Chapter 23: Three-Dimensional Geological Mapping and Modelling at the Geological Survey of Sweden

Lars-Kristian Stölen¹, Philip Curtis², Lars Rodhe³, Eva Jirner⁴ and Ildiko Antal-Lundin⁵

¹ IT Strategist, Geological Survey of Sweden (SGU), Box 670 SE-751 28 Uppsala Sweden.
², ³ Dept. Physical planning, Geological Survey of Sweden (SGU), Box 670 SE-751 28 Uppsala Sweden.
⁴ Dept. Geohydrology, Geological Survey of Sweden (SGU), Box 670 SE-751 28 Uppsala Sweden.

Introduction

The Geological Survey of Sweden – SGU – is the expert agency for issues relating to bedrock, soil and groundwater in Sweden.

Our key task is to meet society’s need for geological information. SGU is also responsible for the national Good-Quality Groundwater objective, which also involves reducing the use of natural gravel.

Organizational Structure and Business Model

The Geological Survey of Sweden – SGU has its main office in Uppsala and local offices in Luleå, Malå, Stockholm, Gothenburg and Lund. The total staff of SGU is 300. SGU is an agency under the Ministry of Enterprise, Energy and Communication.

SGU is organized in five departments, Mineral resources, Physical Planning, Geohydrology, Mining Inspectorate and Operational Support.

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All the developments of geodatabases and web map services are based upon national and international standards where available.

Overview of 3D-Modelling Activities

Until a few years ago, the 3D-modelling activities at SGU were restricted to the interpretation of different geophysical data, both from airborne and ground surveys. Now, 3D-modelling, including layer-modelling, implicit as well as explicit, is undergoing a rapid development at SGU. We expect that in the near future, modelling will be incorporated into our standard mapping methods, for example, involving the ore-bearing structures, local and semi-regional subsurface geology and layered geological formations in general.

Below are listed some of our ongoing projects/activities that include 3D-modelling aspects.

• Soil-depth/rockhead modelling (implicit modelling): the national soil depth model, one of SGU’s most requested products, is remodelled/updated at least once a year, using new information from bore holes, geophysical measurements and surface mapping.

• Aquifer identification and modelling: SGU is commissioned by the government to identify and map aquifers needed for the water supply in areas frequently subject to shortage during drought. The modelling activities include producing resistivity-models from airborne TEM-measurements (Transient Electromagnetic Measurements), geological layer sequences and voxel modelling. The geological features modelled are eskers and other glacial deposits (see case history below), as well as sedimentary bedrock (Proterozoic and Mesozoic).

• Fault modelling in urban areas: engineering geological information from existing tunnel systems is combined with data from other sources to produce a 3D-model of the fault network in the Stockholm region. The faults are characterized and combined with soil depth, rock and soil type profiles in a 3D presentation on our website. The aim is to provide a basis for the initial planning stages of future infrastructure projects.

• Mapping 3D-distribution of acidic sulphate soil in coastal areas of northern Sweden (implicit modelling).
• Mapping 3D-distribution of quick clays (based on resistivity models).

• Overview 3D-model of Swedish bedrock (Figure 1): a three-dimensional model has been created representing the lithotectonic units and their bounding regional deformation zones in the bedrock of Sweden. The model is a development of the existing lithotectonic subdivision included in the bedrock map of Sweden at a scale of 1:1 million. The model has linked descriptions and is available on our website. The aim is to provide a basic framework and background information for more detailed regional and local scale models.

• Near mine semi-regional 3D-modelling in Bergslagen area, Lindesberg (Figure 2).

Resources Allocated to 3D-Modelling Activities

About 10 geoscientists (bedrock- and Quaternary geologists, hydrogeologists and geophysicists) are involved in geological (explicit) modelling, of which 2-3 allocate most of their working hours to modelling.

The total budget of the projects which include 3D-modelling is in the order of 20 MSEK (200,000 euros). It should be mentioned that these projects comprise not only actual modelling, but also field investigations, airborne geophysical surveys (TEM), collection of data from various external archives, development of database and webservices. In fact, the actual modelling constitutes only a minor part of the total costs.

Overview of Regional Geological Setting

The bedrock of Sweden consists of three main components: Precambrian crystalline rocks, the remains of a younger sedimentary rock cover and the Caledonides.

The Precambrian rocks are part of a stable rock area known as the Baltic Shield (or Fennoscanadian Shield). The oldest rocks in Sweden are Archaean, i.e. they are more than 2,500 million years old and only occur to a limited extent in the northernmost part of Sweden. The rocks in the rest of the north of Sweden and in the eastern and southern parts of the country are mostly between 2,000 and 1,650 million years old. They formed, and were in many cases also metamorphosed, in connection with the Svecokarelian orogeny. That orogeny has also affected the Archaean rocks. The bedrock in southwestern Sweden is mainly between 1,700 and 1,550 million years old. It was metamorphosed during the Sveconorwegian orogeny, which occurred about 1,100–900 million years ago.

Phanerozoic sedimentary rocks are resting upon the Precambrian shield area. They are less than 545 million years old and cover large parts of Skåne, the islands of Öland and Gotland, the Östgöta and Närke plains, the Västgötö mountains, the area around Lake Siljan in Dalarna and areas along the Caledonian front.

Figure 1. Overview 3D-model of Swedish bedrock. Produced in GoCad/Mira Geoscience software.
in northern Sweden. The youngest rocks in Sweden are Tertiary rocks, formed about 55 million years ago. They occur in the most southerly and southwestern parts of Skåne.

The Caledonian orogeny is the most recent in Sweden – it occurred about 510–400 million years ago. The rocks in the mountain chain vary in age from Precambrian to Silurian, which means that they are more than about 420 million years old.

The overburden is mainly formed by numerous periods of glaciation and deglaciation. The most common soil type is till, covering about 75 % of the landscape.

The average thickness of the till deposits is less than 10 m. A network of glaciofluvial eskers appears all over the country. Many of these eskers are aquifers of great importance to the supply of drinking water. Low-lying areas of Sweden were covered by the sea subsequent to the last glaciation, due to the isostatic subsidence of earth crust. In these areas, there are widespread sedimentary clays and frequently occurring littoral sediments.

**Data Sources**

- Updated 2D-geological maps (bedrock and Quaternary deposits including marine geological maps); harmonized codes, revised geometry, scale 1:25,000 – 1:50,000. For regional models, maps in smaller scale (<1:100,000) may be used.
- DTM (2 m grid) - national data set.
- Soil depth/rock-head model - national dataset developed by SGU (undergoes revision during the modelling process).
- Published geological sections - various sources and quality.
- Bore hole data from the national well archive at SGU: providing information of depth-to-rock head, sometimes also lithology. Variable accuracy. At present about 0.5 million wells are registered. Well-drilling companies have a statutory obligation to deliver drilling logs to SGU.
- Bore hole data from groundwater investigations from SGU’s own surveys as well as from technical consultants. Consultants have a statutory obligation to deliver results from groundwater investiga-
tions performed in connection with ground water extraction.

- Geotechnical information, mainly from the Swedish Transport Administration and municipalities – voluntary agreements. At present, information from about 300,000 geotechnical drillings are included in SGU databases and used mainly for soil depth/rock- head modelling.
- Resistivity models based on airborne TEM-measurements (transient electromagnetic measurement). There is an ongoing program which includes airborne TEM- measurements mainly in areas with younger (Paleozoic and Mesozoic) sedimentary bedrock.
- Information from geophysical ground measurement from a variety of investigations and methods.
- Marine geological sections based on seismics.
- Bore hole data from the drill core archive in Malå (exploration drill cores)
- Potential field data (magnetic and gravity)
- Electromagnetic data
- Petrophysical data

When working with data that we have collected ourselves, often from our soil and bedrock mapping campaigns, we have a good understanding of the applied mapping standards, appropriate scale and locational accuracy, even though all of these are variables rather than constants and have changed over the years. This type of observational point information, along with its interpretation into traditional maps, has formed the basis for further interpretation into 3D visualizations and models.

There is a growing trend now of incorporating information produced by others into our datasets and resulting interpretations, with associated advantages, disadvantages and challenges. Legal issues concerning the definition and division between raw data, information, design and intellectual property are currently proving to be a barrier to the efficient use of much of this information. Data security and secrecy issues, especially those connected to underground infrastructure, have become more sensitive over recent years. This has led to data being effectively isolated, with organisations unwilling to take the risk of losing control of what they perceive as being ‘their’ data, even though often it is the Swedish taxpayer who has directly or indirectly paid for it.

### 3D-Modelling Approach

The applied modelling approach is naturally dependent on the type and aim of any particular model. For example, 3D bedrock models have been a further development from our bedrock maps and additional information. These have involved largely explicit techniques. Other types of models have used explicit techniques to generate a basic model framework that has been further developed using implicit techniques with numerical modelling. An example would be local aquifer models, assessing groundwater fluctuations and availability.

### Clients

For the most part, current 3D-modelling has most focus on groundwater, aiming at ensuring a sustainable water supply and, therefore, municipal water authorities are an important client group. Close cooperation with these clients is essential. When modelling an aquifer, the aim of the modelling is defined after consultation with the client. The client is expected to contribute with information e.g. bore hole information and, if needed, complementary field investigations. This means that we only model aquifers at a detailed scale (1:50,000) when there is a client that is willing to contribute.

Other important client/client groups for SGU’s 3D-information:

- The Swedish Transport Administration, using the national soil depth/rock-head model and modelled deformation zones. This client contributes by providing bore hole information for modelling as well as financially to the development of the soil depth model in areas where new railway routes are planned.
- The Geotechnical institute of Sweden, using 3D-information on soil type distribution (including the soil depth model) for developing methods for predicting construction costs and also for mapping quick clays and landslide risks. The institute, and other stakeholders within this sector, contribute financially to some extent.
- We see an increasing interest from local and regional environmental authorities and physical planners to use 3D-geological information, although only in a few cases have we established cooperation with these client groups.
- Exploration and mining companies.
- Universities.

If any client needs support in using the aquifer models, they may take advantage of SGU’s “Loan-a-geologist” free service.

### Recent Jurisdictional-Scale Case Study Showcasing Application of 3D-Models

The city of Uppsala, the fourth largest Swedish city, is located 71 km (44 miles) north of Stockholm. Uppsala Water provides municipal water to the city of about 141,000 inhabitants by extracting groundwater from the Uppsala esker. With a growing population, safeguarding the esker’s continued viability as the main water supply for Uppsala, is a major concern for Uppsala Water.

The Uppsala esker is a key water source. It trends northeast to southwest across the Uppland region and
has a total length of 200 km (125 miles), a maximum width of 1 km (3300 ft), and a maximum height of 75 m (245 ft) (Johansson 2006). Most of the esker is covered with clay, providing some protection against contamination from adjacent land uses, but regulation of nearby activities is very important where the esker is more exposed. In 2013 Uppsala Water, in cooperation with the Swedish Geological Survey (SGU), initiated a strategic study of the central portion of the Uppsala esker. SGU developed a digital database and a 3D geological model to investigate the geometry and stratigraphy of the Quaternary deposits of the entire groundwater catchment area. The 3D geological model covers an area of about 300 km² (117 miles²) and extends about 42 km (26 miles) in a north-south direction (Figure 3). Subsequently the 3D geological model units were assigned appropriate hydraulic properties, producing a conceptual 3D hydrogeological model of the main Uppsala esker, smaller tributary eskers, and the entire recharge area. The model revealed that the maximum thickness of the main esker to be at least 30 m (100 ft), and it is often in direct contact with the bedrock. The tributary eskers are thinner, usually with thicknesses of 5-10 m (16-33 ft).

Uppsala Water used the 3D hydrogeological model to develop a numerical groundwater flow model. The process is similar to that described by Royse et al. (2010). The groundwater model is an important tool for evaluating the viability of current and future water supplies. Groundwater conditions are controlled by a predominant flow from north to south and annual recharge of approximately 250-300 mm/yr (10-12 in/yr) in areas where the esker outcrops.

The model has also been used as a base for a vulnerability map helping the city planners and the local environmental authority to minimize the risks of contamination of the groundwater body. In 2018, there was an emission of diesel oil from an overturned tanker within the esker area. The model, visualized by a web-based “section visualizer” was successfully used to plan the remediation actions. This web-service is run by the British Geological Survey.

A printed physical 3D-model of the Uppsala esker, with removable layers, has proved to be a very efficient eye-opener to planners, decision makers and politicians, in making them understand the importance of being aware of the subsurface geology.

Figure 3. Overview of Uppsala esker model. The inserted section shows a representative generalized lithostratigraphy of the esker. Red: crystalline bedrock, light blue: till, green: glaciofluvial sand and gravel (esker), yellow: clay. Vertical exaggeration of section: 5x.
when planning for smart cities and a sustainable urban development.

**Current Challenges**

Due to the stresses on Sweden’s groundwater supply the survey received funding for a 3-year 3D programme (2018 – 2020) with focus on 3D-modelling of groundwater resources and development of modelling workflows. The modelling activities are based on TEM geophysical surveys in areas with sedimentary rocks and on quaternary mapping, georadar, boreholes and geophysics when modelling ground water within eskers.

The main challenge for the survey is to develop processes for modelling, storage, life-cycle management and distribution of 3D data and models as well as connecting these processes to a geological framework/architecture, while at the same time solving standardization and quality issues.

SGU is using several 3D-modelling software solutions depending on the purpose of the modelling. The diversity of modelling software results in interoperability problems regarding storage, sharing and distribution of 3D-models.

**Lessons Learned**

- When working with ‘3D’ it is natural to have an initial focus of the modelling and visualization software tools available. As our experience grows it becomes obvious more emphasis needs to be placed on all aspects of the input data and storage of the output products. The key phrases being data quality, product compatibility and flexibility.

- Concerning the input data, complex fundamental issues still need to be resolved. These issues involve data ownership, right of use, secrecy and security. Security is a never-ending issue as technology continues to rapidly develop. These are difficult issues for any geological survey to solve by themselves and require external specialist resources, however, unless they are resolved, they remain a significant barrier to effective modelling work.

- As our experience grows with 3D-modelling and it becomes incorporated in all our workflows, it becomes less and less relevant to single out ‘3D’ as being a specific subject area.

**Next Steps**

- Creation of high-resolution 3D geological models for the underground in the major cities and areas with large investments in the national infrastructure (railroad, road and housing) to meet the ever-increasing demand for a quantitative characterization of the subsurface.

- Solving the interoperability issues when providing 3D-models and geological data to support Building Information models (BIM) in urban underground planning have a high priority for future work.

- Updating the geology part of the national framework for geodata in 3D.

- Providing data for pan-European 3D initiatives i.e. the European fault database within the GeoERA project.

- Participate in Nordic cooperation on 3D geological model database development.

**References**


