship between shear stress and shear rate.
 - The constitutive relation could be expressed in terms of apparent viscosity.
 - Several predefined inelastic non-Newtonian constitutive models are available (e.g. Power Law, Carreau, Bingham-Papanastasiou).
 - A viscoelastic non-Newtonian fluid where the curve of shear stress to shear rate tends towards the shear-stress axis.
 - The constitutive equation defines the extra elastic stress contribution not included in the two previous methods.
- Meshing:
 - Use a moving mesh to model deformation. The mesh would be remapped at different time steps to provide accurate representations of the geometry, mesh and physics.
 - Mesh refinement can be used to improve accuracy in key regions, particularly in GDF depth range of 1-2km.
- Computation time could be expected to vary between hours to a day dependent on model complexity.

It would be recommended that modelling be undertaken first in 2D, using the same surfaces from the models built in FLAC3D, before expanding the model into the 3D domain using the full surfaces provided by the SpannEnD team. It would be beneficial to build and run models in OpenGeoSys in parallel to modelling work in either COMSOL or FLAC3D. This would provide scope to explore the feature set of OpenGeoSys, as well as result in a benchmark model which could be compared with the outputs from other codes.

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