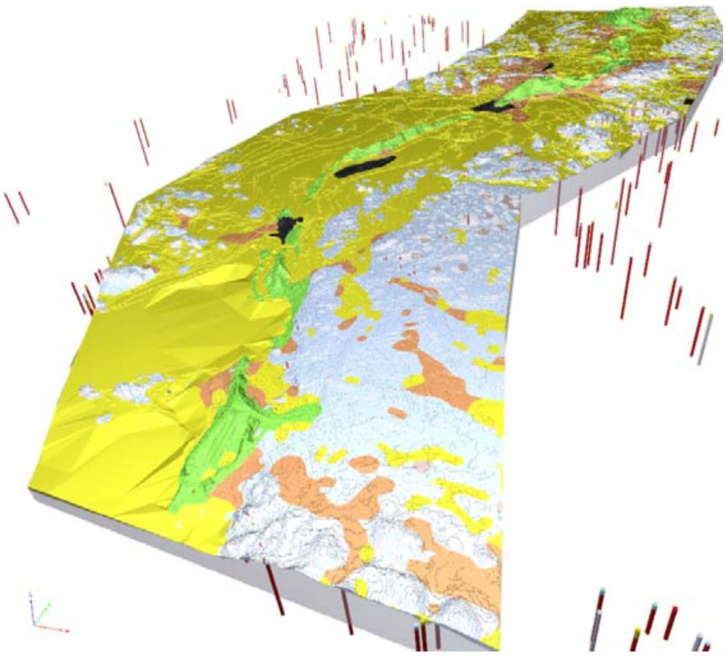
Enköping Esker Pilot Study - Workflow for Data Integration and Publishing of 3D Geological Outputs

GeoAnalytics and Modelling Programme

Open Report OR/17/003



BRITISH GEOLOGICAL SURVEY

GeoAnalytics and Modelling PROGRAMME

OPEN REPORT OR/17/003

Enköping Esker Pilot Study - Workflow for Data Integration and Publishing of 3D Geological Outputs

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Enköping Geological Model with boreholes

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) which describes the BGS role for helping to develop a workflow for preparing data for use in the SubsurfaceViewer (INSIGHT) software and exporting the data outputs into various formats for publication for the Swedish Geological Survey (SGU) into the following:

- 3D Geological Model Web Viewer
- 3D PDF (Cross-sections, boreholes, Shells)
- 3D Shapefiles (Cross-sections, Boreholes)
- Grids (ASCII)
- Minecraft
- Deployment in GeoVisionary Version 3
- Groundhog Version 1.7

In addition to this, BGS hosted a 2-day workshop at their Keyworth office to present the results and finalise outputs from the geological model for delivery to SGU. I would like to thank the following people on this project for making the above possible:

Steve Thorpe

Andy Bean

Rachel Heaven

Ben Wood

Holger Kessler

Jonathan Lee

Acknowledgements

In addition to the BGS staff acknowledged in the Foreword, we would like to thanks Hans-Georg Sobisch (INSIGHT) who kindly allowed BGS to have a 6-week demo license of the SubsurfaceViewer to test inputs and outputs from this software into BGS systems for 3D Model publication.

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Summary

This report describes the workflows for preparing the data for constructing and publishing a geological model of the Enköping Esker, Sweden. This pilot study was a collaborative effort between the British Geological Survey (BGS) and Swedish Geological Survey (SGU). The main role of the BGS was to help prepare the data for the geological model, provide advice about the construction of the model, technical check the model and create the publication methods for the dissemination of the model. The main role of SGU was to construct the geological model using the SubsurfaceViewer software (INSIGHT).

The following publication methods were deployed:

- Synthetic Geological Model Web Viewer
- Minecraft
- 2D and 3D shapefiles
- ASCII grids (Top, Base, Thickness and Rockhead (base of superficial deposits))
- Groundhog Desktop compatible project files and set up
- GeoVisionary v3 compatible project files and set up
- Subsurface Viewer files
- GOCAD-SKUA surfaces (.ts) – top, base and shells

A number of suggestions were made by the BGS to improve the workflow methodology. These included:

- Using Groundhog in the initial stages of model development to minimise snapping and model checks in cross-section
- Bathymetry would have improved the modelling of the distribution of superficial deposits at the lake bed surface
- Using the Unlithified Coding Schema (Cooper et al 2006) for the coding of boreholes
- Ensuring that the borehole index information is correct (start heights) which can reduce the error in the elevations when correlating stratigraphy
- Looking at stochastic methods for modelling lithofacies in eskers
- Developing simple visualisations of uncertainty in 2D based on quantitative information

1 Introduction

BGS and Swedish Geological Survey (SGU) collaborated within this project to construct a geological model of an esker in Enköping, southern Sweden. An esker is a long sinuous ridge of predominantly coarse-grained sorted sediments that were deposited by glacial meltwater within ice-walled channels which flowed either beneath or within the glacier (Warren & Ashley, 1994). Eskers are common glacial landforms in Sweden and other formerly glaciated areas, including elsewhere in Scandinavia like Finland, and are important local sources of groundwater (Kløve et al., 2012). The aim of the project was to conceptualise the geology to aid planners, decision makers, politicians and the public to better understand the subsurface conditions for the protection and abstraction of groundwater. The BGS role in the project was to provide advice and support with regards to:

- Data input into the geological
- The geological model construction workflow
- Data output, deployment and publishing of the model
- Scope out and deliver the model in Groundhog Desktop, 3D PDF and Web GIS

The role of SGU was to construct the geological model and develop methodologies based on those advised by the BGS for constructing further geological models for eskers using a cross-section based approach for constructing 3D geological objects (Kessler et al, 2009). The model was to mirror the geological model constructed in Uppsala (Jirner et al, 2016) using the SubsurfaceViewer software (INSIGHT).

2 Project Plan

2.1 OBJECTIVES

The initial objectives of the project were:

From Eva Jirner (SGU)

1. ‘A conceptual geological model for planners, decision makers, politicians and citizens in general.
   (Use Uppsala Esker model as template – explain geology, and make planners aware of the subsurface and groundwater)
2. Create a base for effective protection measures for the aquifer
3. Input for groundwater simulations with different tools
   (FeFlow and ModFlow)
4. Visualisation in 2D and 3D

   We also want to take part of your competence concerning:

5. Structured work flow in general
   (From maps/boreholes to cross-sections to model to visualisation)
6. Structured handling of model in data (boreholes, profiles...)
   (Boreholes in different databases in Oracle, not well structured – changing to SQL server Cross-section – nothing implemented as yet’

2.2 TIMESCALE

November 9th 2016 to 22nd December 2016

Date of visit to BGS = $8^{th}/9^{th}$ December 2016

Timescale revised after workshop deadline 6^{th} January 2017

2.3 PROJECT PLAN

From the intial project objectives as stated in section 2.1, the following plan was implemented to prepare the data (Section 3), construct the model (Section 4 and 5) and deliver the outputs in the various formats agreed with SGU (Section 6).

2.3.1 Plan Outline

BGS Role:

1. Provide advice and support during data preparation, modelling and data output
2. Help prepare data for geological model construction and….
3. Document and report data formats required for use in geological modelling and visualisation (GeoVisionary)
4. QA of the geological model produced using BGS standard procedures for QAing GSI3D models.
5. BGS to action and deploy following data outputs in conjunction with SGU:
    1. Grids (to be loaded into FeFlow or ModFlow)
    2. 3D PDFs – Shells, cross-sections and boreholes
    3. 3D Shapefiles of cross-sections and boreholes
    4. Web based synthetic outputs (akin to Geology of Britain Viewer) hosted by BGS (Andrew Bean)
    5. Deployment in GeoVisionary v3
    6. Groundhog Desktop project
6. BGS to scope out and document the requirements for the following outputs:
    1. Groundhog Desktop for borehole and data access
7. Organised 2-day workshop at BGS to discuss (8^{th}-9^{th} December 2016):
    1. Model workflow – lessons learned
    2. Data storage and access – recommendations
    3. Data publication and delivery
    4. Next steps – Training, further model deployment, future collaboration,

SGU role:

- Provide data and information about the data (metadata) to BGS for preparation for geological modelling
- To construct the geological model of the Enköping Esker in the SubsurfaceViewer ahead of the Workshop
    - Model Construction in SubsurfaceViewer
- Provide model to BGS for QA and model output initiation
- Contribute to ‘Geology’ of report in style of BGS model metadata report

2.3.2 Plan Timeline

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
When	7 –11 Nov	14 – 18 Nov	21-25 Nov	28 Nov – 2 Dec	5 – 9 Dec	12 – 16 Dec
What	-Data Preparation -Report (Data Preparation Spec)	-Model Construction	-Model Construction	-QA -Report	-Model Publication Outputs -Workshop	-Finalise Report and outputs
Who	Ricky/Eva	SGU	SGU	Steve Thorpe and Jon Lee	Ricky, Andrew and Steve T	Ricky, Steve T and Jon

2.3.3 Detailed Project Plan

Project plan details and time allocations:

1. Provide advice, support and help for data preparation for Subsurface Viewer Software
    a. DTM
    b. Boreholes
    c. Geological Map Linework
    d. GVS
    e. Legend
    f. Sections – GPR and Seismic sections
    g. Others – Superficial Deposits Thickness, GEOSIGMA data

Time allocated = 2 days

2. Document and report data formats required for use in visualisation (GeoVisionary)
    a. Boreholes
    b. Terrain
    c. Gridded data (Superficial Deposits Thickness/Rockhead)
    d. Model outputs (Shell, Cross-sections, Platypus Voxel model)
    e. Geological Linework
    f. Buildings? (See Luz for city data download using Info??)

Time allocated = 0.5 days

3. Technical QA of model (Calculation checks in cross-sections, unit thickness checks/helper sections) using the BGS QA procedures (See Appendix)

   a. Using SubsurfaceViewer or GSI3D to check model in cross-section using the Post Model Calculation Checks procedure
   b. Check thickness of units using ArcGIS – add helper sections in areas where deposits are not calculating any thickness but should be by checking against the envelopes

Time allocated = 2 days

4. Geological check of model using BGS QA procedures (See Appendix)
   a. Action model checks

Time allocated = 2 days

5. Create and deploy the following outputs from the geological model:
   a. ASCII Grids of the TOP, Base and Thickness (FeFlow grids can be exported directly from the SubsurfaceViewer)
   b. 3D PDFs – Shells, cross-sections and boreholes
   c. 3D Shapefiles of cross-sections and boreholes
   d. 2D GIS layers (Envelopes, Sections and borehole locations) – GSI3D conversion of the project
   e. Web based synthetic outputs (akin to Geology of Britain Viewer)
   f. Test output to Minecraft (Steve Thorpe)

Time allocated = 7 days

6. Groundhog Conversion of project
   a. DTM
   b. Boreholes
   c. Geology lines
   d. Cross-sections
   e. GVS
   f. Legend

Time allocated = 1 day

7. Scope out and document the requirements for Groundhog Desktop for borehole and data access (Will be in response to what is learned in workshop) – this was not implemented as no information was forthcoming at the workshop with regards to and the time was used to

Time allocated = 1 day

8. Organise 2-day workshop at BGS to discuss (**8th-9th December 2016**, I3DVF – Keyworth, Nottingham):

a. Model workflow – lessons learned
b. Data storage and access – recommendations
c. Data Delivery
d. Next steps – Training, further model deployment, future collaboration, Groundhog Desktop enabled

Time allocated = 2 days

9. Report

Write project plan and report.

Time allocated = 2 days

Total of BGS time required = 19.5 days

2.3.4 Post Workshop – Plan

After the workshop, it was decided that BGS would take on the role for the technical checking of the Enköping geological model using the standard checking procedures used for all BGS GSI3D models. A copy of the checking document is in the appendix. The main aspects of this checking procedure include:

- Snapping all sections to cross-sing sections, outcrop and subcrop (this was undertaken in Groundhog Desktop as explained sections 5.7 and 6.5)
- Ensuring the units calculate correctly – cross-section calculation checks and checking for thickness anomalies
- Unit names and cross-sections names are consistent

This work was undertaken as a bolt-on to the main project above. A further 5 days was added to the project for this task and was undertaken in the period between 13th December 2016 and 6th January 2017 (taking into consideration the intervening Christmas Break).

3 Data

Detailed description about data provided by SGU to BGS for preparation into 3D modelling software.

3.1 PROJECTION SYSTEM

SWEREF99_TM

WKID: 3006 Authority: EPSG

Projection: Transverse_Mercator

False_Easting: 500000.0

False_Northing: 0.0

Central_Meridian: 15.0

Scale_Factor: 0.9996

Latitude_Of_Origin: 0.0

Linear Unit: Meter (1.0)

Geographic Coordinate System: G

Angular Unit: Degree (0.0174532925199433)

Prime Meridian: Greenwich (0.0)

Datum: D_SWEREF99

Spheroid: GRS_1980

Semimajor Axis: 6378137.0

Semiminor Axis: 6356752.314140356

Inverse Flattening: 298.257222101

3.2 AREA OF INTEREST

Area of interest: Enköping.

Enkoping is situated near Lake Mälaren, about 78 km west of Stockholm and has approximately 22 000 inhabitants. It is also close to other large Swedish cities such as Uppsala and Västerås.

The total area that was under consideration 126 ^{2}km. The total area of the calculated model was 46 ^{2}km which was buffered around the central area in which contained the esker itself (Figure 1).

The depth to which the model was to be modelled was to the base of the superficial deposits (i.e. geological rockhead), with an undifferentiated bedrock unit forming the base of the model. The maximum thickness of superficial deposits encountered beneath the study area was 46 m according to the national superficial deposits thickness model (Section 3.8)

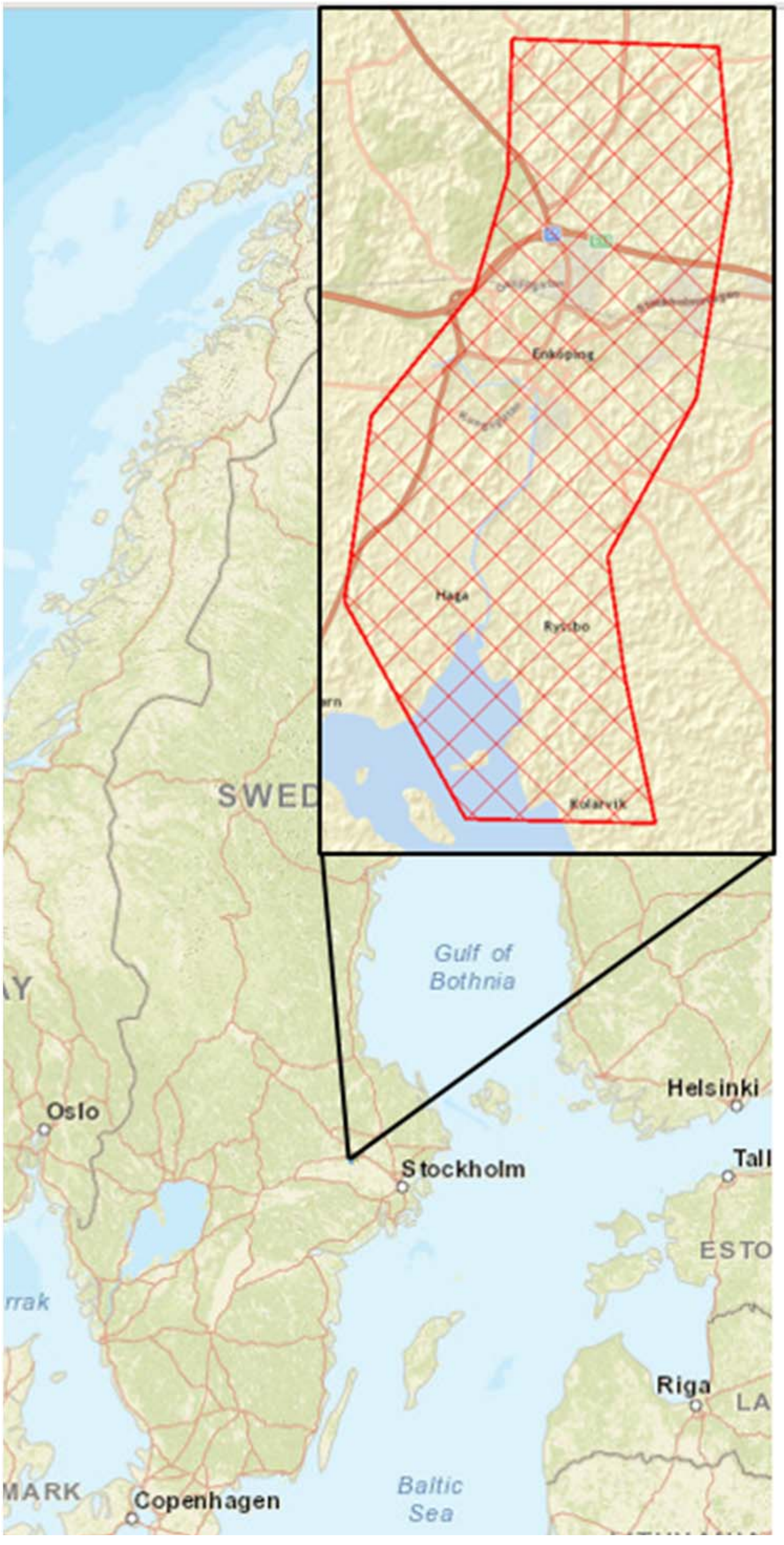
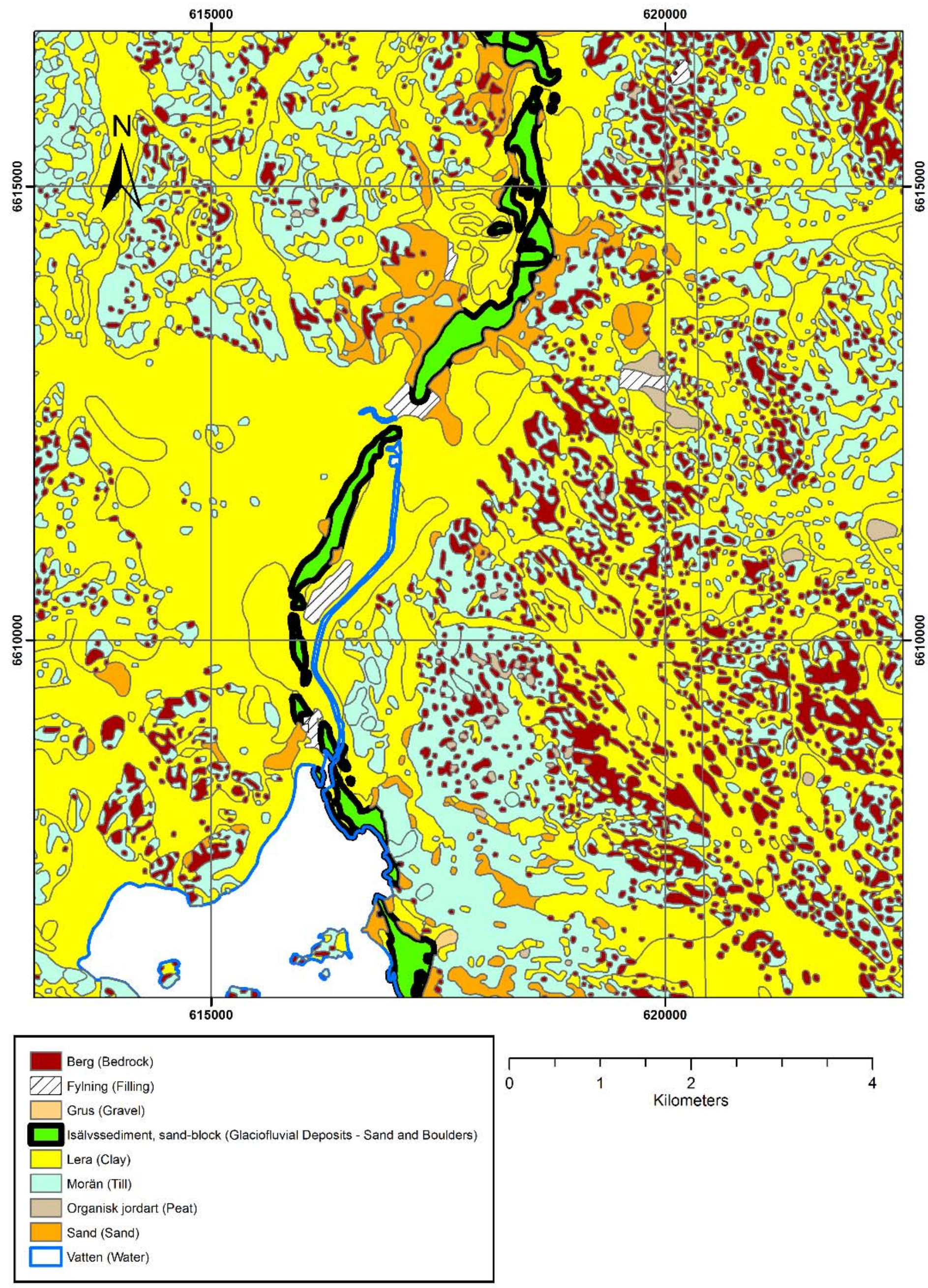


Figure 1 Enköping Location and Model Boundary

(ESRI Streets Base Map)

3.3 GEOLOGICAL MAP LINEWORK

The geological map provided is 1:50 000 scale and shows the main lithological units with no stratigraphic sub-division. The surficial geology of the area is dominated by clay and till with the esker itself composed of a mixture of sand, boulders and clay (Figure 2). The esker feature (Isälvssediment) is highlighted by the black outline in the figure below, showing the surface



distribution of the esker.

Figure 2 Quaternary Geology Map

3.4 BOREHOLES DATASETS

Three borehole datasets have been provided in Excel and Shapefile format. These boreholes were missing a start height (collar height) value. The surface elevation value from the DTM was used as the ground level value. The boreholes are classified based upon their bulk lithological properties and possess a varying degree of detail. A summary of the borehole datasets provided are below including a map showing the distribution of the borehole datasets (Figure 4),

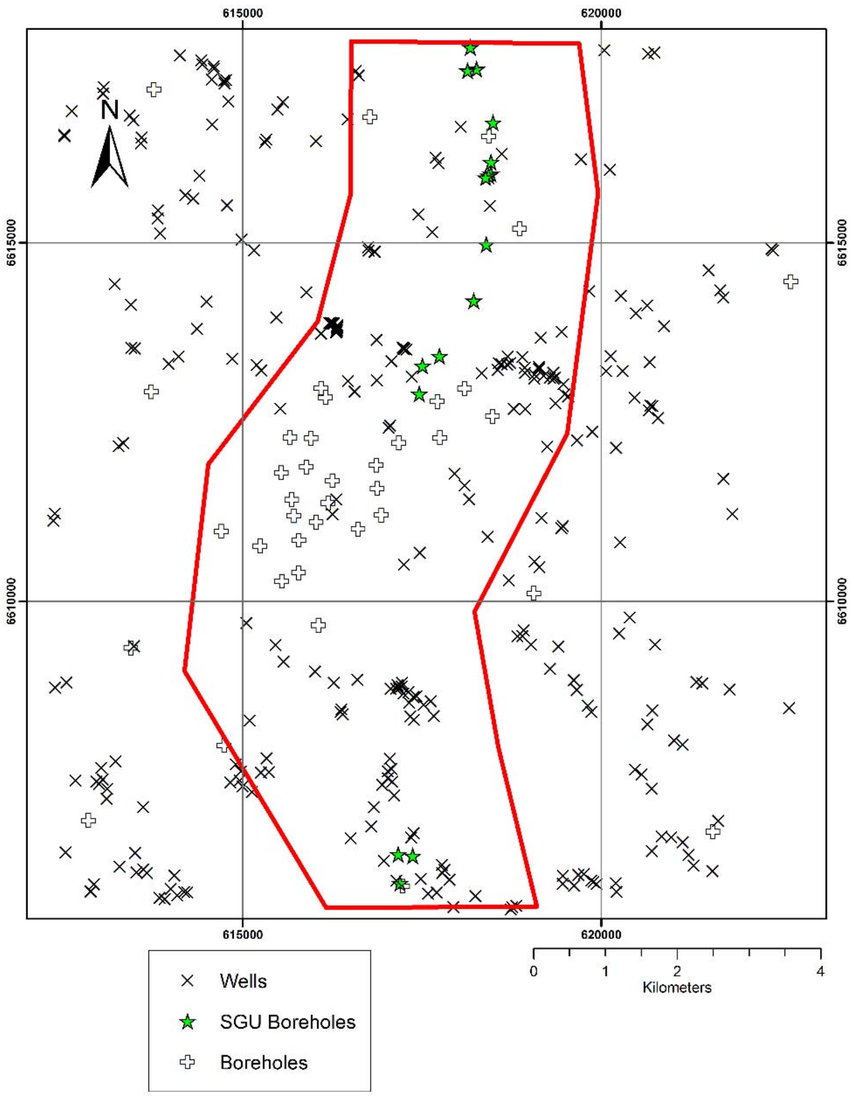


Figure 3 Borehole distribution map

3.4.1 SGU boreholes and Boreholes (Investigation Boreholes)

Although these were provided as two datasets, these should be considered as one dataset as they are essentially showing the same information and will be merged into the same database by SGU in the future. 16 SGU boreholes were available to the study although these were principally restricted to the northern part of the Esker, with 3 boreholes south of the mapped esker feature. These were provided by SGU from their Hydrogeological Database (HPAR) which contain both

SGU and consultant reports. Boreholes range from a few metres to approximately 33 m in depth. The boreholes had a limited lithological description recorded (Figure 5).

_DA	LOAD_DATE	OBJECTID	LITH	Swedish	English	RASTERVALU	DTM
	11/03/2016	25833	LERA	LERA	clay	27	27
	11/03/2016	25834	SAND	SAND	sand	27	27
	11/03/2016	25835	LERA	LERA	clay	26	26
	11/03/2016	25836	SAND	SAND	sand	26	26
	11/03/2016	25837	SAND	SAND	sand	26	26
	11/03/2016	24557	FINSAND	FINSAND	fine sand	13	13
	11/03/2016	24558	MELLANSAND	MELLANSAN	medium sand	13	13
	11/03/2016	24559	MELLANSAND	MELLANSAN	medium sand	13	13
	11/03/2016	24560	MELLANSAND	MELLANSAN	medium sand	13	13
	11/03/2016	24561	SAND	SAND	sand	8	8
	11/03/2016	24562	LERA	LERA	clay	8	8
	11/03/2016	24563	FINSAND	FINSAND	fine sand	8	8
	11/03/2016	24564	MELLANSAND	MELLANSAN	medium sand	24	24
	11/03/2016	24565	MELLANSAND	MELLANSAN	medium sand	24	24
	11/03/2016	24566	MELLANSAND	MELLANSAN	medium sand	24	24
	11/03/2016	24567	MELLANSAND	MELLANSAN	medium sand	24	24
	11/03/2016	24568	GROVSAND			24	24
	11/03/2016	24569	LERA	LERA	clay	21	21
	11/03/2016	24570	SAND	SAND	sand	21	21

30.26 30.86 Centimeters

Figure 4 Example Borehole Attribute Table - SGU Boreholes

The 'Boreholes' contained a total of 38 boreholes with approximately 19 boreholes within the Esker boundary as shown on the geological map. This was provided by SGU from their JSTR database, which is a stratigraphy database containing various datasets including geotechnical reports and sections from pits. These range in depth from a few metres to approx. 36 m. Many of the boreholes were clustered in the central part of the Esker area. This borehole dataset tended to be limited in the description of the lithology, usually stating the dominant 2 lithologies with little in the way of description apart from stating the main lithological units, e.g. Lera-Silt = Clay Silt or Sand-Block = Sand-Boulders (Figure 6)

Sten-block

oles_V3_FromXL

D	Shape	LAGERNR	ID	DJUP_FRAN	DJUP_TILL	LAGERTYP	OBJEKT	OBJEKT_TXT	ORG_BENAMN	KORNSTLK	KORNSTLK_T	KORNSTLK2	KORNSTLK2_
6	Point	2	STJ512963	24	26	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd
7	Point	1	STJ512952	0	17	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
8	Point	1	STJ512946	0	16	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
9	Point	1	STJ512932	0	12	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
10	Point	2	STJ512927	10	10.5	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd
11	Point	1	STJ512927	0	10	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
12	Point	1	STJ512855	0	10	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
13	Point	1	STJ512948	0	3	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
14	Point	1	STJ512944	0	3	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
15	Point	1	STJ512951	0	15	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
16	Point	1	STJ512949	0	4	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
17	Point	1	STJ512929	0	20	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
18	Point	1	STJ512971	0	19	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
19	Point	1	STJ512954	0	35	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
20	Point	1	STJ512972	0	36	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd
21	Point	1	STJ512933	0	10	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
22	Point	1	STJ512962	0	18	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
23	Point	2	STJ512945	15	16	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd
24	Point	1	STJ512943	0	12	JORD	0	ej bedömd		26	lera-silt (kohesionsjord)	0	ej bedömd
25	Point	2	STJ512960	13	20	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd
26	Point	2	STJ512955	20	30	JORD	0	ej bedömd		33	sand-block (friktionsjord)	0	ej bedömd

Figure 5 Borehole Attribute Table - Boreholes

3.4.2 Wells

The ‘Wells’ (BARK) archive dataset contained a total of 428 boreholes with 22 occurring within the esker boundary according to the geological map. The Wells Archive contains information on the technical design, depth, yield, groundwater level, geographical location, soil depth etc. of around 500 000 wells and boreholes. It is based on the reports which, since 1976, all well drillers have been required by law to submit to SGU. These were evenly and widely distributed across the esker area. Boreholes extend to over 200 m below ground level in places. Two or three lithological units have been described, with little or no geotechnical description coded (Figure 7).

Table

Wells_English_v2

FID	Shape	BRUNNS_ID	N	E	LAGERNR	FRANDJUP	TILLDJUP	JORD_BERG	OBJECTID	Swedish	English	DTM
33	Point	986127512	661321	62029	2	3	4	GRUS	381823	GRUS	gravel	24
34	Point	986127520	661425	62027	1	0	4	LERA	381824	LERA	clay	29
35	Point	986127538	661341	62013	1	0	6	LERA	381826	LERA	clay	26
36	Point	986127611	661322	61855	1	0	5	LERA, PINNMO	381831	LERA, PINNMO	clay, till	17
37	Point	995011897	660854	61981	3	9	90	GRANIT	394170	GRANIT	granite	27
38	Point	995011905	660828	62064	3	12	81	SKIFFER	394173	SKIFFER	slate	19
39	Point	995011913	660806	62101	1	0	3	SAND STEN	394174	SAND STEN	gravel stones	24
40	Point	995053550	660781	61533	3	9	90	BERG	396621	BERG	bedrock	12
41	Point	995029824	660605	61292	1	0	3	LERA	397978	LERA	clay	19
42	Point	993041813	660713	61361	1	0	1	LERA	407175	LERA	clay	2
43	Point	996063004	660834	61738	2	5	12	SKÖRBERG	420306	SKÖRBERG	broken bedrock	27
44	Point	996063053	660631	62128	1	0	1	SAND	420319	SAND	sand	21
45	Point	996063087	660623	62155	3	6	73	GRANIT	420330	GRANIT	granite	18
46	Point	996055497	661683	61261	1	0	2	FYLLNING	427280	FYLLNING	filling	30
47	Point	997034996	660621	61351	1	0	7	STEN-GRUS	428992	STEN-GRUS	rocks-gravel	19
48	Point	996049854	661504	61498	1	0	8	LE, ST, GR	435437	LE, ST, GR	clay, stones, gravel	26
49	Point	996049938	661047	61913	1	0	2	JORD	435454	JORD	topsoil	24
50	Point	996043485	661672	61646	1	0	2	SAND, LERA	443959	SAND, LERA	sand, clay	29
51	Point	996043485	661672	61646	3	6	90	BERG	443961	BERG	bedrock	29
52	Point	997081443	661341	61869	1	0	3	JORD	461051	JORD	topsoil	21
53	Point	997057963	661318	61833	1	0	21	SAND-GRUS	466225		Sand and Gravel	7

17 (0 out of 951 Selected)

Wells_English_v2

Figure 6 Borehole Attribute Table - Wells

3.5 DIGITAL TERRAIN MODEL

A 2m LiDAR dataset was provided by SGU for the area of interest and the wider area. For the geological modelling this was sub-sampled to 5 m horizontal resolution to ensure software performance was maintained in both the SubsurfaceViewer and GSI3D software. (Figure 8). In Groundhog software, the horizontal resolution of 2 m was retained for all snapping and checking after a draft of the model was produced in the SubsurfaceViewer.

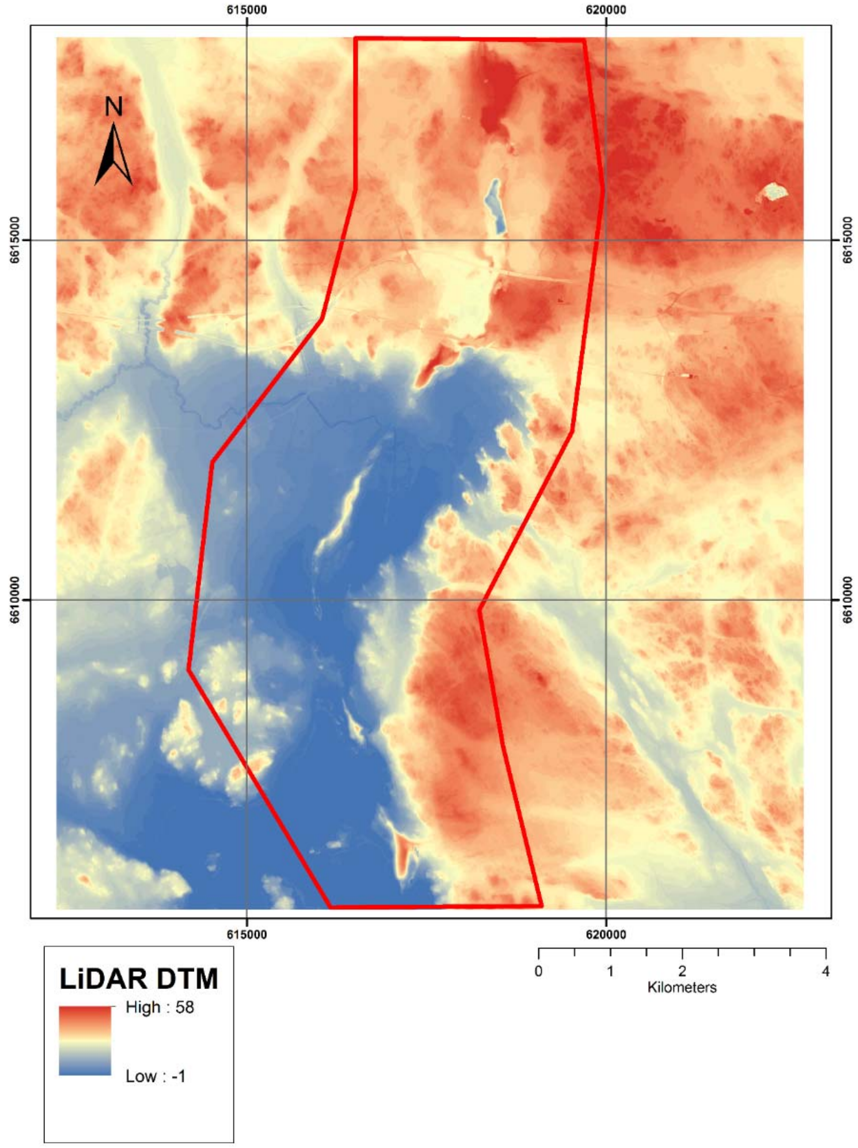


Figure 7 Digital Elevation Model

3.6 GEOPHYSICS

Two sets of geophysical data have been provided which were mainly restricted to the northern half of the model area with two Georadar (Ground Penetrating Radar) lines south of the main Esker feature (Figure 9)

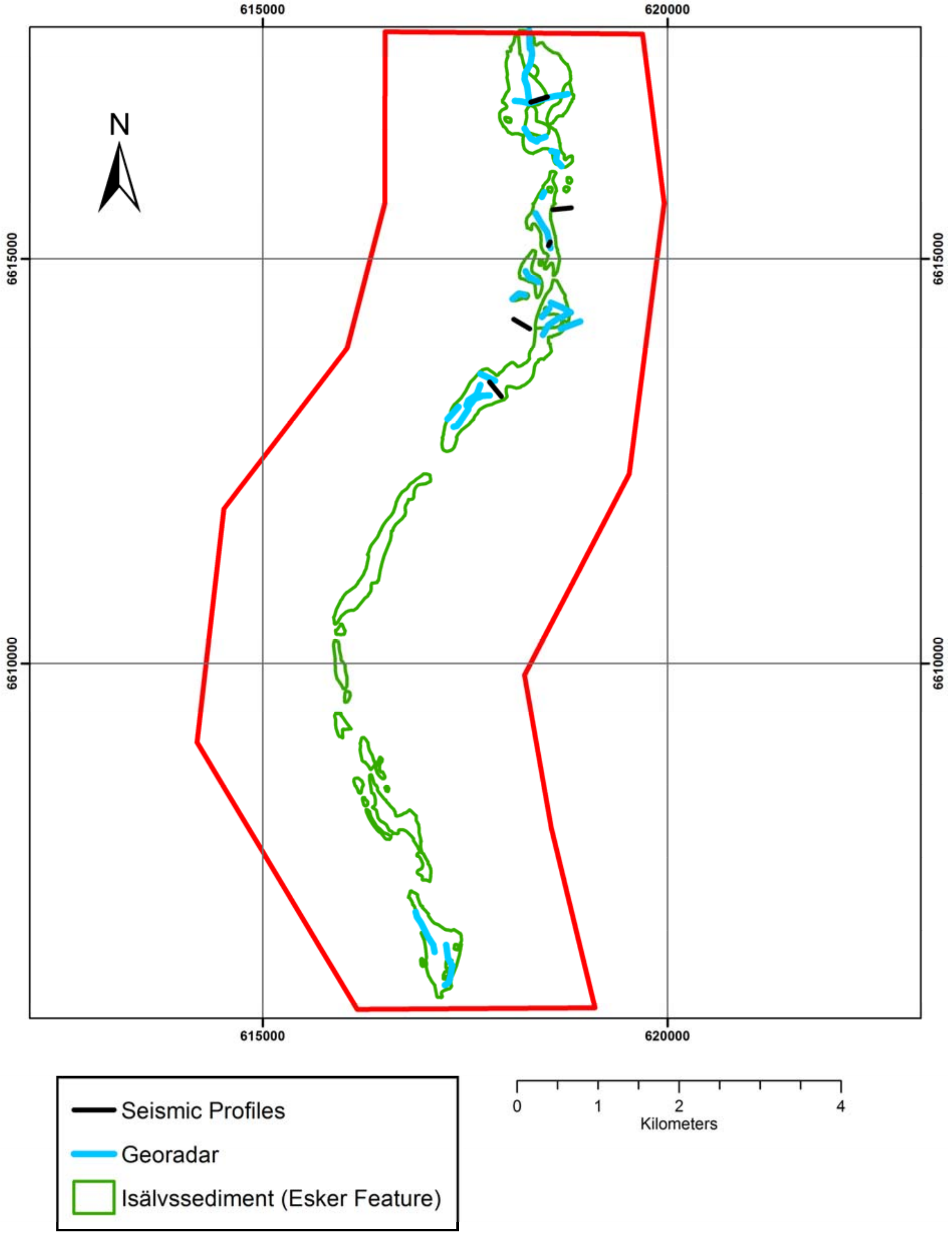


Figure 8 All Georadar and seismic profile locations

3.6.1 Georadar (GPR)

There were 18 TIFF images of the georadar sections that have been depth converted, some of which have been partially interpreted based on the colour scheme below. Examples of these can be seen in the following figures (10, 11 and 12):

Red = Bedrock

Yellow = Clay

Blue = Groundwater

Of the 18 Georadar images, only the following have had some form of interpretation. These are

R1-01.tif (Only groundwater shown)

r2-01.tif – some clay

R3-01.tif – some clay

r5-01.tif – Only bedrock. No correlation added

r6-01.tif – some clay

r8-01.tif - Only bedrock. No correlation added

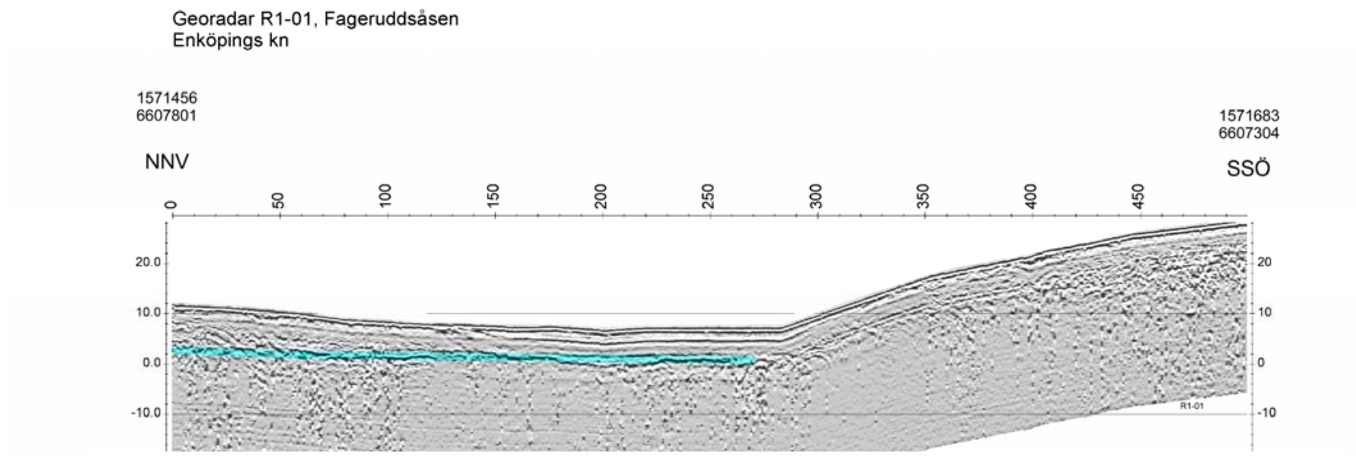


Figure 9 Georadar image with groundwater level interpreted

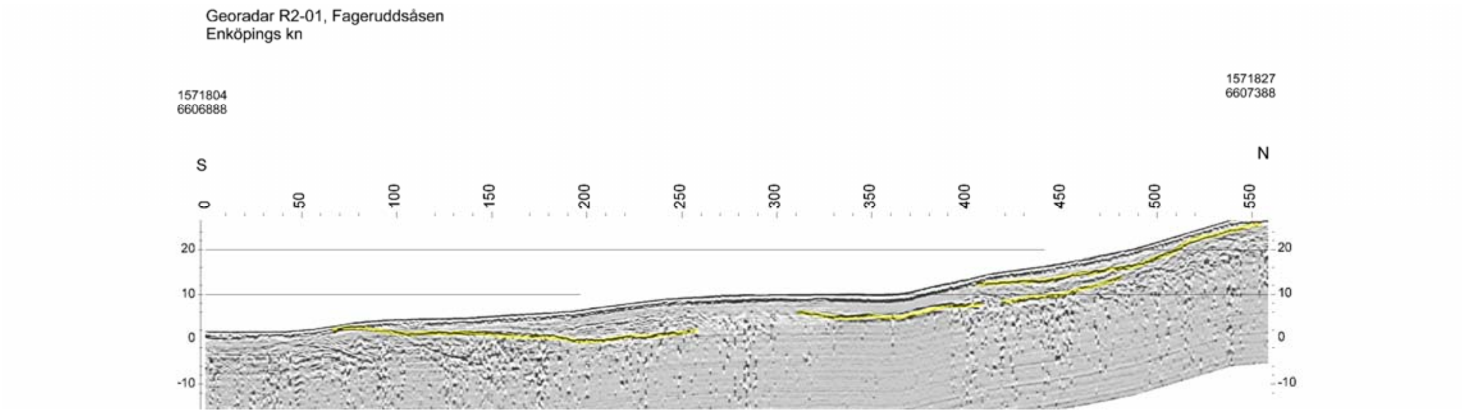


Figure 10 Georadar image with clay interpreted

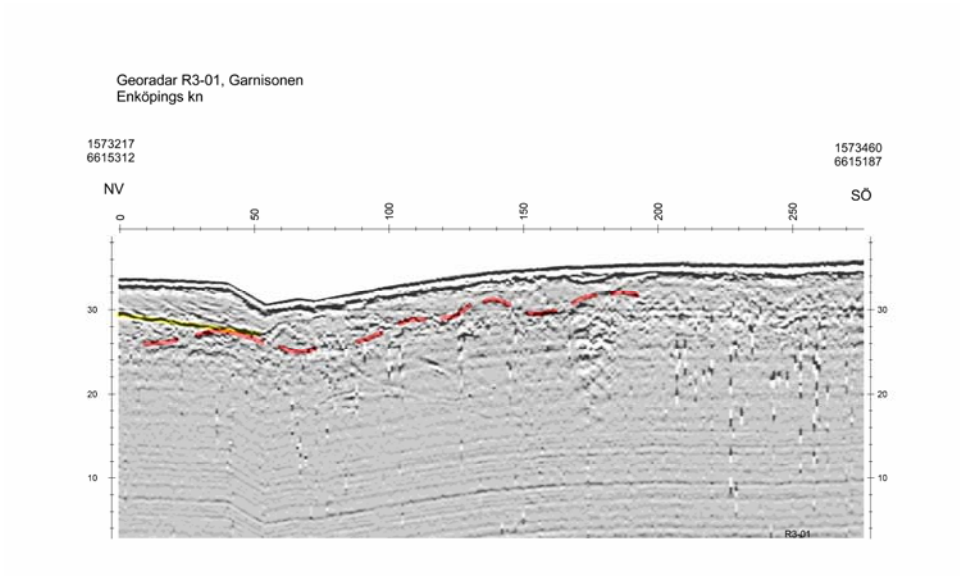


Figure 11 Georadar image with clay and top of bedrock interpreted

Figure 13 shows the location of the seismic and georadar profiles.

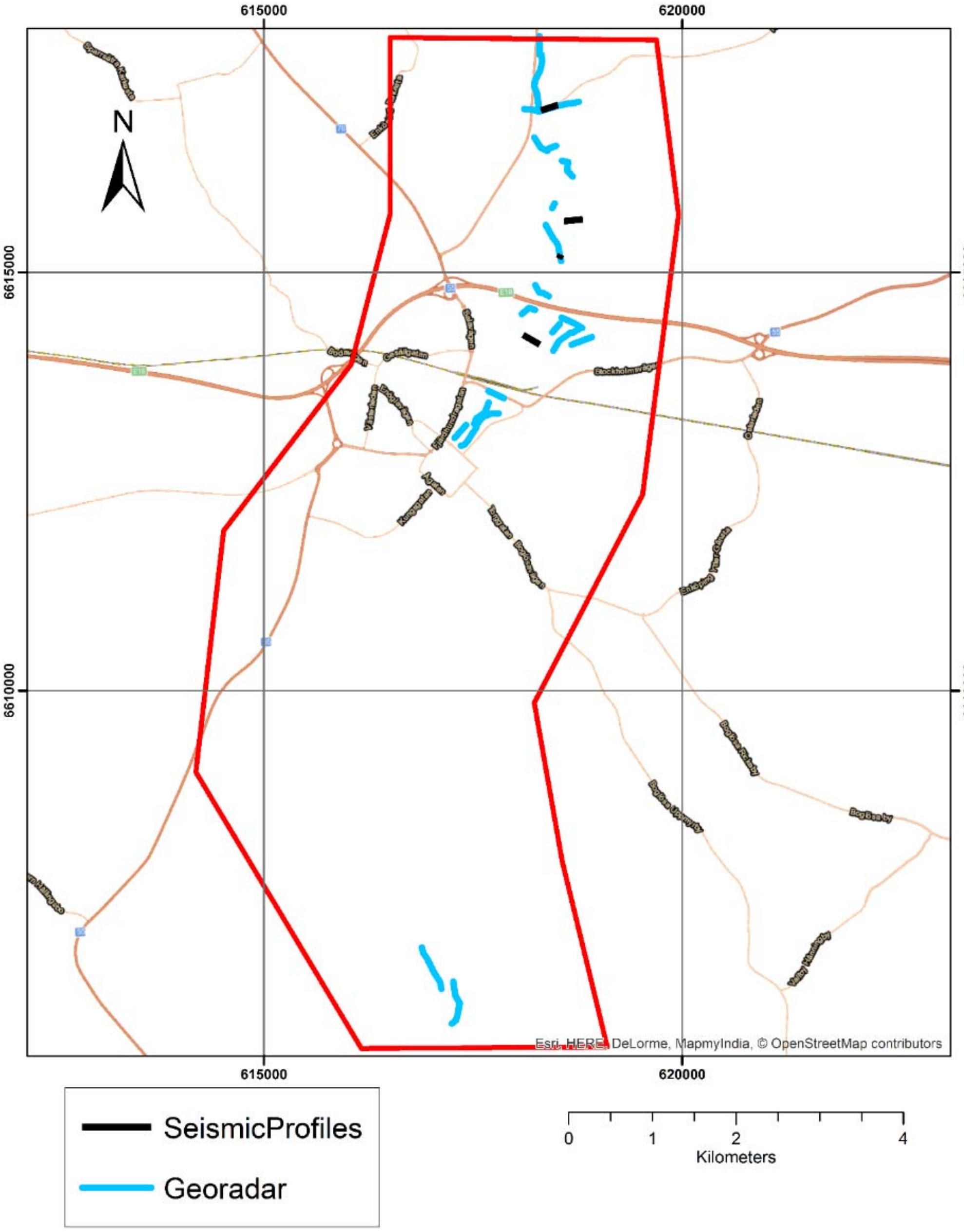


Figure 12 Locations of Interpreted Georadar (GPR) with major and minor roads

3.6.2 Seismic Profiles

Five depth converted seismic profiles exist in and around the Enköping Esker. These have been interpreted and can be used directly for cross-section interpretation (Figure 14)

S1-01 - Clay overlying Sand and gravel

S2-01 – Silt – Overlying silt and sand

S3-01 – Didn't match DTM?

S4-01 - Sand overlying Silt? Correlated as Sand and gravel

S4-02 – Sand and gravel

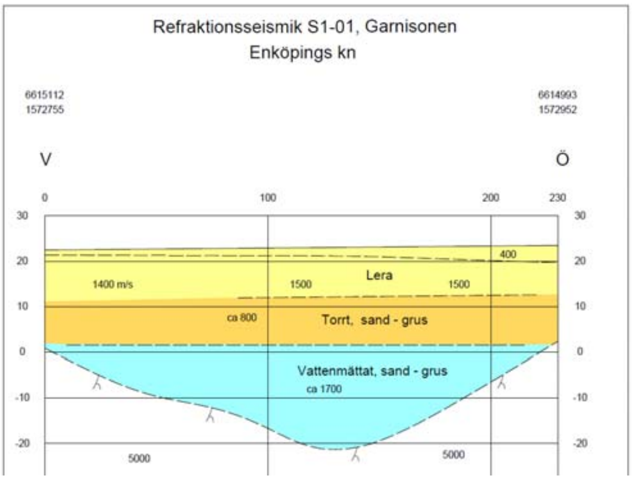


Figure 13 Example seismic section figure

The location of these seismic lines are restricted to the northern part of the Esker (Figure 13)

3.7 IMAGERY/TOPOLOGICAL DATA

Topology imagery provided by SGU (Figure 15)

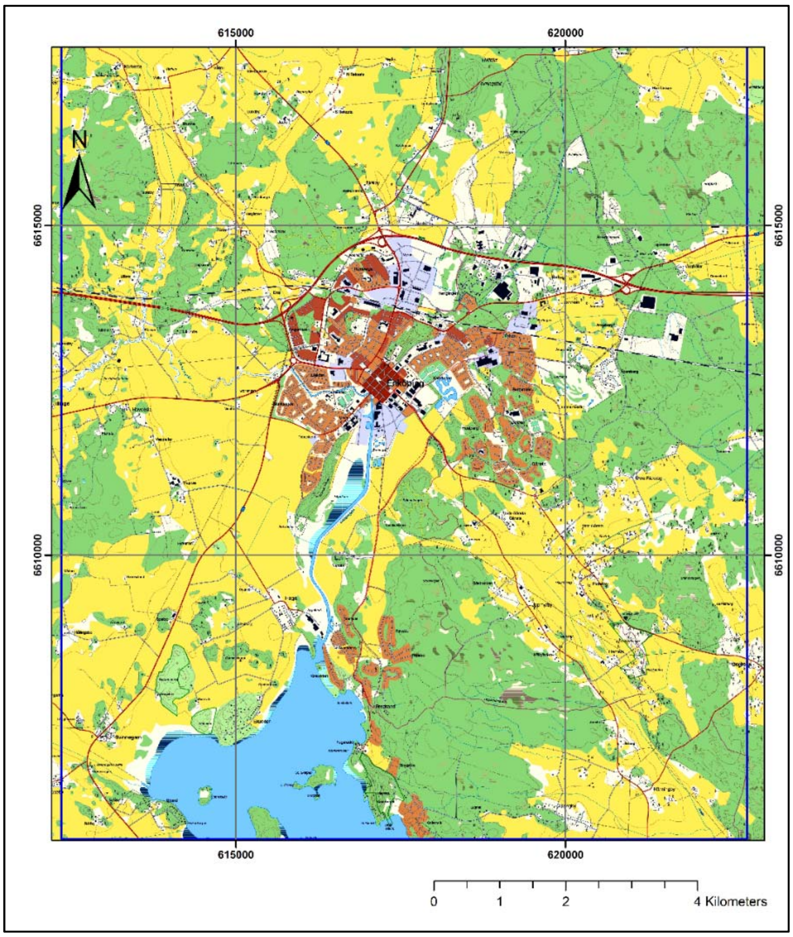


Figure 14 Topographic Map - Enköping

3.8 SUPERFICIAL DEPOSITS THICKNESS

The superficial deposits thickness grid was supplied from the SGU national model. This was sampled at 10 m cell size and in the area of interest is up to 46 m thick (Figure 16). Rockhead has also been calculated by subtracting the superficial deposits thickness from the DTM which can aid the interpretation where there is little borehole geophysical constraint in cross-section.

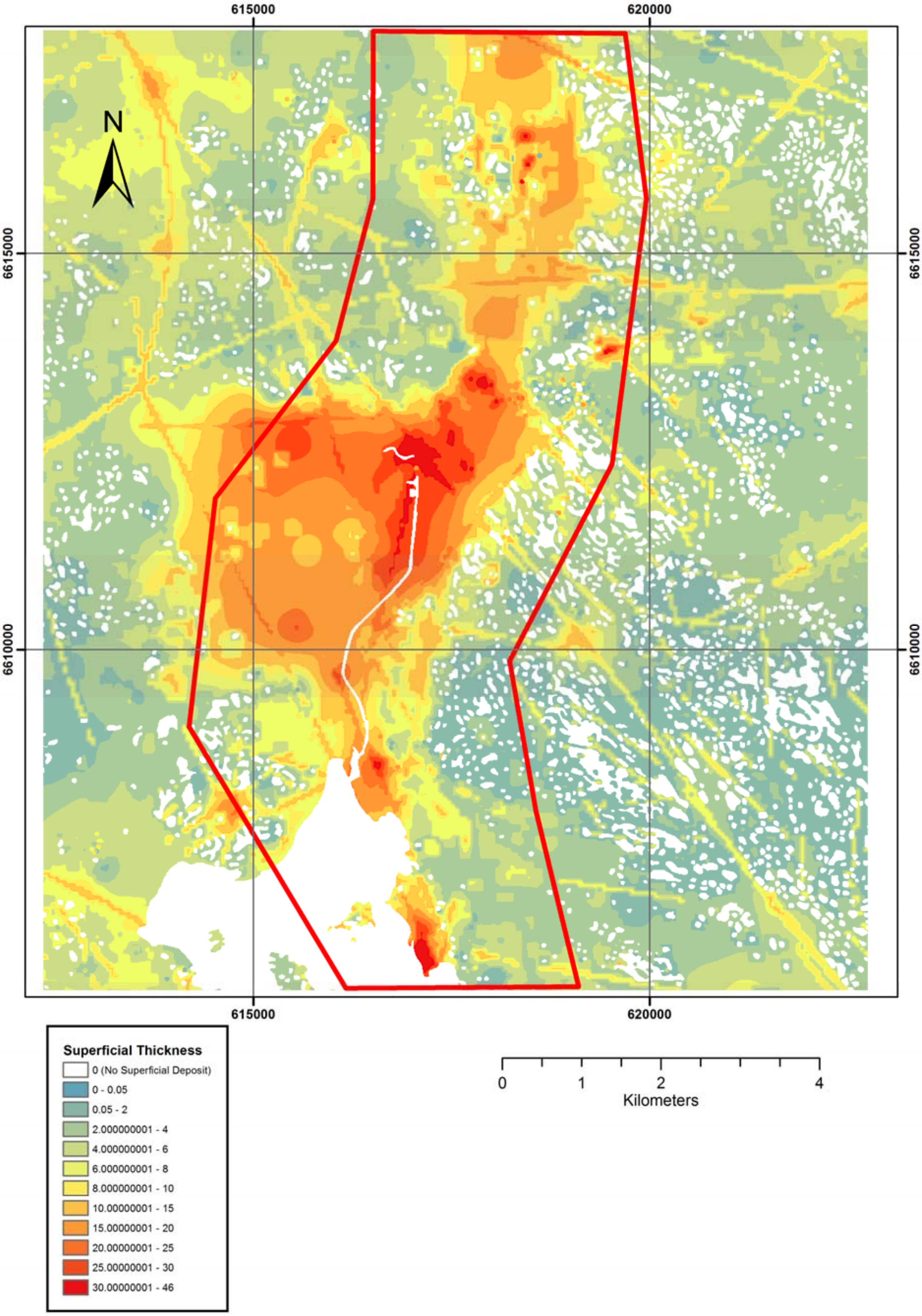


Figure 15 SGU Superficial Deposits Thickness Model

3.9 GVS/LEGEND

A pre-existing generalised vertical section (GVS) and model legend (.gleg) from the Uppsala geological model was used for Enköping Esker model, but later modified in discussion with SGU (Table 1)

name	id	Stratigraphy	UNIT_TYPE	English Translation
Vatten	10	Vatten	Vatten	Water Body
Ospecifierat	20	Ospecifierat	Ospecifierat	Unspecified/Artificial Ground
Organiskt sediment	30	Organiskt sediment	Organiskt sediment	Organic matter
Svallsediment	40	Svallsediment	Svallsediment	Outwash Material
Lera	50	Lera	Lera	Clay
Isälvssediment	60	Isälvssediment	Isälvssediment	Primary glaciofluvial
Morän	70	Morän	Morän	Till
Berggrund	80	Berggrund	Berggrund	Bedrock

Table 1 GVS for Enköping Geological Model

Name	Description	R	G	B	Transparency	Texture
Vatten	Vatten	255	255	255	255	TEXTURES\black.jpg
Ospecifierat	Ospecifierat	0	0	0	255	TEXTURES\black.jpg
Organiskt sediment	Organiskt sediment	217	191	158	255	TEXTURES\black.jpg
Svallsediment	Svallsediment	243	149	63	255	TEXTURES\black.jpg
Lera	Lera	255	255	0	255	TEXTURES\black.jpg
Isälvssediment	Isälvssediment	128	255	38	255	TEXTURES\black.jpg
Morän	Morän	217	247	255	255	TEXTURES\black.jpg
Berggrund	Berggrund	230	230	230	255	TEXTURES\black.jpg

Table 2 Legend for Enköping Geological Model (model units only)

3.10 ADDITIONAL MODEL DATA

A study for groundwater was conducted by GEOSIGMA, entitled 'Enköpingsåsen Hydrogeoutredning' and published in November 2012, which covered a large proportion of the esker in Enköping. There are several boreholes, maps, cross-sections and surfaces which might be useful to include within the model. The surfaces needed further formatting and refinement before they can be incorporated directly in this model. Further investigation is also required to convert these into a suitable format. However, boreholes from this additional dataset proved not to be adequate in detail or depth to improve the geometries of the units constructed.

4 Geology

The Enköping esker is part of a larger system of eskers starting south of lake Malaren (Dunker, east of Malmkoping) and continuing north towards Heby and Tarnsjo. The model area was originally isostatically-depressed beneath sea-level by the weight of the Fennoscandian Ice Sheet. Immediately following the removal of glacier ice from the model area, the landscape was submerged beneath sea-level (Åse & Bergström, 1984). However, following deglaciation, ongoing isostatic rebound has led to the uplifting of the model area well above modern sea-level. Winnowing of the glaciofluvial deposits by coastal processes (wave action) during uplift has resulted in the removal and re-sedimentation of finer-grained deposits as a thin drape across the area (Åse & Bergström, 1984). The preservation of this fine-grained layer, which occurs widely throughout the study area, implies that isostatic uplift following deglaciation was rapid.

The southern part the esker is about 35 meters above sea-level, and its thickness is about 25 m. Large areas of the esker are covered by silt and clay. In central Enköping, the esker is even thicker, up to 40 m. The esker is usually situated directly on the bedrock that locally consists of granite, syenite, and metagreywacke.

The northern part of the esker, situated to the north of the urban area of Enköping, is wider than the southern part and generally not covered my fine-grained sediments. The thickness here is up to 30 m, and the highest part is situated at 50 meters above sea level. The esker has been locally quarried for sand and gravel pit. The esker/glaciofluvial deposit is used for the municipal drinking water supply. In areas beyond the esker, there is usually a thin (1-5 m) layer of silty-sandy till directly on the bedrock.

5 Geological Model

The model input files used to create the geological model for Enköping have been described in Section 3. The file formats are described in Table 3. The Generalised Vertical Section (GVS) defines the lithostratigraphic structure of the 3D geological model and its geological and geotechnical descriptions. The index level and downhole geological data files (.bid and .blg files respectively) were derived from the borehole information provided by SGU. All borehole coordinates were in SWEREF 99TM.

	Format (resolution)
DTM	ASCII (5 m cell size) grid
Quaternary Geology Map	ESRI shapefile
Generalised Vertical Section (GVS)	SubsurfaceViewer/GSI3D ASCII text file
Borehole Index	SubsurfaceViewer/GSI3D ASCII (.bid) text file
Downhole Geology	SubsurfaceViewer/GSI3D ASCII (.blg) text file
Legend	SubsurfaceViewer/GSI3D ASCII (.gleg) text file
Georadar (GPR)	Image file (backdrops in cross-section)
Seismic Sections	Image file (backdrops in cross-section)
Project file	SubsurfaceViewer/GSI3D XML/ASCII (.gsipr) text file to store cross-sections and unit boundaries

Table 3 File formats used in construction of geological model

The format of the downhole geology file was prepared with the following structure (Table 4):

HOLEID	Depth To Base	LITHOLOGY	MAIN LITH	Borehole Source
113300187	42	GRUS	GRUS	Wells
117100006	5	PINNMO	PINNMO	Wells
117100006	81	GRANIT	GRANIT	Wells
117100007	6	PINNMO	PINNMO	Wells
117100007	27	GRANIT	GRANIT	Wells
RSG2002120602	12	MELLANSAND	SAND	SGU
RSG2002120602	13	MELLANSAND	SAND	SGU
RSG2002120602	16	MELLANSAND	SAND	SGU
RSG2002120602	18	MELLANSAND	SAND	SGU
RSG2002120602	19	GROVSAND	SAND	SGU
RSG2002120602	20	GROVSAND	SAND	SGU
STJ512855	10	LERA-SILT (KOHESIONSJORD)	LERA	Boreholes
STJ512869	8	LERA-SILT (KOHESIONSJORD)	LERA	Boreholes

STJ512919	35	SAND-BLOCK (FRIKTIONSJORD)	BOULDERS	Boreholes
STJ512920	7	LERA-SILT (KOHESIONSJORD)	LERA	Boreholes
STJ512921	16	LERA-SILT (KOHESIONSJORD)	LERA	Boreholes
STJ512927	10	LERA-SILT (KOHESIONSJORD)	LERA	Boreholes

Table 4 Downhole geology file format

A total of 477 boreholes were provided by SGU for the construction of the geological model for Enköping. All of these boreholes were considered in the modelling. The orientation of cross-sections was defined by the selection of boreholes by the modeller after manual inspection of each borehole using the borehole viewer function of the SubsurfaceViewer. The best available boreholes were selected for inclusion in the geological model based on a subjective assessment of depth of drilling and quality of description. Each selected borehole was progressively added to the 2D cross-section window to construct a cross-section. 210 or 44% of the total boreholes were added directly to cross-sections in Enköping.

5.1 CROSS-SECTION CONSTRUCTION

Cross-sections displaying downhole borehole information were displayed in turn, in the 2D cross-section window of SubsurfaceViewer. A preliminary assessment of downhole borehole records was used to group similar lithological units together. Where possible, each unit was grouped into the lithostratigraphic framework which came in-part from the Uppsala geological model constructed in 2015-2016 (Jirner et al, 2016). Geological correlation lines, representing the base of each unit, were digitised by the modeller between boreholes corresponding to lithological units proved within them. Each correlated line was given a unique geological code. Geological units were correlated based on their order of superposition and relative age. This order defines which geological deposits can occur stratigraphically above or below others and is stored in the Generalised Vertical Section (GVS) file.

Importantly, each correlation line, corresponding to the base of a lithological unit is made up of a series of nodes digitised by the modeller. Each node stores a location and elevation unique to each geological unit. When all of the cross-sections are combined, the lines and nodes for every geological unit provide the basis for the calculation of the model. This method of on-screen digitisation, using boreholes and digital geological map data to constrain the surface and sub-surface distribution and geometry of the geological units, allows a detailed 3D conceptual model of the area to be developed.

The SubsurfaceViewer methodology provides the flexibility to incorporate the geoscientist's interpretation where borehole or other data may be sparse or not available. For example, where borehole density is low or where boreholes do not penetrate geological rockhead, the modeller can enhance the 3D model, by using surrounding borehole data or locally derived knowledge, to define the thickness or geometry of the geological unit. The resulting 3D model therefore does not rely on borehole data alone.

Consistency between correlation lines on individual cross-sections is maintained by using functionality in SubsurfaceViewer to display equivalent correlations in intersecting cross-sections. These intersections are shown by a colour coded arrow and provide a visual check of intersecting geological units on each cross-section.

To ensure that all intersections with cross-sections, and subcrop and outcrop lines were snapped the project was exported to Groundhog Desktop.

A total of 43 cross-sections were correlated across the area of interest covering a total length of 292 km (Figure 17)

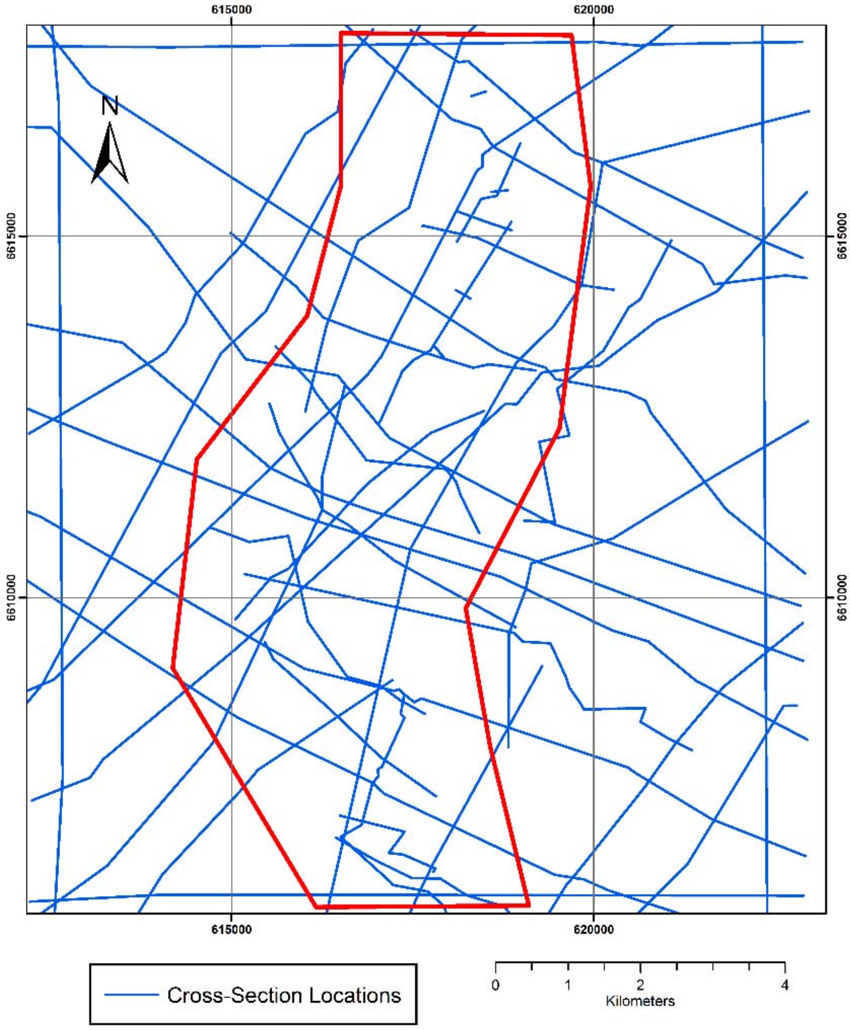


Figure 16 Cross-Section Locations

5.2 ENVELOPE CONSTRUCTION

The Quaternary geological map data were used to aid correlation and provide an initial assessment of the surface distribution of the superficial deposits.

Information derived from the distribution of nodes from geological correlation lines, representing the base of each unit, on cross-sections provided spatial evidence for the surface and subsurface distribution of each geological unit. Functionality in the SubsurfaceViewer and GSI3D™ enables all correlation lines and the points on them, to be identified and displayed in 2D plan view. The distribution of points displayed in 2D plan view, was then used to evaluate and constrain the surface and subsurface distribution of each geological unit. Envelopes defining the boundaries representing the combined surface and subsurface distribution of each geological unit were then constructed. Figure 18 shows the geological unit distribution sequence from the upper most unit to the lowest superficial unit.

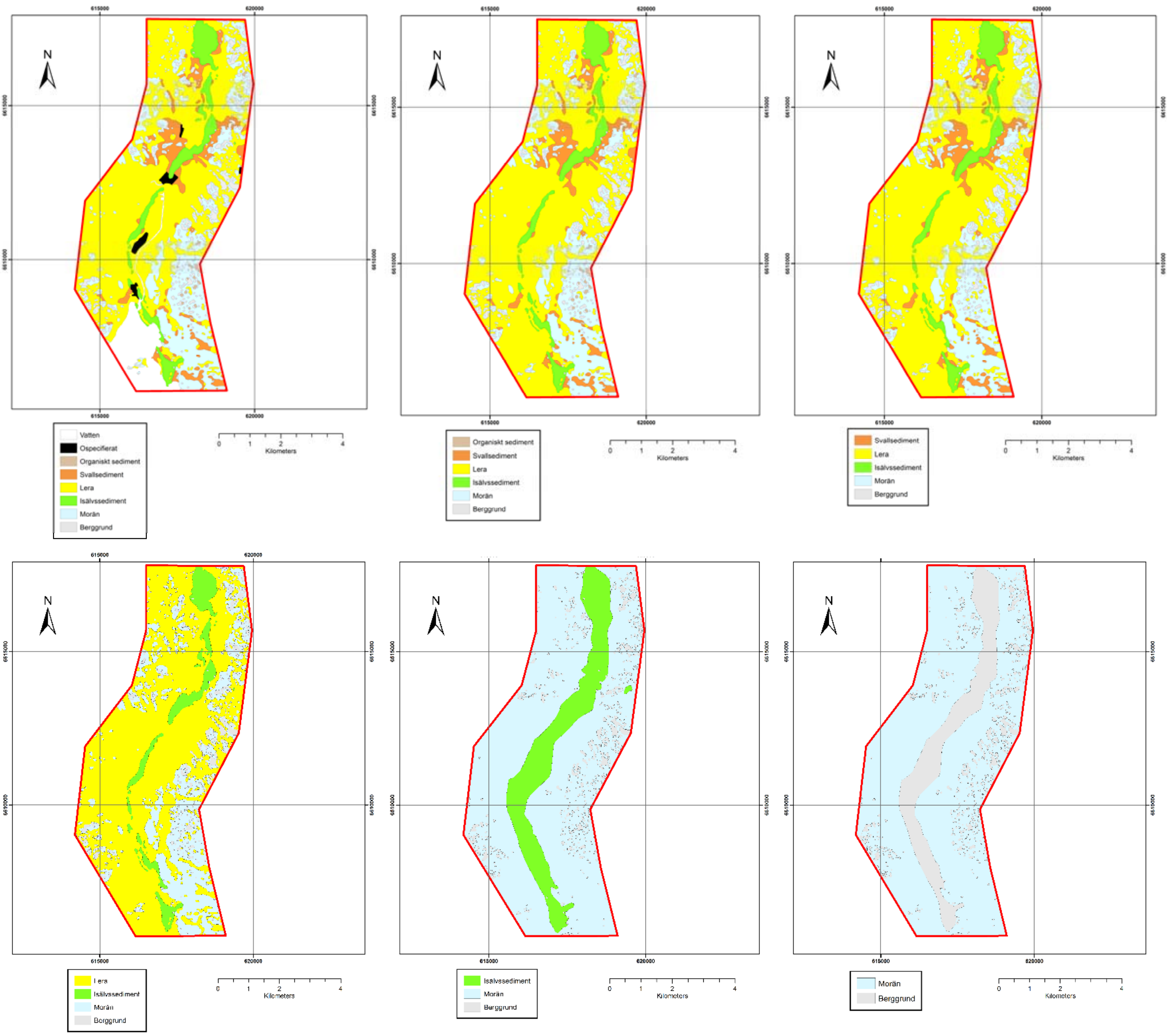


Figure 17 Maps showing full outcrop and subcrop distribution of geological units modelled in Enköping

5.3 MODEL CALCULATION

The 3D geological model was calculated by combining the correlated units present on cross-sections with the envelopes defining the distribution of those units. The modelling calculation in SubsurfaceViewer uses a proprietary Triangular Irregular Network (TIN) algorithm to create a series of surfaces representing the top and base of each geological unit from the individual nodes along correlation lines. The model is calculated 'top-down'; beginning at the ground surface at the DTM and working downwards from younger to older geological units. This stack of surfaces forms the geological model from which the top and base elevation and thickness of every geological unit is calculated and exported.

The elevation and thickness of geological units at outcrop are determined from values derived from the DTM.

The SubsurfaceViewer has an additional function compared to GSI3D where the minimum thickness can be specified to ensure all units have some thickness applied. This circumvents a known issue when only using a direct triangulation of the points which can lead to spurious triangles occurring at or above the DTM or cause units to cross each other. An example of this can be seen in Figure 19 showing a synthetic cross-section from a model calculation with no minimum thickness applied using GSI3D. Figure 20 shows a cross-section calculation with a 1 m minimum thickness applied using the Subsurface Viewer. This forces surfaces to maintain a thickness of at least 1 m from the DTM using the order prescribed in the GVS.

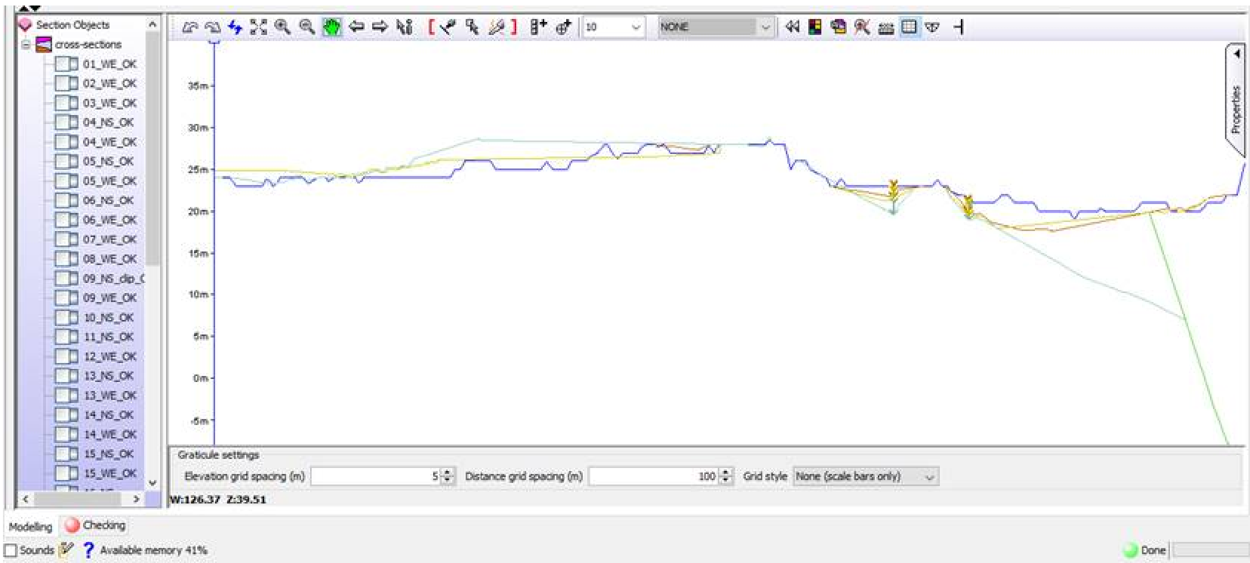


Figure 18 Synthetic cross-section from GSI3D (DTM in dark blue)

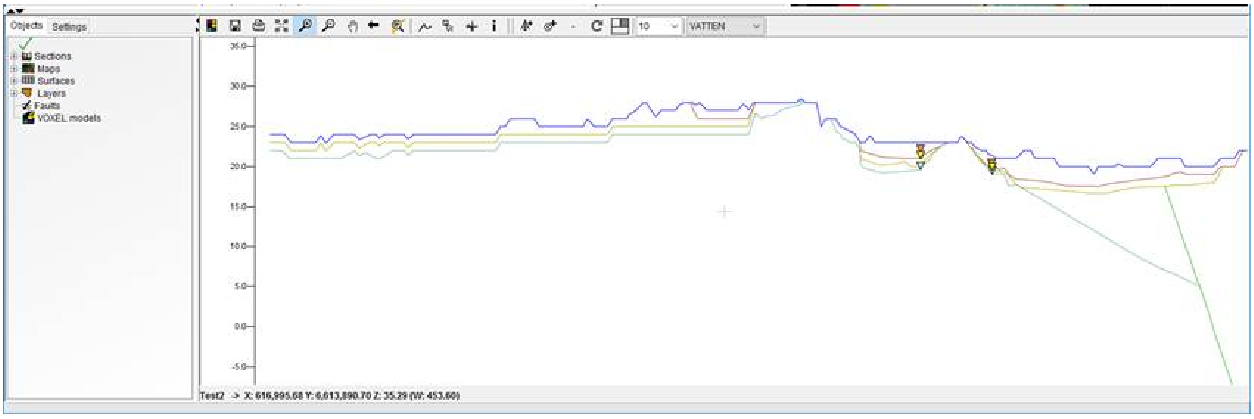


Figure 19 Synthetic cross-section from Subsurface Viewer using minimum thickness value (DTM in dark blue)

5.3.1 Grid Export Parameters

Below are the parameters that were used for the output of the ASCII grids (Top, Base and Thickness) for each unit in the geological model. An example of this output can be seen in Section 6.6. The base ASCII grids produced were used in the Web Viewer output (see Section 6.1)

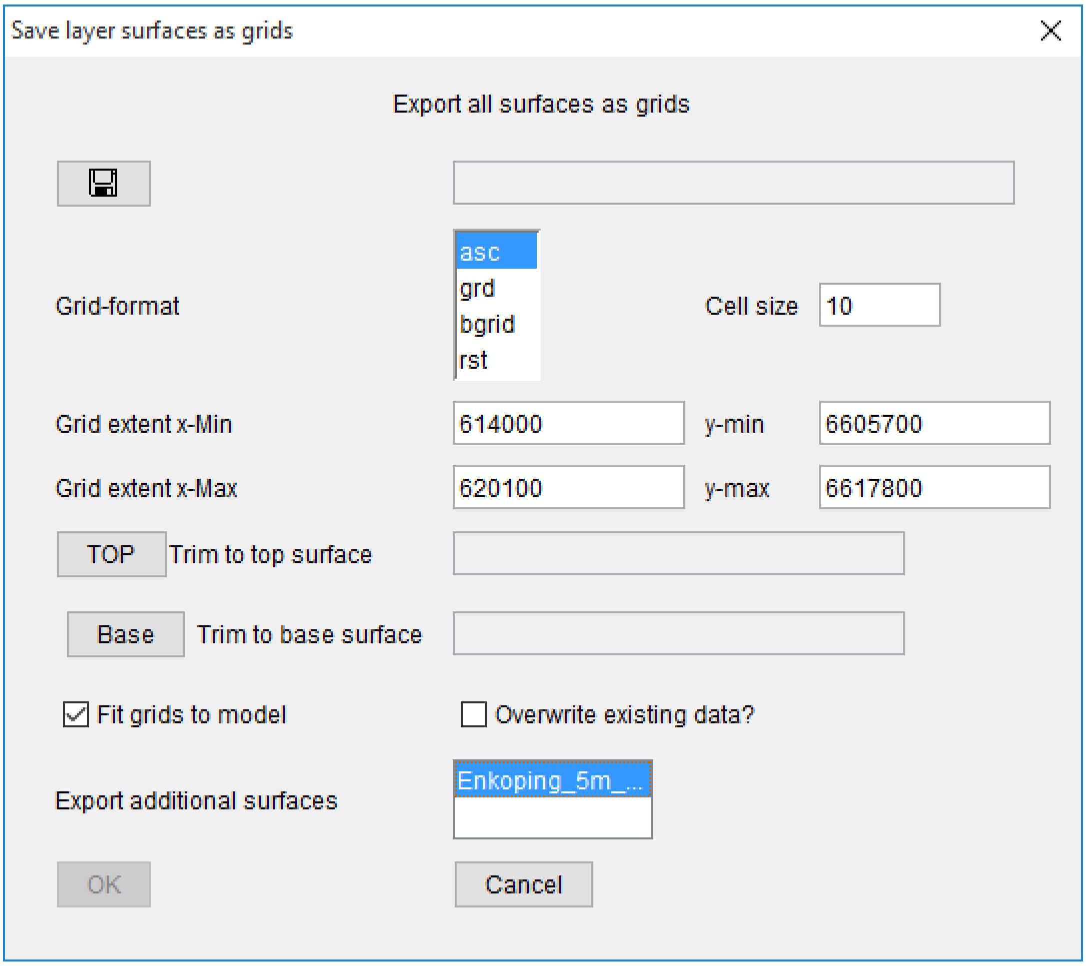


Figure 20 ASCII grid export parameters

5.4 QUALITY ASSURANCE

Creating a 3D geological model in SubsurfaceViewer is an iterative process. The 3D model was verified for geological accuracy and consistency with the outputs of the related geological mapping programme in two main phases. The first phase of model verification was undertaken by the modelling team in consultation with Ricky Terrington and Steve Thorpe using the BGS in-house QA procedure (see appendix for QA worksheet). Cross-sections were assessed for geological consistency and a subset of boreholes were examined prior to the modelling phase to ensure the stratigraphy recorded was consistent with descriptions found in logs.

The second phase of model geological verification was carried out following modification of the model on the basis of this first phase of model assessment and review. This involved looking at the thickness of the deposits against the expected distribution of that unit (the total outcrop and subcrop combined). To increase the accuracy of model calculation, additional cross-sections were constructed around the perimeter of the project area and 'helper' infill sections were used to constrain units that had little or no borehole or cross-section data to constrain their thickness.

5.5 LIMITATIONS OF THE GEOLOGICAL MODELLING

The SubsurfaceViewer is similar to the GSI3D approach for constructing geological models. They both are explicit modelling methodologies. This methodology has been the established approach for modelling Quaternary and simple bedrock horizons at the British Geological Survey for the past 15 years (Kessler et al, 2009). Cross-sections are correlated between physical data such as boreholes, seismic data, topographical features and constrained by geological maps where available. Cross-sections can also be drawn where little physical data exists instead using qualitative reasoning and knowledge to apply thickness and geometry to the stratigraphy. Therefore, surface horizons and volumes will have the greatest constraint close to cross-sections controlled by the physical data and be less constrained where cross-section correlations have been inferred by the geologist with little physical data control. In general, areas with little physical data and cross-section control will be the least constrained and therefore the least certain.

The location of cross-sections will impact on the calculated surface and thickness of each geological horizon. GSI3D uses Triangulated Irregular Networks (TIN) to interpolate between the X, Y and Z co-ordinates of every node drawn in cross-section combined with the 'envelope' which is the outcrop, sub-crop or a combination of both for each geological horizon. By using this interpolation method, the contours and isopachs generated will be less constrained further away from cross-sections and may generate spurious results particularly for thinner geological horizons where the topology or included surfaces such as in the DTM or the bathymetry vary significantly in elevation.

5.6 MODEL CHECKS

The BGS have developed a standardised methodology for checking 3D models, which involves a series of 3 checking stages. The only check completed on the Enköping Esker model was a 'technical check'. This process reviews the model for internal consistency by checking that all cross-sections match with the distribution described in 2D (outcrop and subcrop), that all croplines are snapped to either the DTM or a subcrop position, and that all cross-sections snap to each other. This checking process also follows a series of questions that dig into the modelling process, the data used, and the standards followed when modelling to ensure consistency. These questions can be found in the Appendix.

Much of the work was to ensure that the envelopes showing the full outcrop and subcrop of each unit matched the cross-sections. In nearly all bedrock outcrops encountered on cross-sections the Morän underlying the Lera had the same distribution in 2D, but the cross-sections were drawn with the Moran slightly pinching out against the Lera as shown in Figure 22.

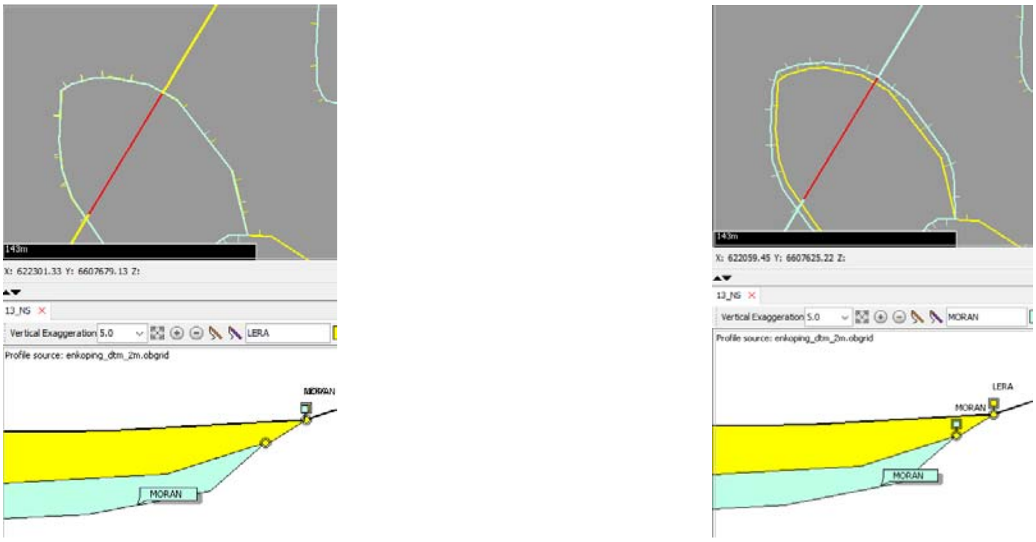


Figure 21 Left-hand image shows Lera and Morän coincident whereas the cross-section shows the Moran to be slightly offset and pinching out in the subcrop which is the correct geometry for this unit.

Although all cross-sections bisecting this type of issue were resolved, there still exists numerous further bedrock outcrops away from cross-sections that were not 'fixed'. A recommendation for future work would be to resolve these.

5.7 WORKFLOW SUMMARISED

Data Preparation & Testing → Geological Modelling → Model QA and Output Generation

Data Preparation & Testing (British Geological Survey, Natural Environment Research Council)

Data Preparation:
- DTM
- Boreholes
- Geological Map Linework
- GVS
- Legend
- Sections – GPR and Seismic sections
- Others – Superficial Thickness, GEOSIGMA data
- Data projection checking

Output testing:
- Web Viewer
- 3D PDF
- Minecraft
- Groundhog Desktop

Geological Modelling (SGU, Sveriges geologiska undersökning, Geological Survey of Sweden)

Cross-section and Envelope construction using the Subsurface Viewer software

(British Geological Survey, Natural Environment Research Council)

Support and advice during geological modelling

Model QA and Output Generation (British Geological Survey, Natural Environment Research Council)

Model QA:
Model snapping and QA using BGS standard GSI3D workflow QA procedures

Outputs:
- Web Map Viewer (Synthetic Cross-section, borehole and horizontal slices)
- 3D PDF
- ASCII grids (Top, Base, Thickness)
- 2D GIS layers - shapefiles (Envelopes, sections and borehole locations)
- Minecraft
- GOCAD (Top, Base and Shells)
- 3D Shapefiles (Cross-sections and boreholes)

6 Publication Methods and Outputs

The following published outputs were developed by BGS and delivered to SGU as part of the study.

6.1 WEB VIEWER

A web viewer was developed for the Enköping geological model, so that the user can interrogate the model by producing synthetic boreholes (Figure 24), cross-sections (Figure 25) and horizontal slices (Figure 27) which can be relative to sea-level or ground level, using the tools in the bottom left of the map interface. Each of these items can be published as a PDF file with a legend attached. The map interface also includes the surface geological map (including a legend) as provided by SGU (section 3.3) and the locations and names of boreholes considered and used in the construction of the geological model. The geological map and boreholes can be turned on and off using the slider bar to change their transparency (Figures 23 and 26). The red hatched box indicates the location of the model from which the above synthetic outputs can be generated.

Currently, the data is hosted by BGS and the map viewer can be accessed using the following URL:

http://mapapps.bgs.ac.uk/sweden_esker_pilot/

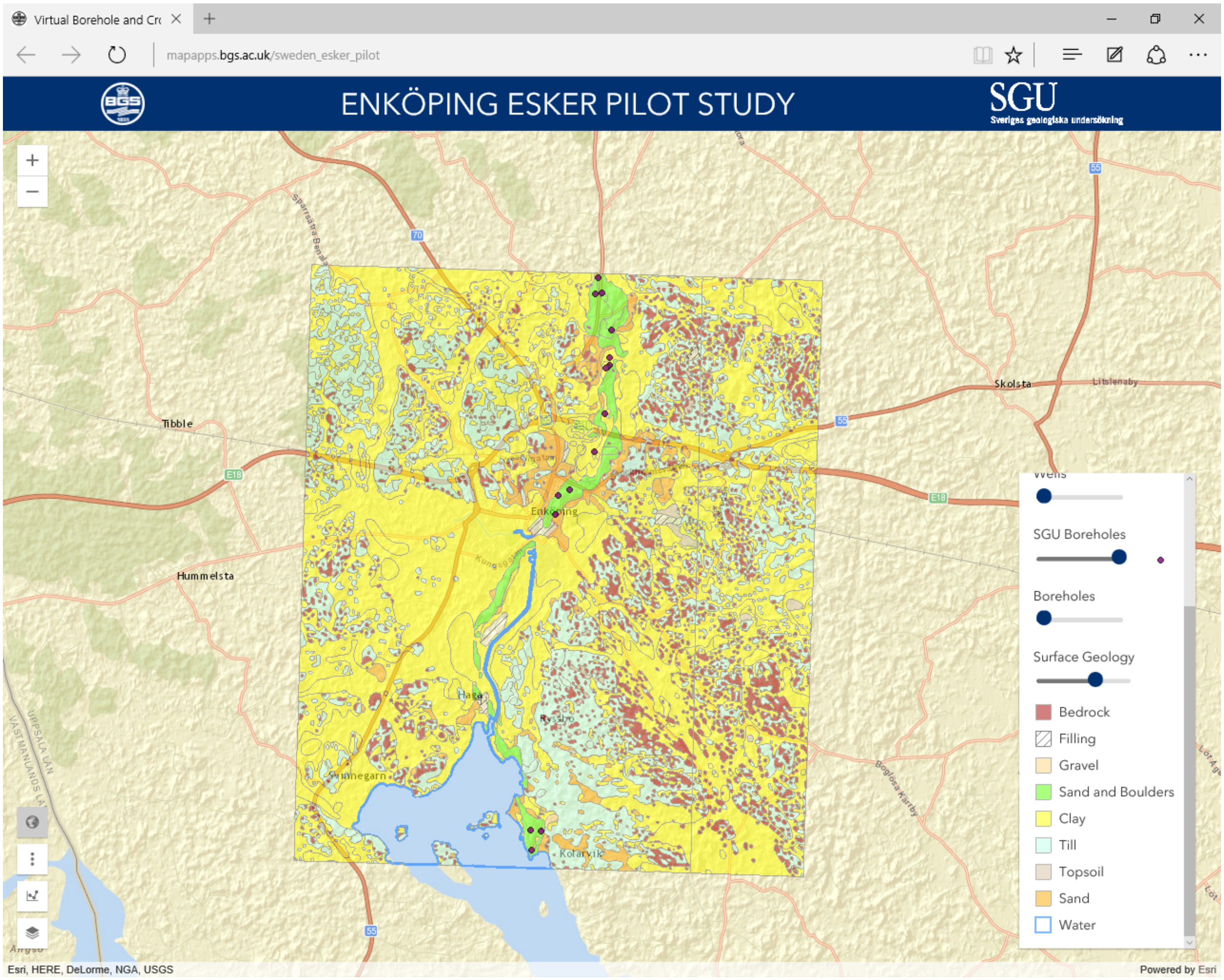


Figure 22 Enköping Geological Model Interface – Web Map Viewer

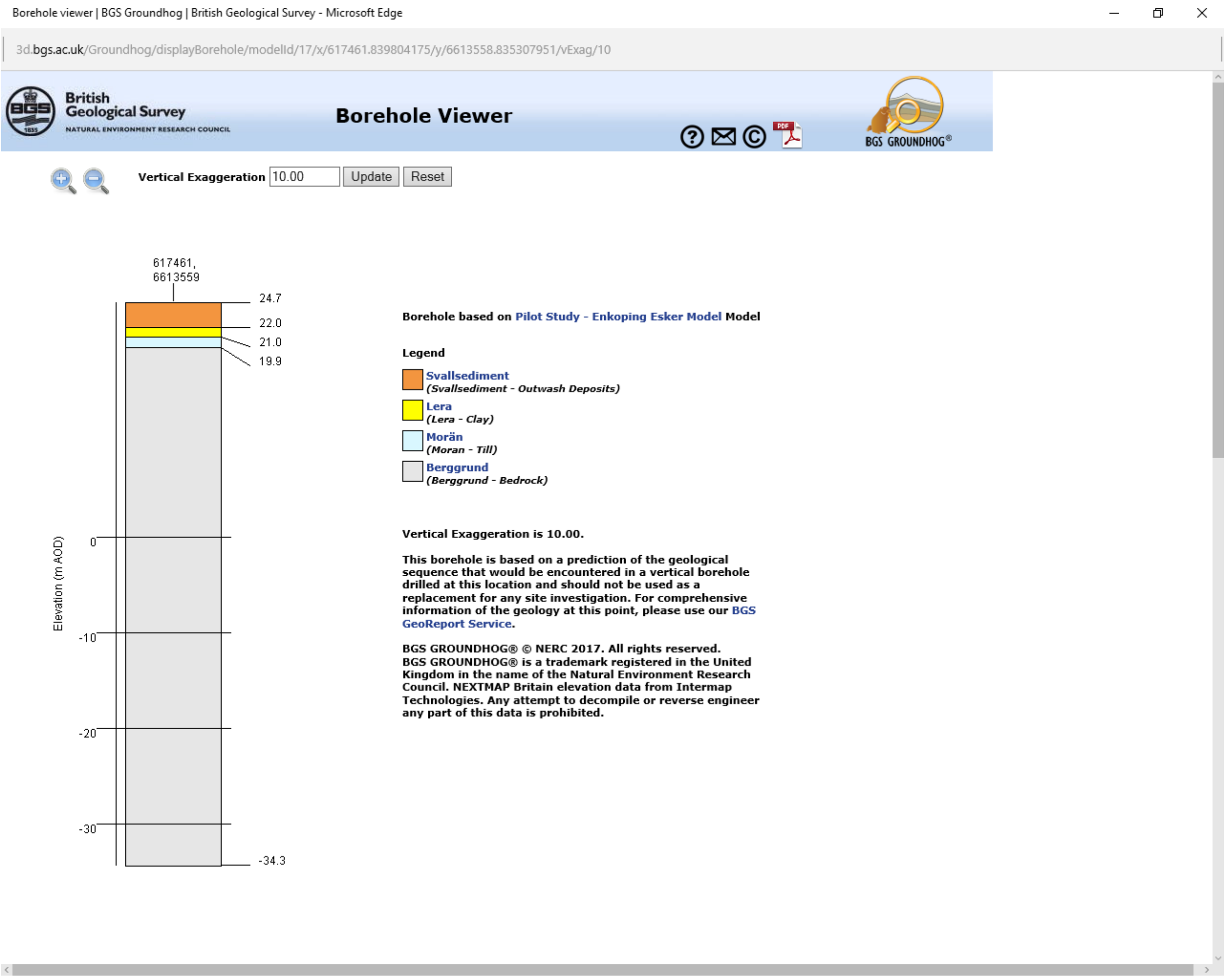


Figure 23 Synthetic Borehole – Web Map Viewer

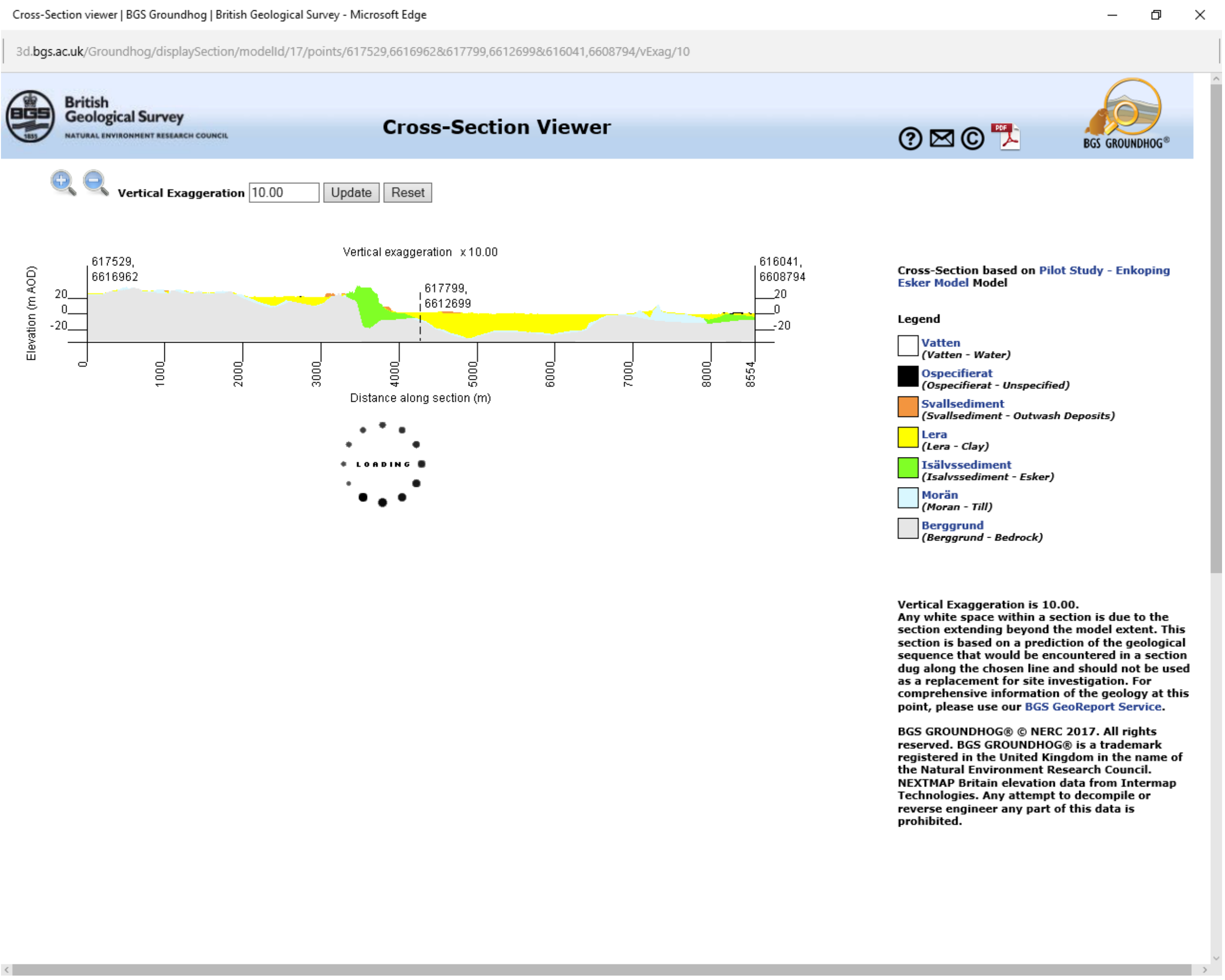


Figure 24 Synthetic Cross-section – Web Map Viewer

To remove the section and begin a new section, close the points that have been generated for the previous section:

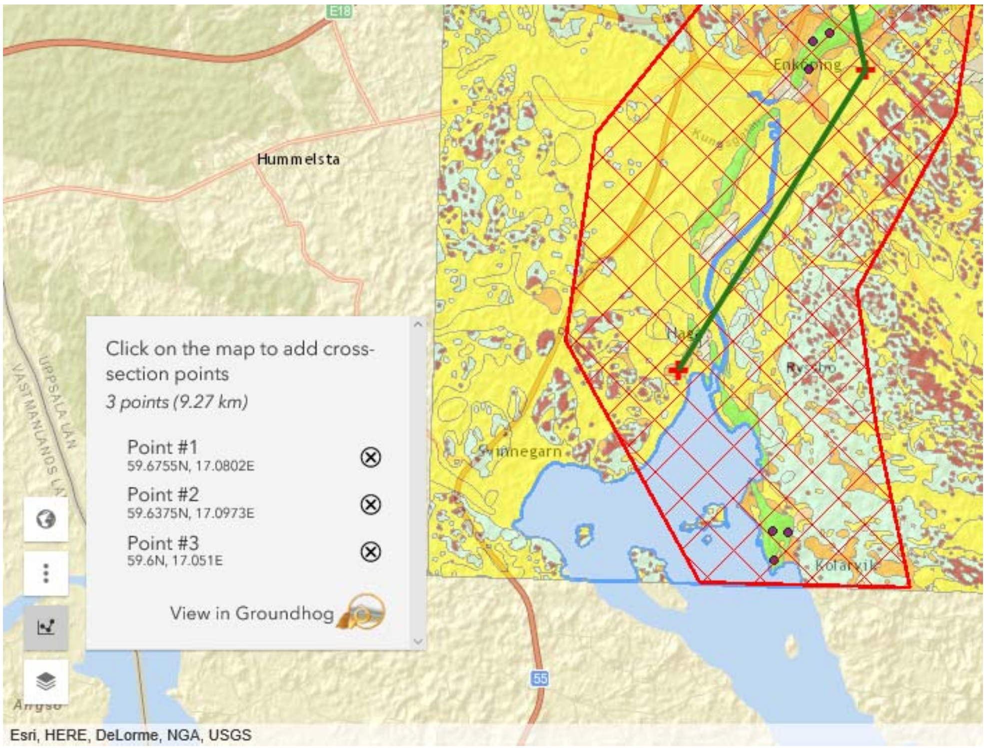


Figure 25 Synthetic Cross-section Points - Web Map Viewer

Horizontal sections are pre-set to 75 pixels and can lowered to improve performance. Elevation is in metres relative to sea-level or the depth in metres below ground level. The horizontal slice will be generated for the whole of the model area.

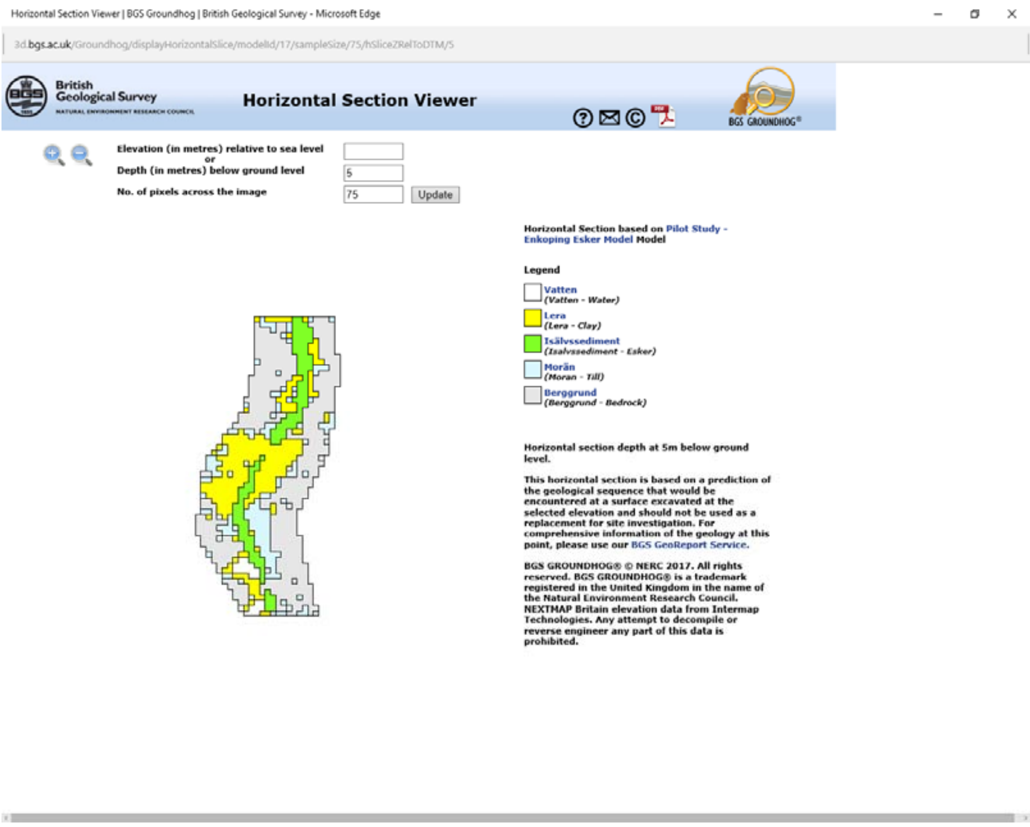


Figure 26 Synthetic Horizontal Slice - Web Map Viewer

6.1.1 Web Map Viewer - Future

If further models were to be hosted by BGS for SGU (e.g. Uppsala), then new arrangements would be needed to cover costs and resources. The actual method in which grids are loaded into the Web Viewer will be changed in the future so that the same mechanism that is used within the Web Viewer will be the same that is implemented in Groundhog Desktop system.

The BGS are developing new methods for visualising 3D data within the Web Viewer such DTM's, cross-sections and boreholes. The 3D Geology of Britain Viewer will be implemented in 2017 and could potentially host and deliver the synthetic model data for borehole, cross-section and horizontal slice generation.

6.2 MINECRAFT

Minecraft is a sandbox video game originally created by Swedish game designer Markus "Notch" Persson, and later developed and published by Mojang. The creative and building aspects of *Minecraft* enable players to build constructions out of textured cubes in a 3D procedurally generated world. Other activities in the game include exploration, resource gathering, crafting, and combat. Multiple gameplay modes are available, including survival mode where the player must acquire resources to build the world and maintain health, a creative mode where players have unlimited resources to build with and the ability to fly, an adventure mode where players can play custom maps created by other players. The spectator mode where players can fly around and clip through blocks, but cannot place or destroy any. The PC version of the game is noted for its modding scene, where a dedicated community creates new gameplay mechanics, items, and assets for the game.

https://en.wikipedia.org/wiki/Minecraft

BGS has developed a methodology for converting 3d models into a Minecraft world, and have released 4 Worlds available for free to download. The methodology takes each geological surface from a 3d model and converts it to a point-cloud, and using a software called FME, writes out this point-cloud to a Minecraft world. The world is made of glass blocks and each block is given the standard BGS colour found in our maps and models. The glass blocks allow the user/player to see through the model slightly to the units above or below as they explore.

The Enköping Esker model allows the player to explore the Esker, and its shape and size under the ground. The Minecraft world contains the eight geological units found in the model, and to finish the world scene, the surface has been covered with a grass block (Figure 28). This could be improved further by including the topography within the FME process to apply roads, railways, water, trees and buildings. This has been applied in the BGS released worlds.

For those new to Minecraft there are numerous resources our there to help the beginner, but a good place to start is the Minecraft Gamepedia -

minecraft.gamepedia.com/Tutorials/Beginners_guide

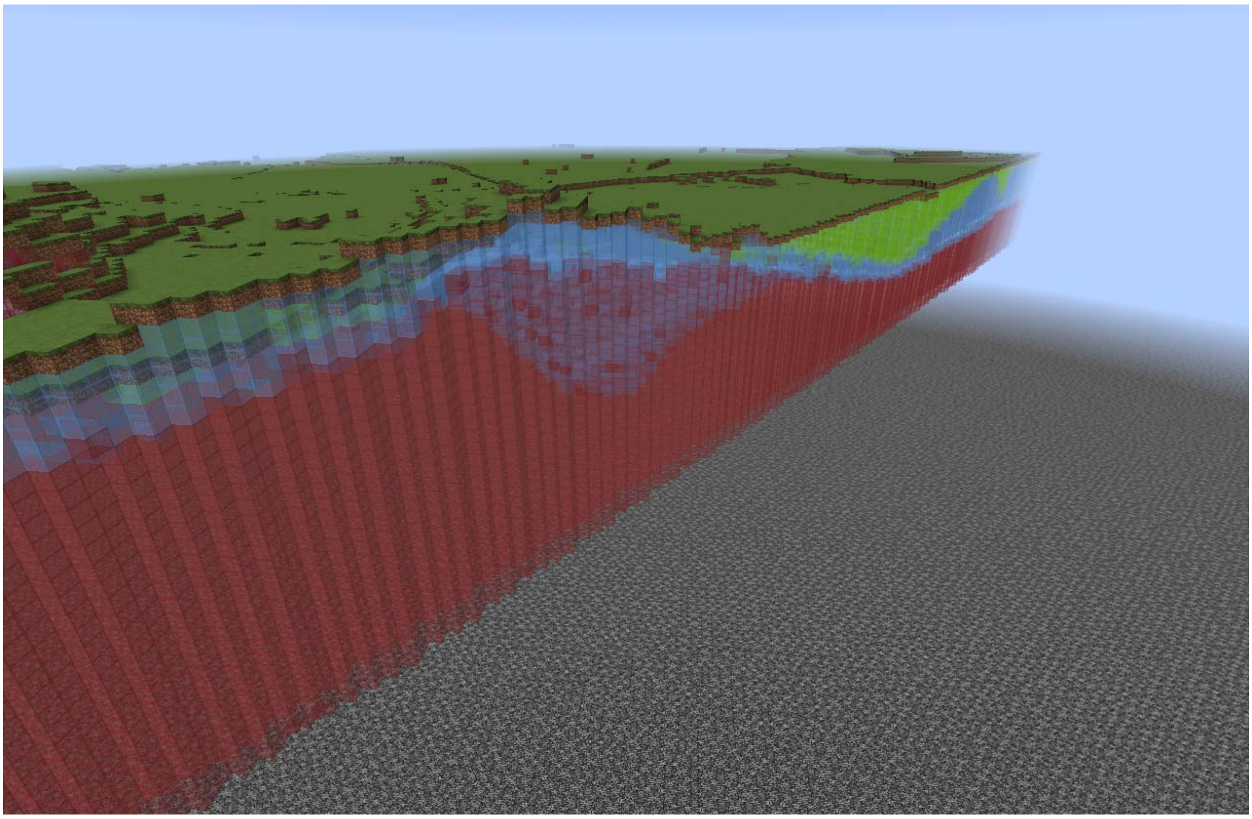


Figure 27 Enköping Esker Model in Minecraft

6.3 GEOVISIONARY

The Enköping model was compiled into GeoVisionary v3.0.17 (Figure 29). The following datasets were included:

1. CAD model of city (Collada (.dae) file)
2. Quaternary Geological Map
3. Boreholes (both as 3D shapefiles and CSV)
4. Cross-sections (3D shapefiles)
5. Shells (GOCAD tsurfs)
6. Grids (ASCII files)

Further training is required by SGU to use the latest version of GeoVisionary (Version 3) as the interface and the number tools, data loaders and interactivity has changed and increased markedly from version 2.5. The newer version includes GPS, WMS/WFS, sensor feed data, SEGY and geophysical data.

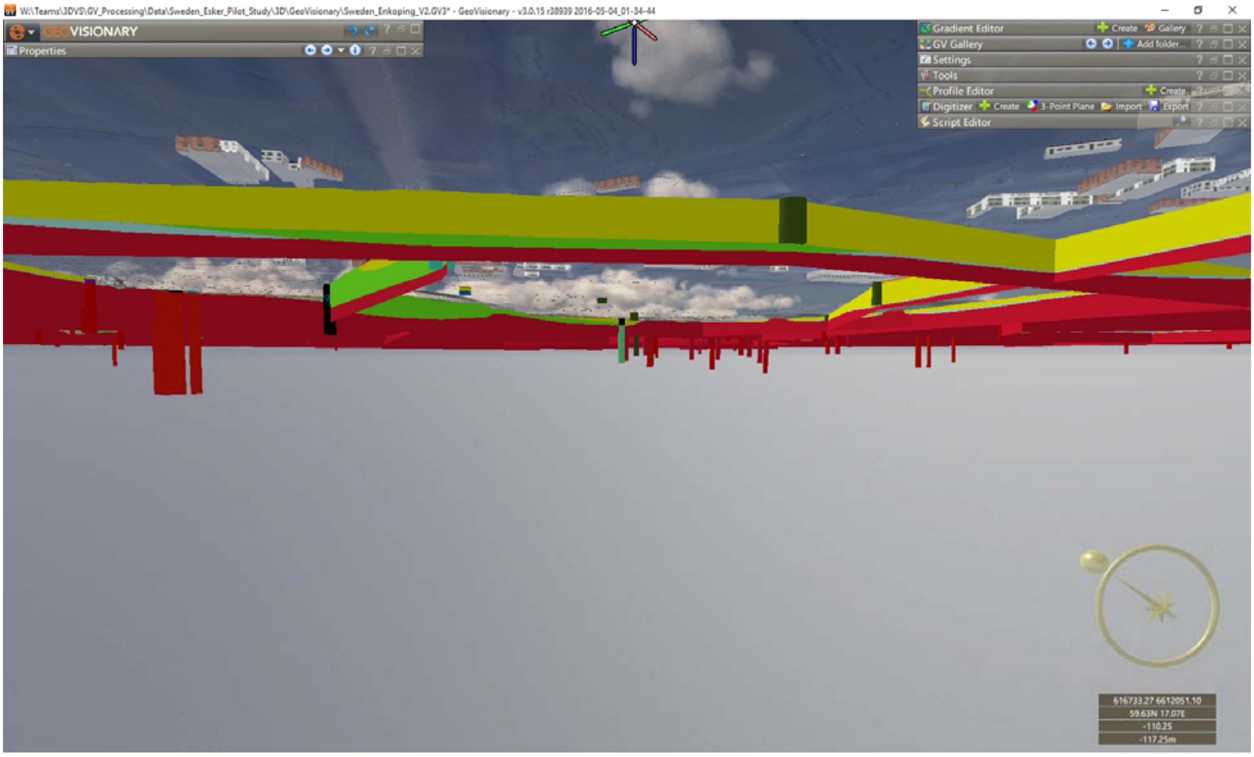


Figure 28 GeoVisionary Project with cross-sections, boreholes, DTM and buildings

6.4 3D PDF

The 3D PDF of the Enköping geological model (Figure 30) was produced in Feature Manipulation Engine (FME) where the model objects (boreholes and cross-sections as 3D shapefiles, and geological unit shells as OBJ CAD objects) were integrated together with the Enköping topographical map. The 3D PDF has been pre-set to a vertical exaggeration to x5. The model tree list is in alphabetical order.

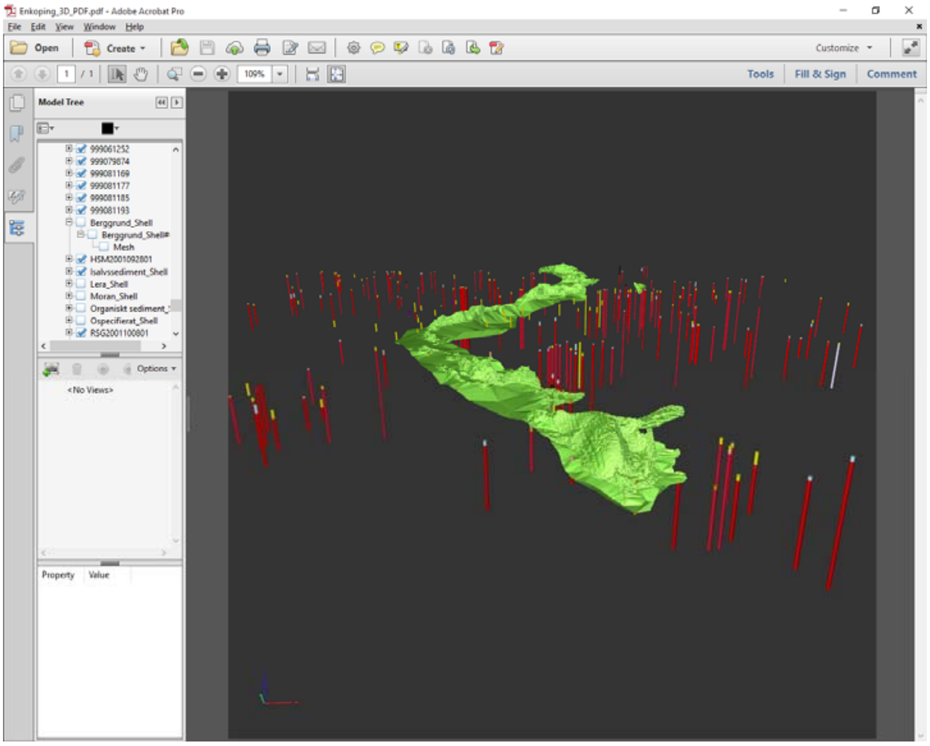


Figure 29 3D PDF image of Enköping esker with boreholes

6.5 BGS GROUNDHOG DESKTOP

BGS Groundhog Desktop GSIS (desktop geoscientific information system) is a graphical software tool developed by the GeoAnalytics and Modelling directorate of BGS for the display of geological and geospatial information such as interpreted (correlated) geological cross sections, maps and boreholes.

Groundhog Desktop is intended as a basic geoscientific information system (GSIS) - a software tool that facilitates the collation, display, filtering and editing of a range of data relevant to subsurface interpretation and modelling. Groundhog Desktop is able to load and display certain types of borehole data, geological map linework, interpreted (correlated) cross sections and faults. It also supports reference data such as elevation models and images and has basic editing capabilities.

http://www.bgs.ac.uk/research/environmentalModelling/groundhogDesktop.html

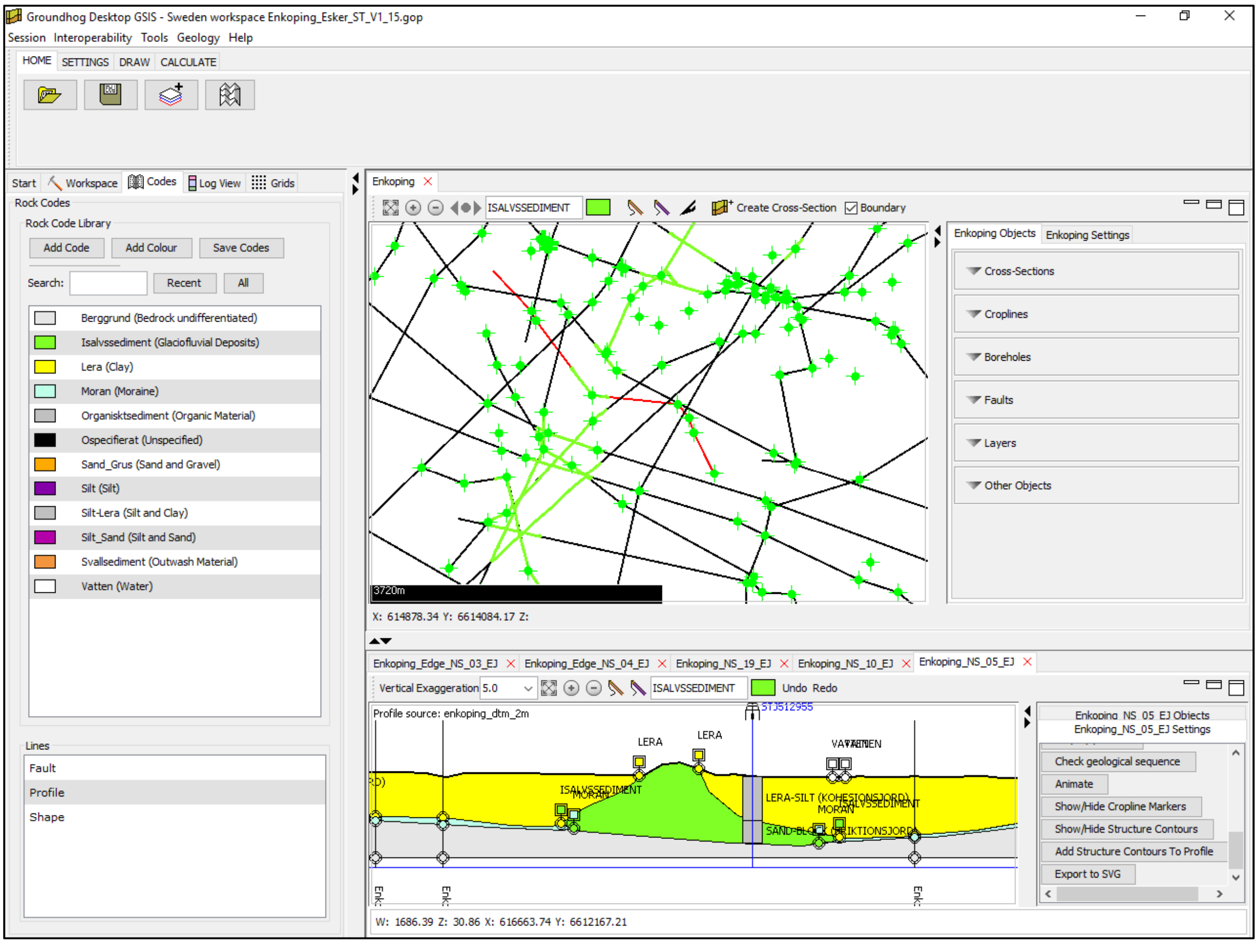


Figure 30 Groundhog Example of Enköping Project

As part of the pilot study, the boundary polygon has been replaced with a boundary for Sweden. Groundhog offers superior snapping capability, therefore the cross-sections were cross checked and snapped in Groundhog desktop by BGS to ensure the cross-section geometries matched and were consistent with the surface and subcrop of the units within the model (Figure 31). The snapping capability and ease in which cross-sections can be drawn in Groundhog Desktop may influence future workflow options for both collaborative and in-house model construction.

6.5.1 Groundhog Desktop GSIS - Future Developments

The BGS objective is to make Groundhog Desktop the most useful general-purpose interpretation tool for the practising geologist. To this end, the development team are committed to ongoing extensions and improvements within the software, with investments in key areas such as:

1. Support for labelling, scaling, printing, PDF and vector graphics output,
2. Support for common formats such as MS Office, CSV, XML, LAS, AGS,
3. Basic 3D visualization and a link to GeoVisionary for advanced work,
4. Support for upscaling and exporting structural models into common numerical models such as MODFLOW and FEFLOW,
5. Tools for working with contours and structural measurements (dip/azimuth),
6. Tools for consuming and displaying data from sensor arrays,
7. Interpolation of surfaces and properties and improved support for grid layers and voxel models,
8. Development of a plugin framework to enable 3rd-party customization of the software.

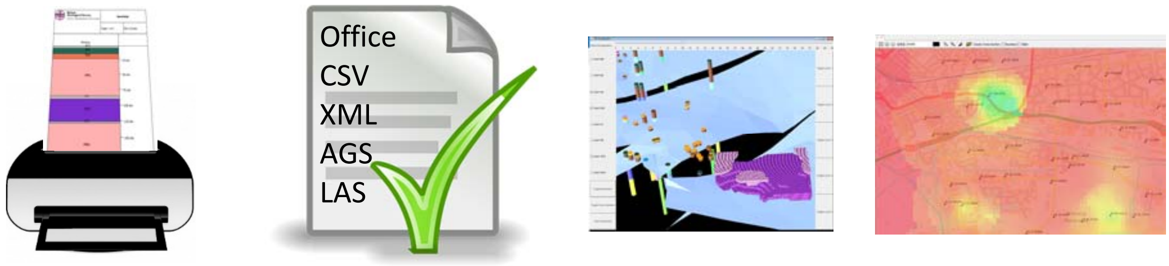


Figure 31 Groundhog Desktop Future Developments

6.6 ASCII GRID OUTPUT

Each geological unit was exported as an ASCII grid using the parameters stated in section 5.3.1. The top, base and thickness of each geological unit was exported. The ASCII grids that showed thickness were particularly useful for checking the model for anomalies that may have occurred during the calculation, and forms part of the post calculation checks for geological models. Below is an example of the Isälvssediment (main esker unit), showing a thickness of up to 65 m in some areas which is almost 20 m thicker than was measured from the national superficial deposits thickness model provided by SGU (Figure 33)

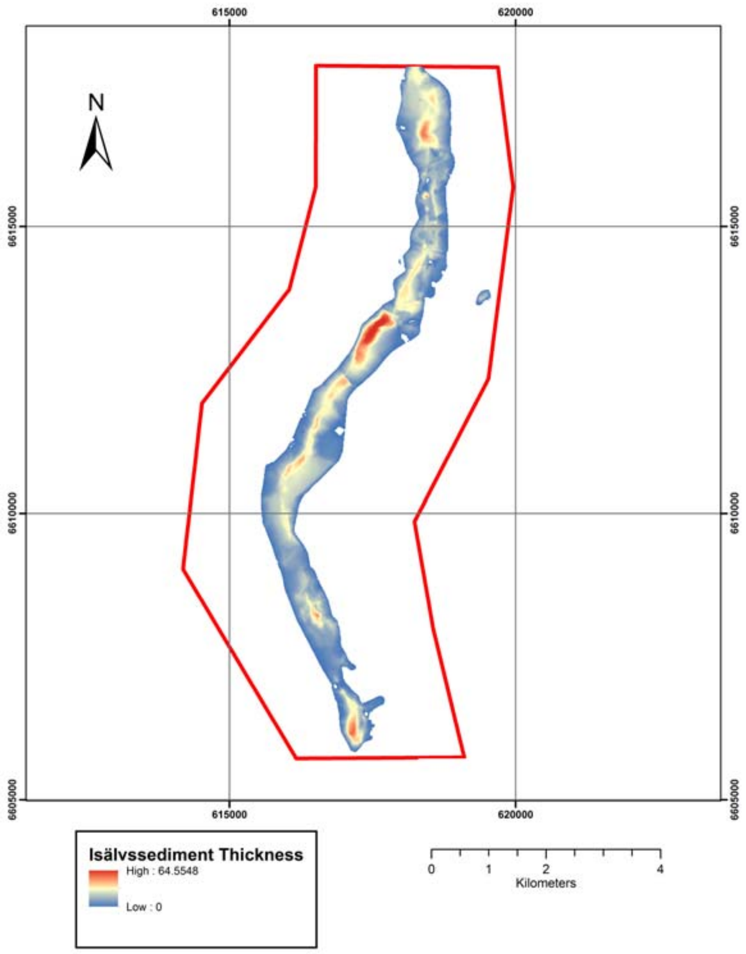


Figure 32 Thickness plot of Isälvssediment (Esker object)

7 Discussion and Recommendations

7.1 INPUT DATA

7.1.1 DTM

The DTM that was provided was in Integer format, which meant that values were rounded up or down to the nearest metre. This in turn means that the ground level can have an accuracy discrepancy of up to 1 metre. This was rectified in the 2nd phase of the pilot study as a DTM with floating data values (decimal places) was made available to the BGS when checking the geological model.

7.1.2 Boreholes

The three borehole datasets that were provided by SGU had Easting and Northing information but lacked start height data (the Z elevation at which drilling commenced). This is a vital piece of data, as borehole start height elevations, if measured accurately, can be compared against modern day DTMs to ascertain whether the land level has changed in elevation from when the borehole was drilled. Boreholes may have been drilled prior to some kind of engineered construction such as a road or railway embankment, or for mineral assessment before extraction. Sometimes, there might be more than one type of Artificially Modified Ground (AMG) change. Therefore, start height data can be used map landscape evolution with regards to land-use and the type of potential AMG deposited or removed (Terrington *et al*, 2015). For this study, all boreholes were given a start height elevation applied from the LiDAR DTM and then further changed once the floating point DTM was made available.

As stated in Section 3.4, the borehole datasets had the drillers log information written. For consistency it would be preferential to have a coding schema in place such as the unlithified coding scheme (Cooper et al, 2006) used at the BGS. This is a computer-coding scheme for unlithified deposits, commonly also referred to as superficial deposits, unconsolidated deposits or engineering soils and is approved in the BS5930 documentation. These include clay, silt, sand, gravel, cobbles, boulders and peat plus all the combinations of these deposits (Figure 34). The report describes the former BGS system for coding such deposits and details a logical system for coding many hundreds of lithological mixtures by the simple use of up to seven letters in various combinations. This makes the process for assessing the dominant lithology easier and colouring up of the boreholes using established legends.

CLAY: C

SILT: Z

SAND: S

GRAVEL: V

COBBLES: L

BOULDERS: B

PEAT: P

BS5930 description	RCS description	CODE
SAND	SAND	S
Clayey SAND	SAND, clayey	SC
Silty SAND	SAND, silty	SZ
Gravelly SAND	SAND, gravelly	SV
Cobbly SAND	SAND, cobbly	SL
Bouldery SAND	SAND, bouldery	SB
Silty clayey SAND	SAND, clayey silty	SCZ
Gravelly clayey SAND	SAND, clayey, gravelly	SCV
Gravelly silty SAND	SAND,silty, gravelly	SZV
Bouldery, cobbly, gravelly, silty, clayey, SAND	SAND, clayey, silty, gravelly, cobbly, bouldery	SCZVLB
And so on		

Figure 33 Example of Unlithifed Coding Scheme

The Association of Geotechnical and Geoenvironmental Specialists (http://ags.org.uk/) are in the process of adopting this coding schema in their latest guidance for coding and distributing boreholes data.

7.1.3 Bathymetry

No bathymetry data was provided, however a water body (vatten) was incorporated into the geological model using estimation. Bathymetry could be added to the terrain model to improve the geometry and thickness of the underlying superficial units in these areas.

7.2 WORKFLOW RECOMMEMENDATIONS

In the future, it might be preferential to start all cross-section correlation in Groundhog Desktop to utilise the cross-section snapping capability and then go to the SubsurfaceViewer for calculation and subsequent checking of thicknesses in ArcGIS. This will speed the checking process up as mismatches between cross-sections will be reduced and the tolerance at which correlation lines are snapped to outcrop and subcrop will be increased.

Image sections are easier to locate and move in the backdrop of a cross-section in Groundhog Desktop compared to GSI3D and the SubsurfaceViewer, which will save time.

The base of the model needs to be at a consistent level for neatness of outputs. This can either be done at the correlation stage or by adjusting the values in the xml project file.

Section names can also be adjusted in this way, or renamed in Groundhog Desktop if necessary. The provided schema at BGS is to have the project name followed by section orientation and then number, and the ID of the geologist doing the correlation (e.g. Enköping_WE_1_RTE). These have been re-named by BGS in the Enköping GSIPR.

7.2.1 Stochastic Modelling

In some areas where the data density and detail is sufficient, stochastic modelling might be preferable to the deterministic methodology described in this report. This methodology has been used at the BGS to produce lithofacies models using GOCAD-SKUA®. The reference below has further information and detail about this modelling methodology:

Kearsey, T, Williams, J, Finlayson, A, Williamson, P, Dobbs, M, Marchant, B, Kingdon, A, and Campbell, D. 2015. *Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK*. Engineering Geology, 187, 98-112..

http://nora.nerc.ac.uk/509487/1/Kearsey%20et%20al%202015.pdf.

DINOloket – Provides access to information and data from GeoTOP, a voxel model that (100 x 100 x 0.5 m) that goes to a depth of 50 m and has split the lithostratigraphy up in lithological classes based lithology and grain size. This methodology has been developed by TNO and has been widely documented (Stafleu et al 2012):

https://www.dinoloket.nl/en/want-know-more

7.2.2 Uncertainty in geological models

"The standard uncertainty layer is the display of the location of all input data and section locations, such as in the form of borehole fishnet density plots. Other methods can be applied if agreed upon in discussion with the client and costed appropriately" – this is what is set out in this report and is stated in the 'Specification guidance for input and output data formats and deliverables for commissioned 3D geological models' report (Kessler et al, 2016).

A simple example of a fishnet density plot is in figure 35, which shows the number of boreholes per square kilometre. This does not take in account the depth of the boreholes. Further fishnet density plots can be produced to see how many boreholes intersect major horizons on a square kilometre basis using the depth of the base horizons and the length of the borehole drilled. This will give an indication of how constrained each horizon by boreholes.

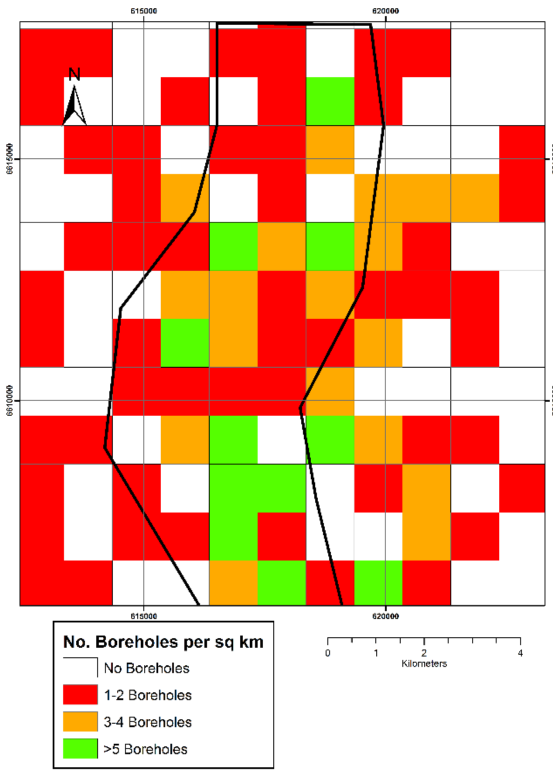


Figure 34 Fishnet density plot so the number of boreholes per square kilometre that were used in the construction of the cross-sections

Appendix 1

GSI3D model (all types) NGM corporate check

Model name with version number	Lead modeller	Project Leader TL reviewer	Date submitted	Technical checker Scientific QA reviewer	Date completed
Enköping Model	Eva Jirner (SGU)	Ricky Terrington (RT)	09/12/2016	Steve Thorpe (ST)	06/01/2017

Major limitations that should be addressed are shown in **bold**. Legacy models may not meet all the checking criteria but may still be included in NGM with noted limitations in metadata shown below in ***bold italics.***

23/10/14: to expedite QA checking, items below marked ** are considered not critical to legacy and internal model approval and may be disregarded.

NB: Model contains # units and # cross-sections.**

Mainly technical checking and metadata QA

Check	Details	QA comment	Name	Date
1. Metadata completed				
Check the metadata report contents page and report details: 1. Is a map of fault distribution included? 2. Are all the units modelled listed? 3. Are the sources of legacy and baseline data identified with version numbers including raster backdrops for maps and sections? (see also 11.4 below) 4. Is the model approval form completed and signed off? 5. Have any raster backdrops for map and section window stated in the metadata been included?		1. N/A – Superficial geology only 2. Yes – in the report and GVS 3. Yes, all included in the report 4. N/A, the Enköping model is not part of the national geological model in the UK 5. Yes, all raster backdrops have been stated in the report	RT	03/01/2017
2. Metadata rules, limitations and exceptions				
1. Check the statements in the metadata fit with the model itself? Is it fit for the purposes claimed in the metadata. 2. Do any limitations stated indicate it is unfit for any other purposes?		1. N/A. Metadata document not produced 2. No – generic limitations have been mentioned only	RT	03/01/2017
3. **Compliance of geological naming conventions**				
1. Check bedrock units against Lexicon and Dic_Rock_All* 2. Is the geological succession used documented in metadata and is it		1. N/A BGS internal procedure only 2. Yes – follows that of the Uppsala model	RT	03/01/2017

Check	Details	QA comment	Name	Date
reasonable, based on regional GVS's, stratigraphic charts etc 3. Any Quaternary deposits must either have lexicon codes or be components of parent units with lexicon codes, these should be based wherever possible on the schema in McMillan et al. A table of hierarchical relationships should be included in the metadata 4. Do artificial deposit names correspond to lexicon codes and recommended deposit types, suffixes may identify multiple units e.g. MGR_1 etc 5. Are any lenses or exceptions clearly stated?		3. N/A – Swedish model 4. N/A 5. Yes		
4. Compliance of model component naming conventions				
1. Are GSI3D files correctly named? 2. Is section naming convention understandable, or documented? ** 3. Are faults correctly named and clean? ** 4. Is the colour schema reasonable? **		1. Yes 2. Yes 3. N/A – Superficial model only 4. Yes – as prescribed by SGU	RT	03/01/2017
5. Compatibility with incorporated or adjacent models				
1. Check the metadata, model approval form, GDI for detail of adjacent/incorporated models. Has appropriate action been taken to fit with or incorporate existing or adjacent models? ** 2. Have surfaces faults or other objects generated outside the modelling workspace been incorporated into the model, is the source documented in the metadata, check consistency **		1. N/A although the geology is similar to that in the Uppsala geological model 2. Yes – all external data sources have been listed and documented	RT	03/01/2017
6. DTM				
1. Does the DTM contain obvious errors e.g. woods, spikes, note if observed. ** 2. Does it honour the geomorphology of landforms such as valleys, terraces, eskers etc and also areas of artificial ground (e.g. quarries, land-raise)? 'Geologically reasonable'? 3. Does the resolution of the geological envelope or baseline data correspond to the DTM resolution?		1. DTM does contain spikes and is blocky. Probably the method that has been used to process the DTM 2. Yes – need confirmation from SGU modellers 3. Yes – need confirmation from SGU modellers	RT	03/01/2017
7. Faults				
1. Fault-fault contacts should exist and faults should be neatly truncated at junctions. There should not be fault-fault gaps (check at calculation)		1. N/A		
8. Geological unit surfaces (QA scientist to use Arc grids generated by Technical checker)				
1. Check for large spikes in calculated surfaces by uncovering the calculated surfaces or volumes ~~in 3D~~ 2. Check for holes within envelopes 3. Are the units 'geologically reasonable'? 4. Do lenses calculate correctly?		1. Yes – thickness checks have been done using the ASCII grids 2. Done – map has been used. 3. Done 4. N/A no lens units	ST/RT	03/01/2017

Check	Details	QA comment	Name	Date
9. Systematic technical check of cross sections				
For each section (**Technical check only**): 1. Is the section correctly orientated? ** 2. Are correlation lines trimmed to section ends? 3. Are croplines snapped? 4. Are crossing sections snapped?		1. Yes 2. Yes 3. Yes 4. Yes	ST	03/01/2017
10. Borehole logs				
1. Do they generally fit the DTM or does the metadata say to hang from the DTM? ** 2. Do the correlation lines reasonably match the logs' LEX-RCS codings (or as qualified in the metadata)? 3. Are they in their correct geographical positions (as inferable from their GLs vs the DTM)? ** 4. Are terminal depths illogically interpreted as unit bases?		1. Yes – all boreholes are hung from DTM 2. N/A BGS internal only 3. Yes – see point 1 4. No.	RT/ST	03/01/2017

Mainly scientific QA

11. Fidelity of model to data				
1. Check that a good representation of available boreholes are included in sections 2. Is the retained fault network adequately honoured allowing for appropriate simplification from map-face? 3. Are structural measurements (e.g. dips) on the corresponding map taken into account as far as reasonable? 4. Check no major data source has been left out (refer to metadata) ** 5. Check modelled horizon extents correspond to geological linework of the appropriate scale? (subject to revisions carried out when modelling, noted in metadata)		1. Yes – 44% 2. N/A 3. N/A 4. Geosigma surfaces and data points could be incorporated at a future date 5. Yes – geological model linework matches map linework provided.	RT	03/01/2017
12. Scientific QA check of cross sections				
See items 11.1-11.5 above. 10-20% of sections checked by scientific QA:		a. [section name – comment]		
13. Fit for NGM purpose				
1. Does the model have sufficient extent and stratigraphic coverage to comprise a credible part of an integrated multi-scaled national model? If not, recommend for either RESTRICTED folder (low priority) or for PENDING ACTION folder.		1. N/A		
14. Any other comments				
		1. Geological check should be undertaken by somebody in SGU.	RT	03/01/2017

* Extract from BGS IDA Rock Dictionaries (RCS) Search and Viewing Application:

BGS.DIC_ROCK_ALL. This dictionary includes all DIC_ROCK_NAMEV3 entries, together with: a. codes for specified composites, such as those approved for use on maps. These composites are defined in terms of the single entries in DIC_ROCK_NAMEV3. b. a number of pragmatic “non-rock” entries that are required to facilitate full coding of (for example) borehole records.

DIC_ROCK_NAMEV3 is Version 3 of the largely RCS-compliant dictionary of rock names - the currently approved version. Most of its content is RCS-compliant, but for the time being it still includes a number of “legacy” entries intended to support authentic coding of historical records. Entries include unique “root” names from the RCS (e.g. “basalt”) as well as a gradually increasing set of approved qualified root names.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

Åse, L.E., Bergström, E. 1984. The ancient shorelines of the Enköping esker, Mälar Valley, southern Sweden. Geografiska Annaler A, 66, 131-149.

Cooper, A.H.; Kessler, H.; Ford, J. 2006 *A revised scheme for coding unlithified deposits (also applicable to engineering soils).* British Geological Survey, 45pp. (IR/05/123)

Kearsey, T, Williams, J, Finlayson, A, Williamson, P, Dobbs, M, Marchant, B, Kingdon, A, and Campbell, D. 2015. *Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK*. Engineering Geology, 187, 98-112..

Kessler, H.; Terrington, R.; Wood, B.; Ford, J.; Myers, T.; Thorpe, S.; Gow, H.. 2016 *Specification guidance for input and output data formats and deliverables for commissioned 3D geological models.* Nottingham, UK, British Geological Survey, 6pp. (OR/16/052)

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Kessler, H., Mathers, S. and Sobisch, H.G., 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. Computers & Geosciences, 35(6), pp.1311-1321.

Kløve, B., Ala-aho, P., Okkonen, J & Rossi, P. 2012. Possible effects of climate change on hydrogeological systems: results from research on Esker aquifers in northern Finland. In: Treidel, H., Martin-Bordes, J.L., Gurdak, J.J. (eds). Climate Change Effects on Groundwater Resources – a Global Synthesis of Findings and Recommendations, Taylor & Francis, London. pp.305-318

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Warren, W.P.; Ashley, G. 1994. Origins of ice-contact stratified ridges (eskers) of Ireland. Journal of Sedimentary Research, 64, 433-449.