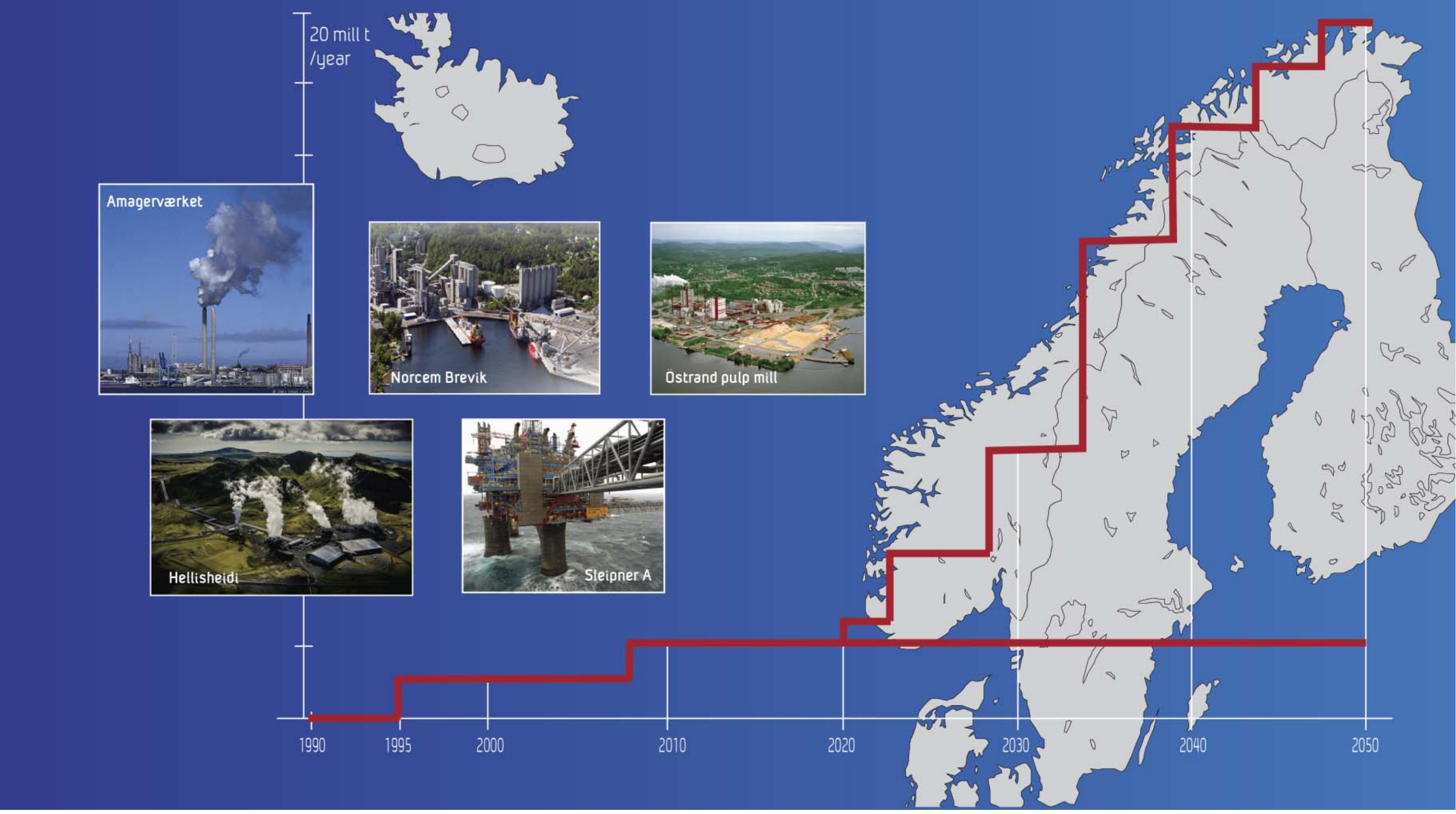

Review of existing CO_2 storage databases

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NORDICCS Technical Report D 6.1.1201

September 2012

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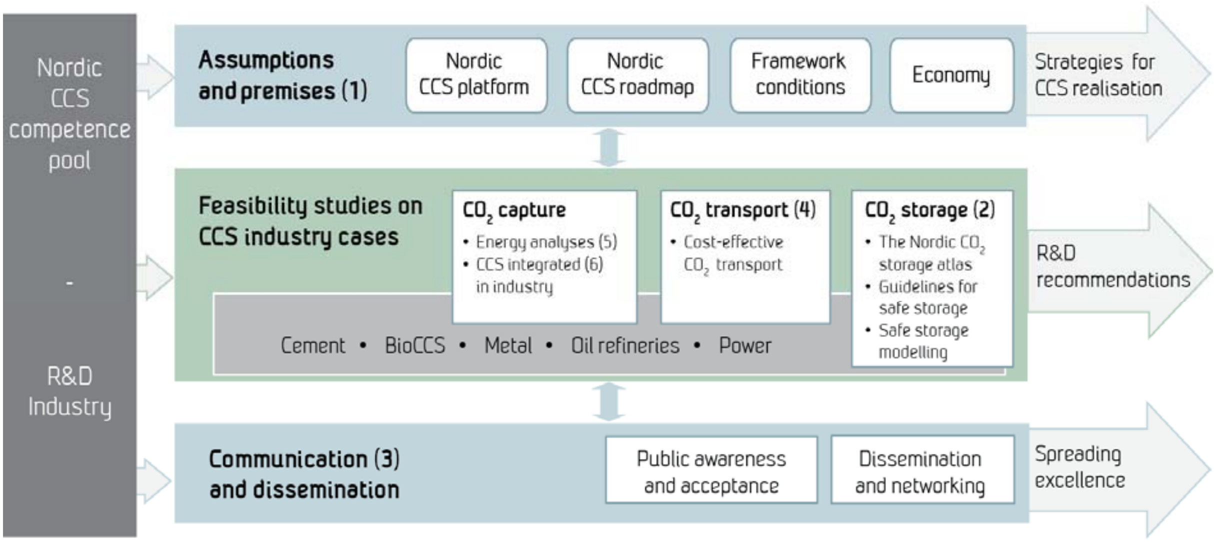

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Summary

An overview of CO_2 storage related data for all five Nordic countries, covering data availability, data format and data copyright issues do not exist at present. This memo aims to compile information on Carbon, Capture, transport and Storage (CCS) data in the Nordic countries, with main emphasis on CO_2 storage data.

Most data on CO_2 storage sites relevant for a Nordic storage atlas exist in all Nordic countries, but there is a variation in level of detail and in what format data exists, which to some extent reflects the nature of national and international Carbon, Capture and Storage (CCS) research projects each country have participated in through the years.

Norway, Denmark and Iceland have most CO_2 storage data available in a GIS (Geographical Information system) format ready to transfer to a new Nordic storage atlas. Sweden has all CO_2 storage relevant data available but only few data are digital or in a GIS ready format. Finland has only minor storage capacity and data can be generated.

Keywords GIS, data formats, database, CO2 storage, CO2 emission, CO2 infrastructure

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Date September 2012

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About NORDICCS

Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.

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Content

6.1.1201
Review of existing CO_2 storage databases

1. Objectives

A review of existing data is necessary to reveal data gaps and make it possible to prepare a strategy on how to extent data input for the coming years, and will furthermore contribute to an overview of what data can be reused in the Nordic storage atlas, and what data have to be generated in the coming years. This review of existing data will cover on geological formations with CO_2 storage potential, formations with sealing properties, hydrocarbon fields, exploration wells, pipeline systems and CO_2 emission sources.

2. Introduction

The main final delivery from WP6 is a Nordic atlas with CO_2 storage site data and the outcome will be a public available, web-based Geographical Information System (webGIS). A web-based storage atlas will allow access for everyone to dynamic maps without the need to have a GIS-software installed and the web-based storage atlas data is easily updated a maintained.

The basis for a webGIS storage atlas is a GIS-database containing digital data. For all data entering the GIS-database a geographical location or outline is needed, either as digital data, as scanned maps or as geographical coordinates in a table, only time required for data processing is variable depending on the data format.

An overview of CO_2 storage related data for all five Nordic countries, covering data availability, data format and data copyright issues do not exist at present. This memo aims to compile information on Carbon, Capture, transport and Storage (CCS) data in the Nordic countries, with main emphasis on CO_2 storage data. Each section in this memo has been written by the country representatives in WP6 and because of the different premises for CO_2 storage in the Nordic country, their contributions to this memo is differentiated.

3. Basic data required for the CO_2 storage atlas database

A GIS map is made up of layers, or collections of geographic objects that are alike. Each geographic object in a layer is called a feature and can be represented as one of three geometrical forms – a point, a line or a polygon (vector data). Information about the features in a layer is stored in a table. The table has a record (row) for each feature in a layer and a field (column) for each category of information, these categories are called attributes.

Following attribute data are requested for the feature layers in order to have a basis for further work in WP6:

Sedimentary basins

Name

Potential CO_2 storage formations (Aquifer formations)

Name, country, age, stratigraphic unit, lithology, depth top, depth base, volume, net/gross, porosity, permeability, efficiency factor, storage capacity, CO_2 density at reservoir conditions and connectivity/reservoir type, salinity

CO_2 storage units (Aquifer storage units)

Name, country, age, stratigraphic unit, lithology, depth top, depth base, volume, net/gross, porosity, permeability, efficiency factor, storage capacity, CO_2 density at reservoir conditions and connectivity/reservoir type, salinity

CO_2 traps (Aquifers traps)

Name, country, age, stratigraphic unit, lithology, depth top, depth base, volume, net/gross, porosity, permeability, efficiency factor, storage capacity, CO_2 density at reservoir conditions, connectivity/reservoir type, salinity

Hydrocarbon fields

Field name, country, content, age, stratigraphic unit, lithology, discovery year, and CO_2 storage capacity

Mineral trapping sites

Name, country, age, stratigraphic unit, mineralogy, depth, volume, CO_2 storage capacity

Sealing formations

Name, country, age, stratigraphic unit, lithology, depth top, depth base, fault density/character

Exploration wells

Name, level above sea level, depth, link to website

Pipelines

Name, country, owner, operator, material, fluid content, diameter, off/on shore, piggy back, bundle, operational status

Pipeline terminals

Name, country, owner and terminal type

CO_2 emission sources

Name, country, city, state/province, industry sector, average CO_2 emission/year, emission average period

Commercial, demonstration or pilot CCS activities

Name, industry type, project type, technology, start year, owner, partners, link to website

4. Data confidentiality and copyrights

During the work process in WP6 it will be necessary to have a work-database containing all feature and attribute data essential for carrying out calculations of CO_2 storage capacities and evaluating the suitability of the storage sites. Because the atlas will be public and some of the data are confidential it will be necessary to settle what data can be public with the copyright holder before releasing the webGIS atlas, this especially concerns hydrocarbon field data. This can be handled by making a sub-set of the work-database were confidential data are excluded into the final storage atlas database.

5. European databases with Nordic CCS data

Several projects concerning mapping and estimation of European storage capacities have been carried out since the beginning of the 90'ties. The first detailed study was the GESTCO project (Assessing European Potential for Geological Storage of CO_2 from Fossil Fuel Combustion) which was co-funded by the European Union (EU), started in 2000 and ended in 2003 (Christensen & Holloway, 2004). The primary goal of GESTCO was to determine whether geological storage of CO_2 captured from large industry CO_2 emission sources was a viable possibility in Europe. But also establishment of a GIS database designed to support economic analysis and strategies for CCS deployment was a main objectivity. Content of the GESTCO GIS database was:

- CO_2 emission sources > 0,1 mega ton (Mt)
- Existing pipelines
- Pipeline terminals
- Saline aquifers
- Hydrocarbon fields
- Coal fields

The GESTCO project had 8 north-western European partners and Nordic partners in GESTCO were Geological Survey of Norway (NGU) and Geological Survey of Denmark and Greenland (GEUS). Even though Norway participated in GESTCO and storage capacity for the saline aquifers were estimated, no digital GIS data of the Norwegian aquifers were included, due to the extensive Norwegian shelf areas and limited resources to carry out detailed mapping. Data in the GESTCO GIS database were restricted to partners within the project.

In 2006 a new EU co-funded CO_2 storage capacity project was launched, named EU GeoCapacity (Assessing European Capacity for Geological Storage of Carbon Dioxide)(Vangkilde-Pedersen, 2009). This project updated and added new data to the former GESTCO GIS database, but also these GIS-data are confidential and restricted to project partners. GeoCapacity had 26 European partners from 21 countries and the only Nordic partner was GEUS, but Norwegian GIS data were transferred from the GESTCO GIS database to the GeoCapacity GIS database, however without being updated (fig. 5.1). The project was completed in December 2008.

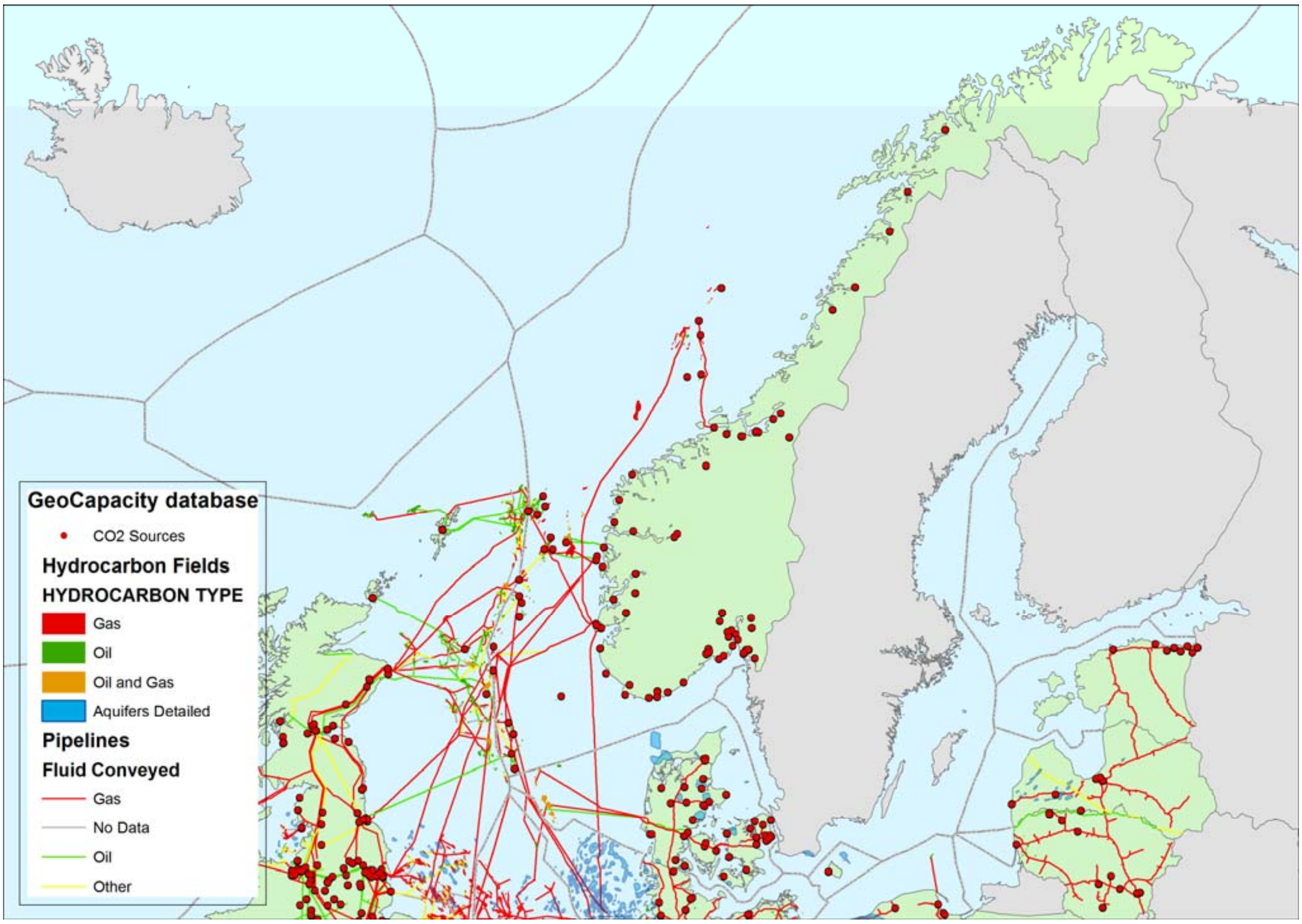

Figure 5.1: *Content of the GeoCapacity GIS database. Only data from Denmark and Norway exist and most important, no aquifer data from Norway are included.*

CO2StoP (CO_2 Storage Potential) is the latest CO_2 storage project co-funded by EU. CO2StoP started in January 2012 and the main objective of the project is to build a GIS-based CO_2 storage database with only public available data. This coming database will not be public available and to some extent build on data from GESTCO and GeoCapacity. GEUS and the Norwegian Petroleum Directorate (NDP) are Nordic partners in CO2StoP. It is expected that the Nordic storage atlas work will follow the CO2StoP project in order to gain synergy between the European CCS database and the Nordic database with respect to database structuring.

6. Sweden

The Swedish contribution is added as an appendix to this memo.

7. Norway

The first major mapping of CO_2 point sources and storage formations in Norway was performed in the JOULE-II project (1995) (Holloway et al., 1996) co-funded by EU. An assessment of theoretical storage capacity of saline aquifers and depleted oil and gas fields was given for Western Europe (EU) and Norway. The Norwegian offshore area covered in JOULE-II was south of the 62° Latitude. The GESTCO report (1999) (Christensen & Holloway, 2004) presents an inventory of CO_2 point sources and CO_2 storage capacity estimates in deep saline aquifers offshore/nearshore Norway in the Southern Barents Sea, the Norwegian Sea and in the Norwegian North Sea. Regions with hydrocarbon production were not included in the study. In 2011 the Norwegian Petroleum Directorate (NDP) presented a "CO_2 Storage Atlas – Norwegian North Sea" providing an overview and capacity estimates over geological formations and aquifers in the Norwegian North Sea suitable for CO_2 storage (south of the 62° Latitude) (Halland et. al. 2011). A GIS database from the CO_2 Storage Atlas is planned to be released in 2012. In addition several formation aquifers have been studied in different projects for CO_2 storage purposes, i.e. Utsira, Johansen, Gassum (Skagerrak), Tubåen (Snøhvit) and Tilje (Halten). The NPD FACTPAGES (http://factpages.npd.no) contains large amounts of information on exploration wellbores, oil and gas fields and stratigraphy on the Norwegian continental shelf.

7.1 Norwegian data

7.1.1 Saline aquifers

Around 40 suitable formation aquifers are presented in the GESTCO study. Evaluated aquifers in the NPD's CO_2 Storage atlas are: Utsira and Skade Formations, Bryne/Sandnes Formations, Sognefjord Delta East (includes Krossfjord, Fensfjord and Sorgefjord formations), Statfjord Formation East, Haldager Formation, Gassum Formation, Bryne Formation, Sandness Formation, Skagerrak Formation, Rotleigend Goup, Johansen and Cook Formations, Fiskebank Formation, Hugin East Formation, paleogene mounds in the Stord Basin (Halland et. al. 2011). Knowledge about the formations is greatly variable since some areas have been studied in detail in connection with hydrocarbon exploration whereas other areas are poorly explored.

7.1.2 Sedimentary geological structures

Both the GESTCO report and the CO_2 Storage atlas give an overview of the geology offshore Norway with description of basins and lithostratigraphic units. The NPD FACTPAGES also contains description of the lithostratigraphic units (groups, formations and members) including links to associated exploration wellbores with core samples. But no geological structures have been mapped in any of these projects.

7.1.3 Hydrocarbon fields

Characteristic properties and estimates of CO_2 storage capacity for the majority of Norwegian oil and gas fields are available either from the JOULE-II report, the SPOR Monograph (Skjæveland & Kleppe, 1992) or from the in-house data base at SINTEF Petroleum research. Properties of importance are; depth, pressure, temperature, porosity, Net-gross ratio, bulk volume, anisotropy, initial oil in place, etc.

7.1.4 Mineral trapping sites

Norwegian mining industry have several types of mineral sources that can be used for mineral trapping of CO_2, specially olivine and nepheline, but also anorthite waste product from titanium mining (e.g. Titania). If industrial mineral trapping can be feasible in the future, there are quite some potential in Norway, but areas with mineral storage potential is not mapped.

7.1.5 Sealing formations

Possible sealing formations to each evaluated aquifer are to some degree defined and described in the CO_2 Storage Atlas.

7.1.6 Exploration wells

Data from all exploration wells offshore Norway are available from the NPD FACTPAGES. Typical data available are: position, wellbore history, overview of samples and tests, coring intervals and scanned photos of cores (if coring was performed), lithostratigraphy and related documents.

7.1.7 Pipelines

Norway's gas pipelines have a total length of 8000 kilometres. Gas flows from production installations to process plants for separation of Natural Gas Liquids (NGL). Dry gas is piped to terminals in Europe. Geography of the pipelines can be downloaded from the NPD FACTPAGES in Shape or CSV format suitable for input to GIS software.

7.1.8 Pipeline terminals

Oil and condensate from offshore production are piped to onshore facilities at Mongstad, Nyhamna Melkøya, Øygarden (Sture Terminal), Tjeldbergodden and Lindås (Vestprosess). Information on these onshore terminals are available on the NPD FACTPAGES.

7.1.9 CO_2 emission sources

Emission source data from all Norwegian stationary sources are included in the GESTCO report (1999).

7.1.10 Commercial, demonstration or pilot CCS activities

Norway has two commercial CO_2 injection projects. These are Sleipner and Snøhvit which injects approximately 1 Mt and 0.7 Mt CO_2 annually, respectively. A centre for large scale testing of CO_2 capture technologies at the Mongstad refinery (The Test Centre Mongstad) was opened in 2012 (see http://www.tcmda.com). At Svelvik the CO_2 Field Lab project is on-going where CO_2 is injected into the shallow sub surface for testing and developing monitoring systems detecting shallow CO_2 migration.

7.2 Summary for Norwegian data

Norway	Availability	Data format	Copyright holder	Public	Comments
Saline aquifers	Partly	Digital	NPD/NGU	Yes/Partly	Data exist of most saline aquifers; data on formations are available at NPD fact pages.
Sedimentary geological structures	Partly	Digital	NPD/NGU	Yes/Partly	Many structures are mapped but need further evaluation regarding CO_2 storage relevance. Data on formations are available on NPD fact pages. (Lithostratigraphy)
Hydrocarbon fields	All	Digital	NPD	Yes	Name, location, status, reserves and produced HC are publicly available at NPD fact pages. Maps can be downloaded in WMS, Shape or CSV format.
Mineral trapping sites	-	-	-	-	Sites not mapped.
Sealing formations	Partly	Digital	NPD/NGU	Yes/partly	Description of formations available on NPD fact pages. Data on sealing properties with respect to CO_2 are published for some formations.
Exploration wells	All	Digital	NPD	Yes	Name, location and partly well logs are available from NPD website. Pictures of drilled cores are available.
Licence areas	All	Digital	NPD	Yes	Maps can be downloaded in digital format from NPD fact pages.
Pipelines	Partly	Digital	NPD	Yes	Main pipeline data exist; digital version can be

					downloaded from NPD fact pages.
Pipeline terminals	All	Digital	NPD	Yes	Data can be downloaded from NPD fact pages.
Commercial, demonstration or pilot CCS activities	Partly	Digital	Statoil	Partly	Some data has been published through various research projects on Snøhvit and Sleipner.

8. Iceland

Carbon dioxide has been injected into deep geologic formations as a separate supercritical fluid. The effectiveness of this CO_2 storage and sequestration method depends strongly on the retention time, reservoir stability, and the risk of leakage. One way to enhance the long-term stability of injected CO_2 is through the formation of carbonate minerals. Carbonate minerals provide a long-lasting, thermodynamically stable, and environmentally benign carbon storage host. Mineral storage is in some cases the end product of geological storage of CO_2. The rate at which mineralization occurs depend on the rock type and injection methods. Mineral carbonation of CO_2 could be enhanced by injecting CO_2 fully dissolved in water and/or by injection into silicate rocks rich in divalent metal cations such as basalts (mafic rock) and ultramafic rocks (Oelkers et al., *2008,* Gislason et al. 2010 and references therein).

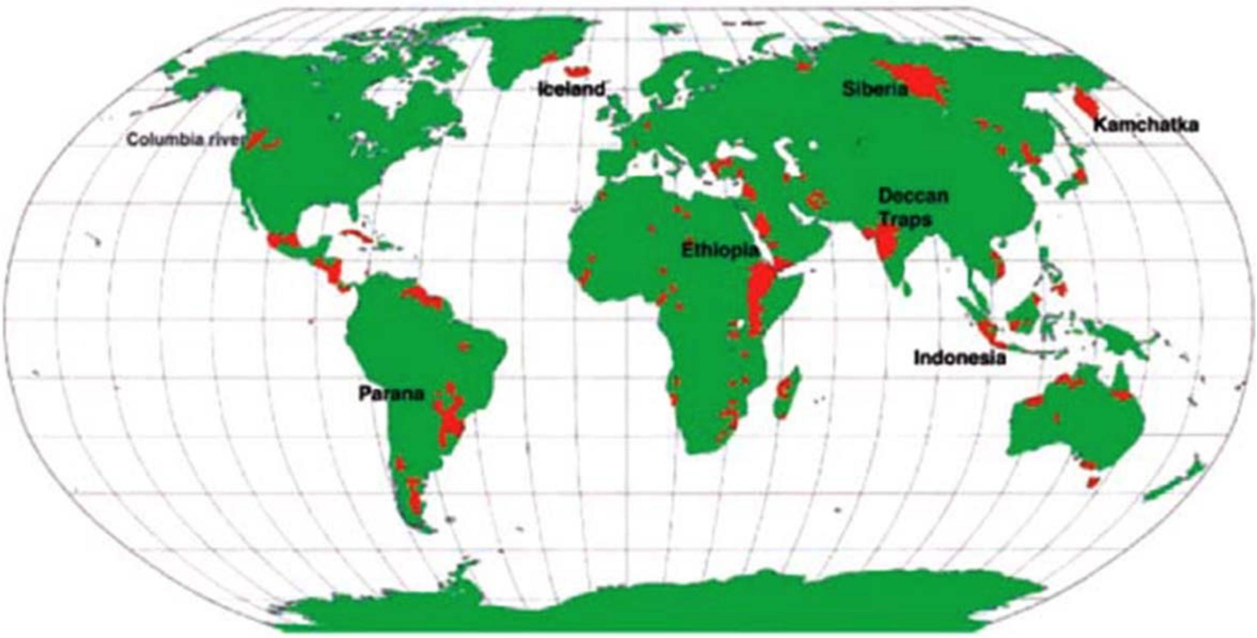

Figure 8.1: *Locations of terrestrial basalts that could serve as in situ mineral carbonation sites (Oelkers et al., 2008).*

Important volumes of mafic and ultramafic rocks are present on the Earth's surface as shown for terrestrial basalt in Fig. 8.1. For example, the Columbia River basalts in the USA have a volume in excess of 200,000 km^3 and the Siberian basalts have a volume greater than 1,000,000 km^3. These large volumes have correspondingly large CO_2 sequestration capacities: McGrail et al. (2006) estimated that the Columbia River basalts alone have the capacity to sequester over 100 Gt of CO_2. Furthermore, Goldberg et al. (2008; 2010) demonstrated the large storage capacity of sub-oceanic basalt formations. Thus, storage in basalts is now considered to be a promising option for CO_2 storage (O'Connor et al., 2003; Oelkers et al., 2008).

The feasibility of CO_2 storage in basaltic rocks is currently investigated in few field-scale pilot injection studies such as into dolerite sills present within the Newark basin, eastern USA (Matter et al., 2007), the Columbia River basalt, western USA (the Big Sky project) (McGrail et al., 2006), and the basalt hosted aquifer system in SW- Iceland (the CarbFix project) (Gislason et al., 2010; Matter et al., 2009; Ragnheidardottir et al., 2011; Aradottir et al. 2012). These field tests are preceded and accompanied by numerous smaller scale studies that investigate several aspects of CO_2-basalt interaction such as general feasibility studies (Gysi and Stefánsson, 2012; Ragnheidardottir et al., 2011), mineral and whole rock dissolution rates (e.g., Gudbrandsson et al., 2011; Schaef and McGrail, 2009; Wolff-Boenisch et al., 2006), its dependence on the solution composition (Flaathen et al., 2010; Wolff-Boenisch et al.,2011, Mesfin et al., 2012), the effect of mineral coating and bacteria on the dissolution rate (Sockmann et al. 2011; 2012) and characterization of the CarbFix injection site (Alfredsson et al., 2008; Alfredsson et al, 2012). For the CarbFix project, a single fluid phase will be injected after complete dissolution of the CO_2 in water to reduce its buoyancy (Gislason et al., 2010). A reactive transport model that is calibrated against a multitude of on-site measured parameters (porosity, permeability, fluid flow velocity, host rock composition) is available for the CarbFix Project and predicts 80 % mineral capture of the injected CO_2 within 100 years of full-scale, 40,000 tonnes/yr injection (Aradóttir et al., 2012). The injected CO_2 gas has been shown to be completely dissolved into water in less than 5 minutes within the CarbFix injection well (Sigfusson et al., 2012).

Theoretically much of Iceland could be used for injecting CO_2, fully dissolved in water, into basaltic rocks. This method requires a lot of water, about 10 to 30 tonnes of water per tonne of injected CO_2 (Gislason et al., 2010). The water availability and transmissivity of wells, and rock porosity will limit the injection on land, but in coastal areas there is endless supply of seawater and sometimes high porosity reactive basaltic sediments are within "reach" from the coast. Therefore, injecting CO_2 charged seawater into basalt is an interesting opportunity that needs to be explored (Goldberg, 2008; Wolff-Boenisch et al., 2011; Mesfin et al., 2012).

Iceland is mostly made of young, 0-20 M yr, igneous rocks and sediment thereof. Over 80% of Iceland is basalt, and most of it is extrusive (Fig. 8.2). The porosity and permeability of the basaltic rock formations vary with the age of the rocks. The youngest formations have the highest porosity but most of the primary pore space in the oldest Tertiary rock is filled with secondary minerals (Neuhoff et al. 1999). The initial porosity of the lava flows range from 5 to 40 % (Franzson et al., 2008; 2010), mostly present in the glassy tops and bottoms of these flows. Some porosity is also contained in cooling cracks and columnar jointing. Alteration of the basaltic lava flows commonly leads to smectite, zeolite and sometimes calcite precipitation and a decrease in porosity to 1 - 10% (Sigurdsson and Stefánsson, 1994; Neuhoff et al. 1999). Younger cracks and faults, due to tectonic activity can increase the porosity.

The overall objective of the Icelandic part of this study is to use the result of the CarbFix pilot study (criteria) and combine it with geological information from Iceland to estimate the overall CO_2 storage capacity on land in Iceland and perhaps off the coast in SW-Iceland.

Iceland has since 2007 been involved in several European and US funded projects related to the CarbFix pilot study, but no attempt has been made to estimate the overall CO_2 storage capacity in Iceland.

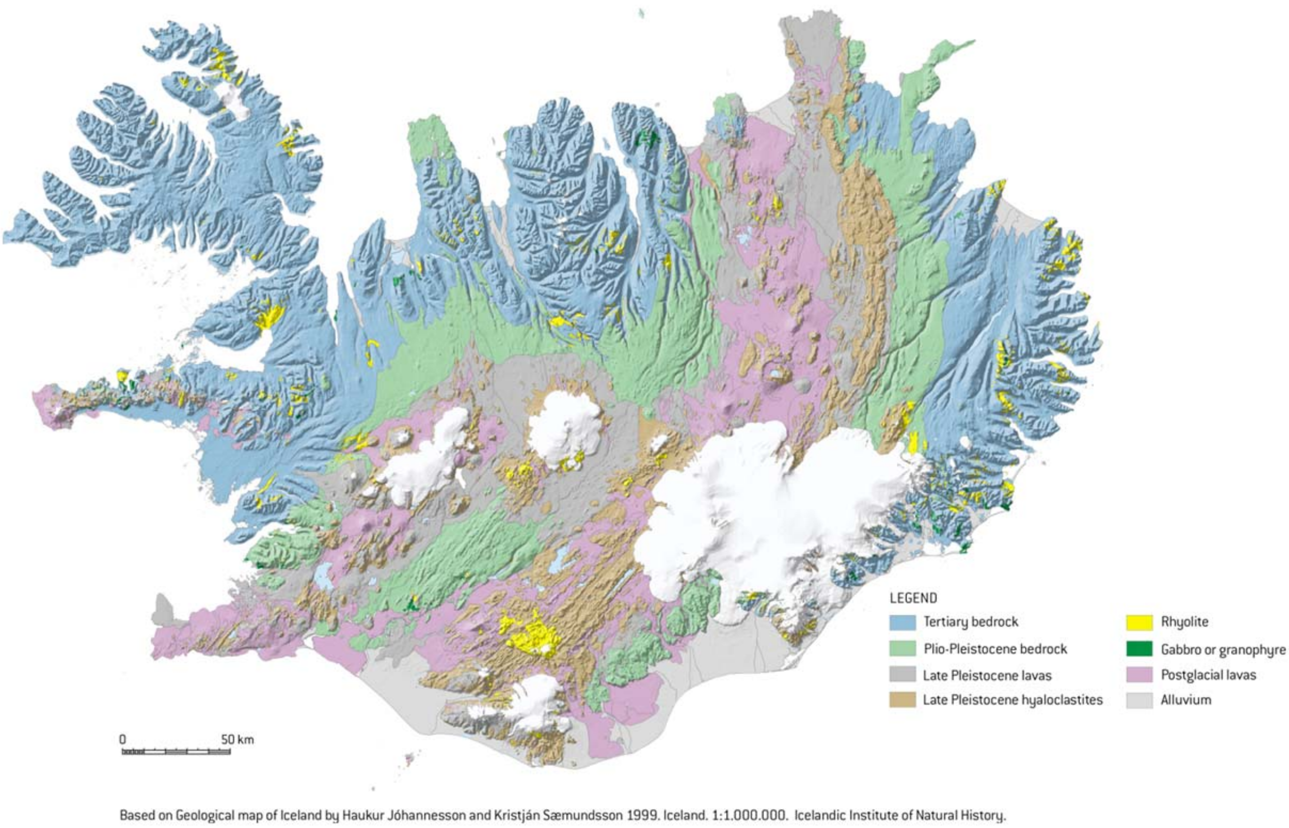

Figure 8.2: *Geological map of Iceland (Jóhannesson, H., Sæmundsson, K. 1999)*

8.1 Icelandic data

Iceland has no sedimentary formations, sedimentary geological structures or hydrocarbon fields suitable for CO_2 storage.

8.1.1 Mineral trapping sites

The CarbFix site at Hellisheidi SW-Iceland is the only site in Iceland where mineral trapping has been attempted. However, numerous wells have been drilled all over the country mostly for geothermal exploration and use. For these wells, an extensive database exists on potential aquifers, transmissivity, alteration state etc. Most of the data resides within the database of the Icelandic Geological Survey, ISOR. This database is maintained and upgraded by ISOR, but information on individual wells is owned by the owners of the wells. Much of this data is publicly available in published reports, but permission is required to enter the database.

The CarbFix injection site was selected in 2007 because of the availability of both CO_2 gas from the Hellisheidi power plant and injection- and monitoring wells within a suitable geological formation. Since then two additional monitoring wells have been drilled.

The Hellisheidi geothermal power plant is located in SW Iceland, at 260 to 290 m.a.s.l., 30 km east of Reykjavík (see Fig. 8.3). The Hellisheidi site has been outfitted with one 2000 m deep injection well, ten monitoring wells ranging from 50 to 1300 m in depth, and various injection and monitoring equipment (Gislason et al., 2010; Matter et al., 2011; Alfredsson et al., 2011; 2012; Aradóttir et al., 2011; 2012). The wells are owned and maintained by the Reykjavík Energy.

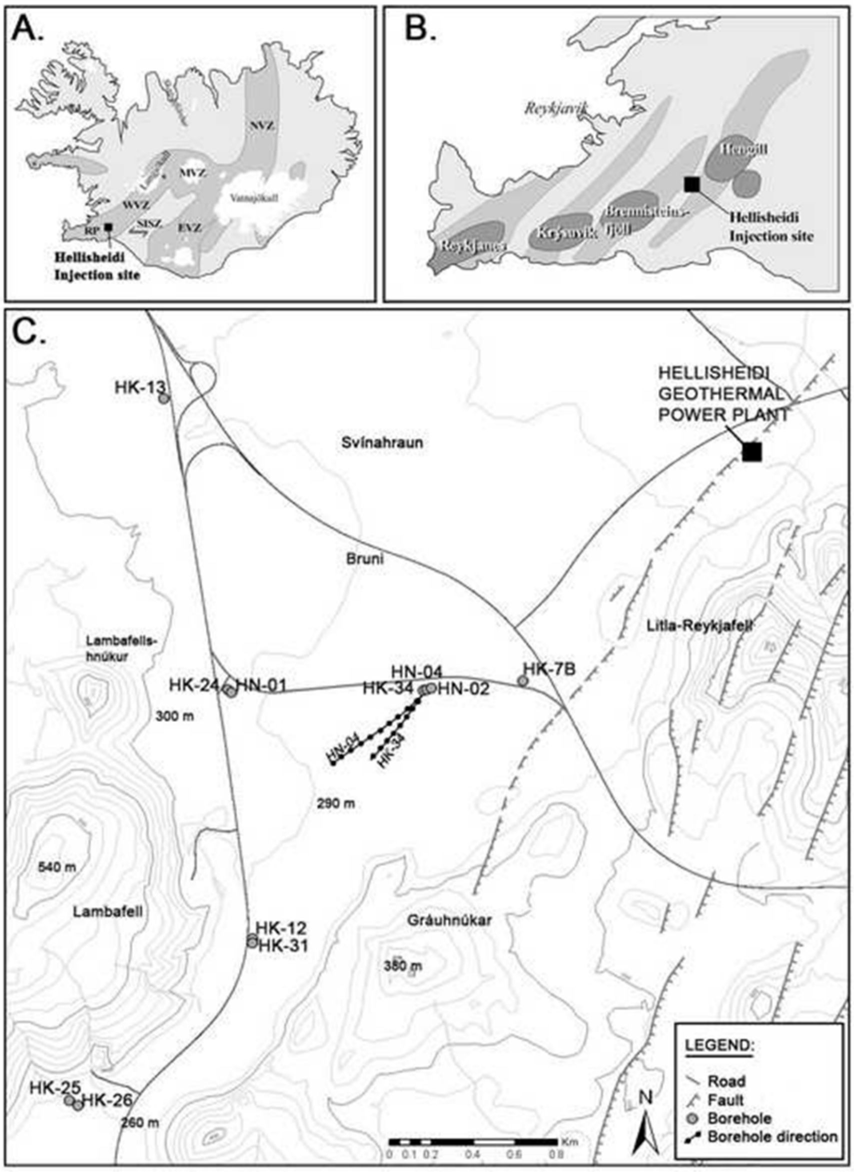

Figure 8.3: *Map of the CO_2 injection site in Hellisheidi, SW-Iceland. The CarbFix wells are shown as labelled gray dots. Mapped bedrock faults are located towards east and are part of the Hengill fissure swarm. The cross section shown in Figs. 2 and 4 is marked A-A' (from: Alfredsson et al. 2012).*

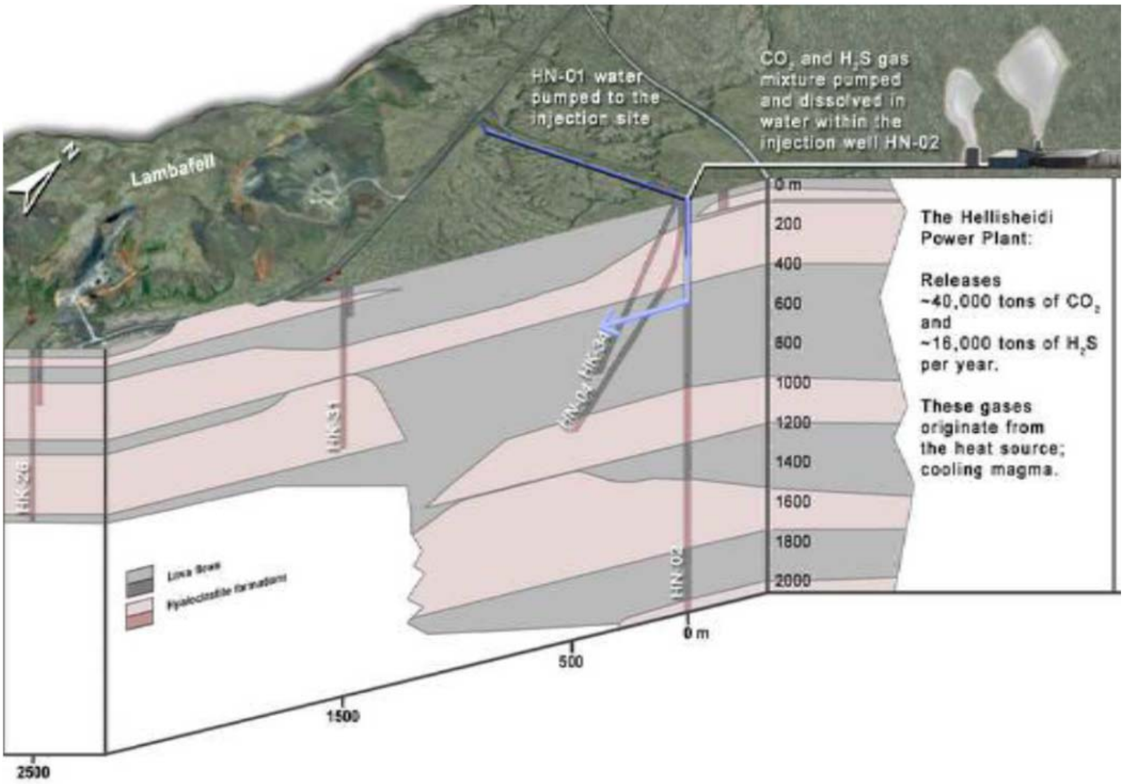

Figure 8.4: *Geological cross section of the injection site in Hellisheidi. The CO_2 –H_2S gas mixture will be separated from other geothermal gases at the power plant, and pumped towards the injection site and mixed with water from well HN-1 within the injection well HN-2. The gas charged waters enters the basaltic formations as single phase; water phase (Alfredsson et al. 2012).*

8.1.2 Exploration wells

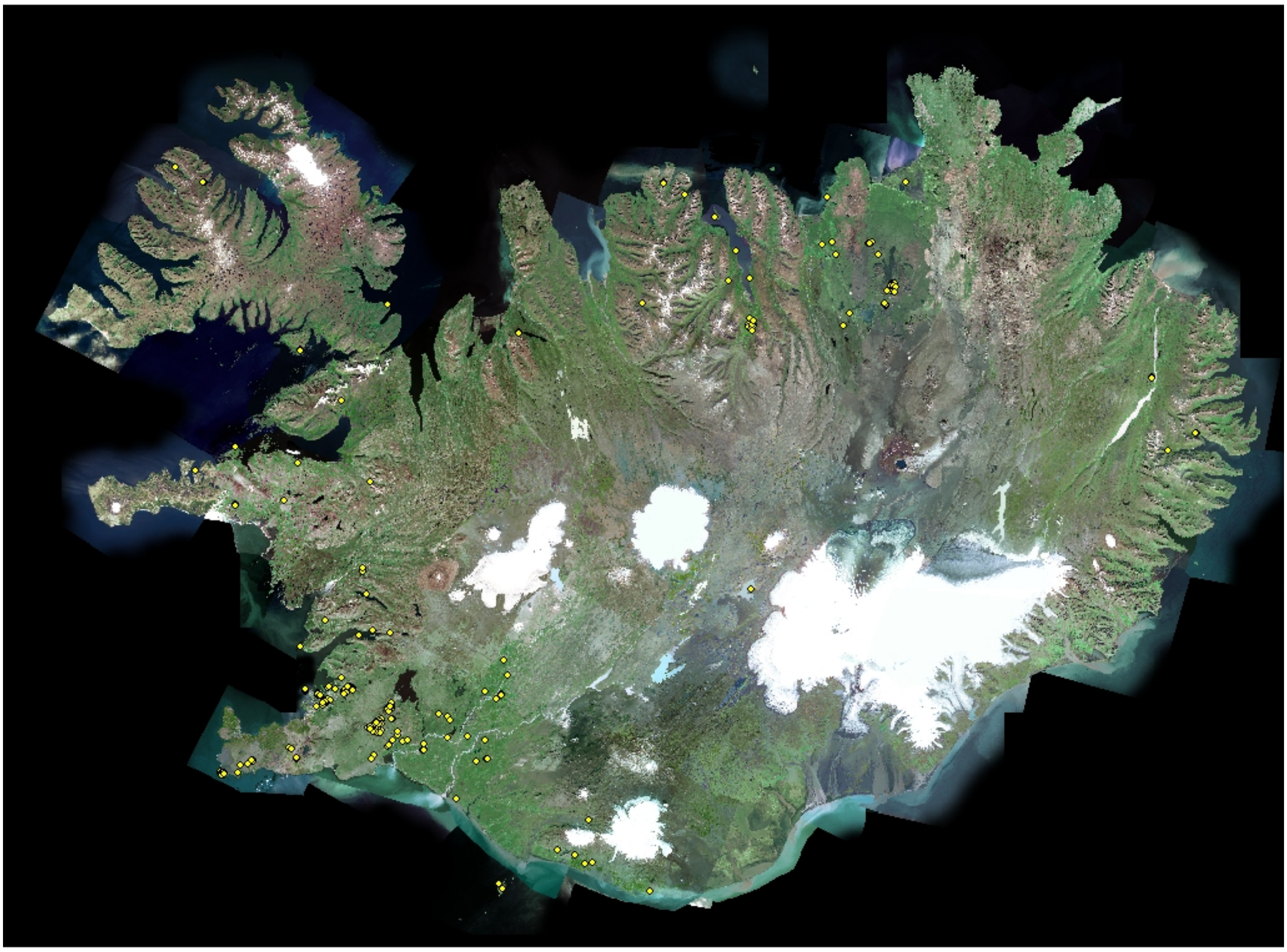

Figure 8.5: *Locations of deep wells (>1000 m) in Iceland. Data from the National Energy Authority.*

Data on wells drilled in Iceland has been collected for several decades by the National Energy Authority of Iceland. In July 2011, 12,735 wells were recorded in the database, the oldest one drilled in Reykjavík in 1904. The database is public and contains information about when the wells were drilled, how deep they are, where they are situated and what was the purpose of the well. Data on location of the wells (coordinates) only exists for part of the wells.

The number of exploration wells (hot and cold water wells, wells for geothermal exploitation) in Iceland are around 4000 and over 500 deep wells (>1000 m) have been drilled all over Iceland, mostly for geothermal exploitation (Fig. 8.5).

Digital data (GIS) is available on some of the wells drilled in Iceland, and on all of the deeper wells (>1000 m) from the National Energy Authority of Iceland. The data are owned by the National Energy Authority and is public, but permission is needed.

High temperature geothermal wells (T>200°C at 1000 m depth) are usually drilled and cased in four phases.

1. 100 m surface casing (22 ½“)
2. 300 m surface casing (13 3/8“)
3. 700-800 m production casing (12 ¼“)
4. Liner or an open well down to the bottom of the well.

Low temperature geothermal wells (T<150°C at 1000 m depth) are more variable.

8.1.3 Pipelines

A wide-ranged network of pipelines is utilised in Iceland for cold water, hot water and sewage. An extensive pipeline network is also in use in relation with the geothermal utilisation, both for energy production and injection of the geothermal fluid.

Data on pipelines in Iceland exists as digital data and is owned by the respective companies (energy companies, heating utilities etc.). A special permission is needed to get access to the data.

Reykjavík Energy, for example, operates 13 district heating utilities all located in South Western Iceland from Stykkishólmur in NW-Iceland to Hvolsvöllur in the S-Iceland as shown in Fig. 8.6.

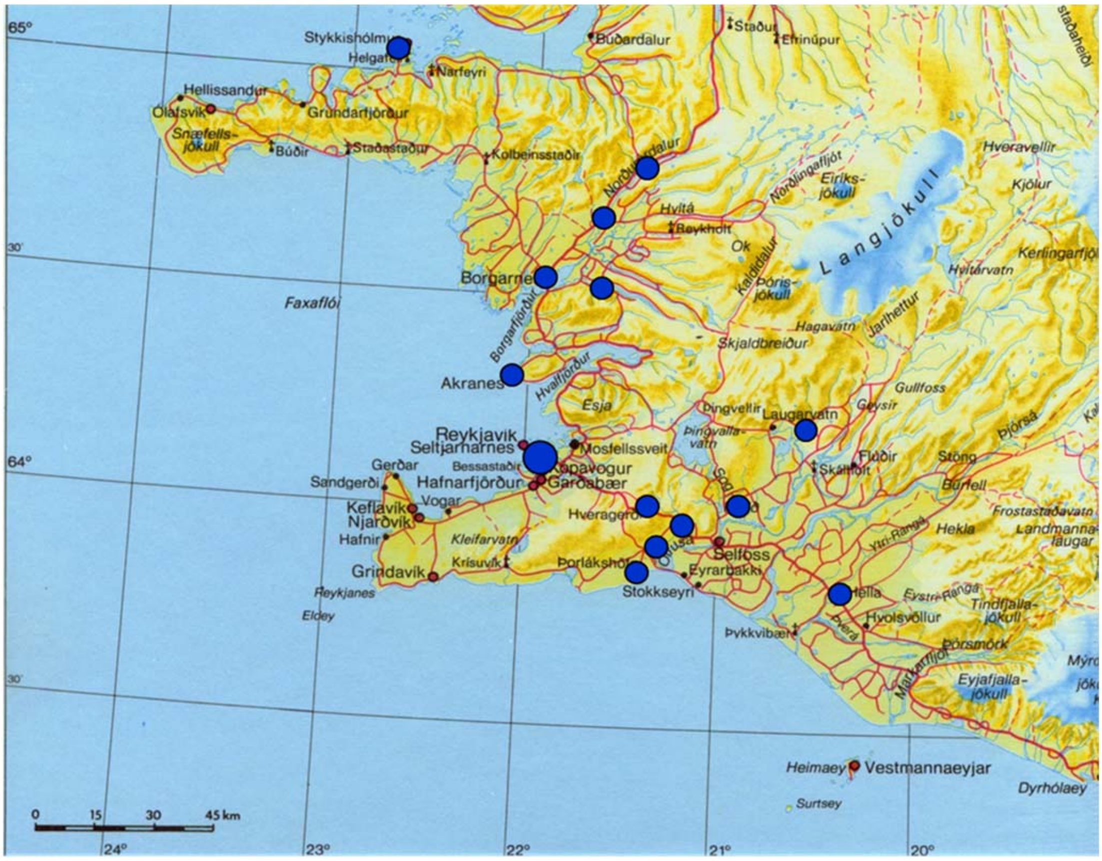

Figure 8.6: *District heating utilities and pipeline network in south-western Iceland.*

The company furthermore operates two high temperature geothermal power plants at Hellisheidi and Nesjavellir that co-produce electricity and geothermal water.

The total length of pipelines that transport geothermal water, and is owned by Reykjavík Energy is 3025 km.

8.1.4 CO2 emission sources

Total CO_2 emissions in Iceland in the year of 2010 were 0,3405 Mt CO_2, which implies an increase of 58% since 1990 and a decrease of 4% since the year before.

The three main sources of CO_2 emissions in Iceland are industrial processes, road transport and fisheries. Electricity and space heating are mostly generated by renewable sources and are therefore low CO_2 emissions. Emissions from stationary combustions are dominated by industrial sources but mobile sources in the constructions are also significant (Fig. 8.7). The largest user of fossil fuels is by far the fishmeal industry.

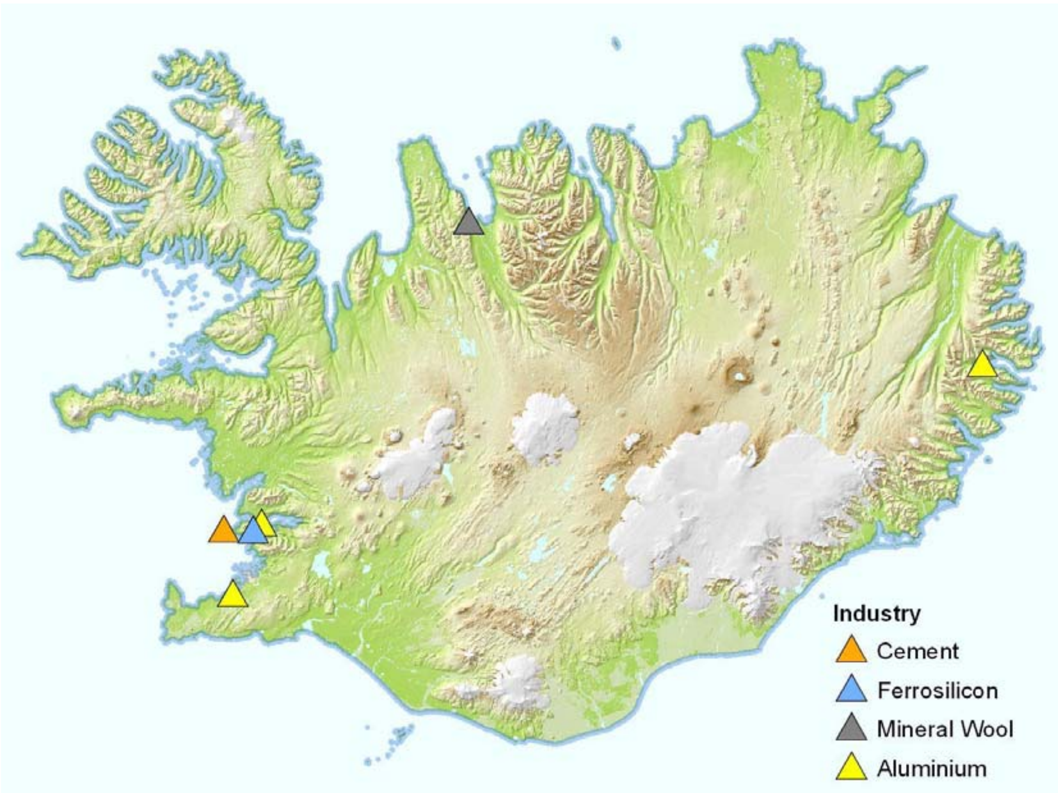

Figure 8.7: *Location of major industrial CO_2 emission sites (Hallsdóttir, B.S. et al, 2012).*

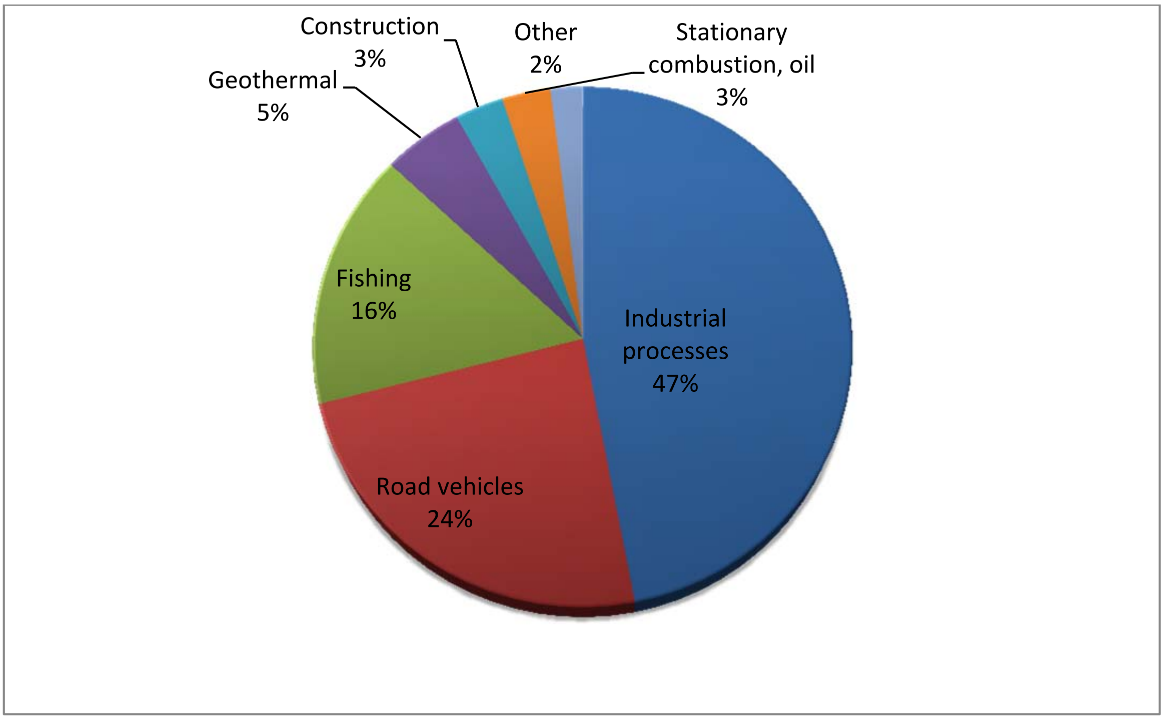

Figure 8.8: *Distribution of CO2 emissions by source in 2010 (Hallsdóttir, B.S. et al, 2012)*

Emissions from geothermal energy exploitation are considerable but other sources of CO_2 emission consist mainly of emissions from non-road transport, coal combustion in the cement industry and waste incineration (Fig. 8.8) *(Hallsdóttir, B.S. et al, 2012).*

Data on CO_2 emission in Iceland is public and available from the Environmental Agency along with annual reports from the largest CO_2 emitting industries in Iceland.

8.1.5 Commercial, demonstration or pilot CCS activities

The CarbFix injection site is located about 3 km south of the Hellisheidi geothermal power plant in SW Iceland, at 260 to 290 m.a.s.l., 30 km east of Reykjavík (see Fig. 8.3). The power plant currently produces 40,000 tons of CO_2 and 16,000 tons of H_2S per year. These gases are a by-product of geothermal energy production and are of magmatic origin. Subsequently, a CO_2 – H_2S – H_2 gas mixture, following its separation from other geothermal gases, will be transported in a pipeline to the injection site shown in Fig. 8.4. A short-term injection test was performed at this site in early 2012, where 175 tons of pure commercial CO2 was injected. This short-term test will be followed by a 1200 ton injection of a geothermal CO2 – H2S – H2 gas mixture over a 6-month period. In both cases the gases will be pumped with water down to 500 m (Gislason et al. 2010; Alfredsson et al. 2012; Aradottir et al. 2012, Sigfússon et al. 2012).

The carbfix project is currently the only CO_2 geological storage project in Iceland, put several CO_2-injection opportunities exists close to the concentrated emission sources in SW-Iceland.

Reykjavik Energy owns the infrastructure at the Carbfix site but the results from the injection is owned jointly by Reykjavík Energy, University of Iceland, Columbia University NY, USA, and CNRS Toulouse, France.

CARBFIX aims at publishing all the results in international scientific journals, after that, the results are in the public domain. Some technical solutions may become patented.

8.2 Summary for Icelandic data

Much of Iceland could be used for injecting CO_2, fully dissolved in water, into basaltic rocks. Over 90% of Iceland is of basaltic composition. The CO_2 needs to be injected fully dissolved in water in tectonic active areas like the oceanic ridges. Fully dissolved CO_2 is no longer buoyant, diminishing the risk of carbon dioxide returning to the Earth's surface during carbon storage. This method is being tested at the CarbFix site in SW-Iceland. Dissolution of CO_2 requires a lot of water, about 10 to 30 tonnes of water per tonne of injected CO_2 (Gislason et al. 2010). The water availability and transmissivity of wells will limit the injection on land, but in coastal areas there is endless supply of seawater and sometimes high porosity reactive basaltic sediments are within "reach" from the coast.

Over 500 deep wells (>1000 m) have been drilled all over Iceland mostly for geothermal exploration and use. Most of the wells are owned by the largest geothermal power companies in Iceland; Reykjavík Energy, Landsvirkjun and HS-Orka. For these wells, an extensive database exists. Most of the data resides within the database of the National Energy Authority and is open for the public but permission is needed for access.

A wide-ranged network of pipelines is utilised in Iceland for cold water, hot water, sewage and in relation with the geothermal utilisation. Data on pipelines in Iceland exists as digital data and is owned by the respective companies and a special permission is needed for access to data bases.

The three main sources of CO_2 emissions in Iceland are industrial processes, road transport and fisheries. Electricity and space heating are mostly generated by renewable sources and are therefore low CO_2 emissions. Data on CO_2 emission in Iceland is public and available from the Environmental Agency along with annual reports from the largest CO_2 emitting industries in Iceland.

Iceland	Availability	Data format	Copyright holder	Public	Comments
Saline aquifers					Not relevant for Iceland
Sedimentary geological structures					Not relevant for Iceland
Hydrocarbon fields					Not relevant for Iceland
Mineral trapping sites	Partly	Digital	Power companies and collaborators	Yes/no	Reykjavik Energy, Landsvirkju, HS-Orka, University of Iceland, Columbia University USA, CNRS France.
Sealing formations					Not relevant, CO2 injected fully dissolved in water.
Exploration wells	Partly	Digital	National Energy Authority	Yes	Digital data is available on most of the wells but permission from the National Energy Authority is needed.
Licence areas					Carbfix site (pilot study)
Pipelines	Yes	Digital	Respective companies	Permission needed	
Pipeline terminals					Not relevant for Iceland.
Commercial, demonstration or pilot CCS activities	Partly	Digital	Reykjavik Energy, University of Iceland, Columbia University USA, CNRS France.	Yes/no	Carbfix site (pilot study, carbfix.com)

9. Finland

The pre study on the potential for applying CCS in the Nordic countries “Potential for carbon, capture and storage (CCS) in the Nordic region” (Teir et al., 2010) concluded that Finland has no storage capacity in sedimentary formations (saline aquifers). Finland has a minor potential for mineral carbonation in ultramafic rocks at about 2-3 Gt (Aatos et al., 2006).

10. Denmark

Denmark has since the beginning of the 90'ties participated in several European CO_2 storage assessment projects and have furthermore been managing the EU co-funded projects GESTCO, 2000-2003 (Assessing European Potential for Geological Storage of CO2 from Fossil Fuel Combustion) and GeoCapacity, 2006-2009 (Assessing European Capacity for Geological Storage of Carbon Dioxide), implying that data needed for the Nordic storage atlas to some extent exist in a digital format.

10.1 Danish data

10.1.1 Saline aquifers

Suitable CO_2 storage formations are the Triassic Bunter sandstone Formation, the Skaggerak Formation and the Gassum Formation, and furthermore the Jurassic Haldager Formation and Frederikshavn Formation (Fig. 10.1). Knowledge about these formations are greatly variable, as some areas have been studied in detail in connection with hydrocarbon exploration whereas other areas are poorly known. Based on well data and to some extent seismic data the distribution of the aquifers are basically known and digital outline of the formations exist.

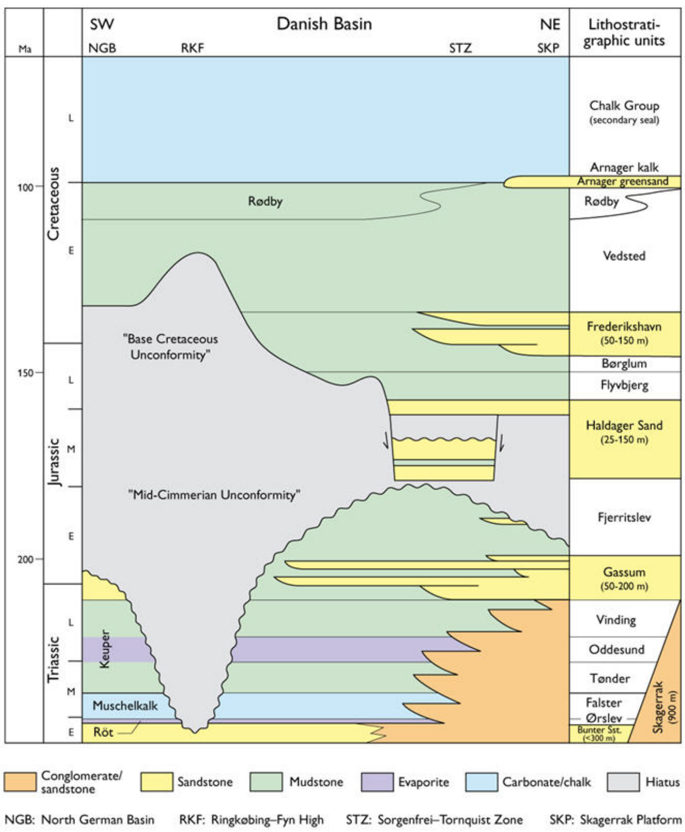

Figure 10.1: *Lithostratigraphic diagram for the Danish sub-surface.*

10.1.2 *Sedimentary geological structures*

In the GESTCO and the GeoCapacity projects, 10 geological structures (original 11, but one was later removed) were selected as the most prospective CO_2 storage sites. But in Denmark more than 100 onshore and offshore geological structures have been mapped, and only further research can determine whether these structures are potential candidates for CO_2 storage (fig. 10.2).

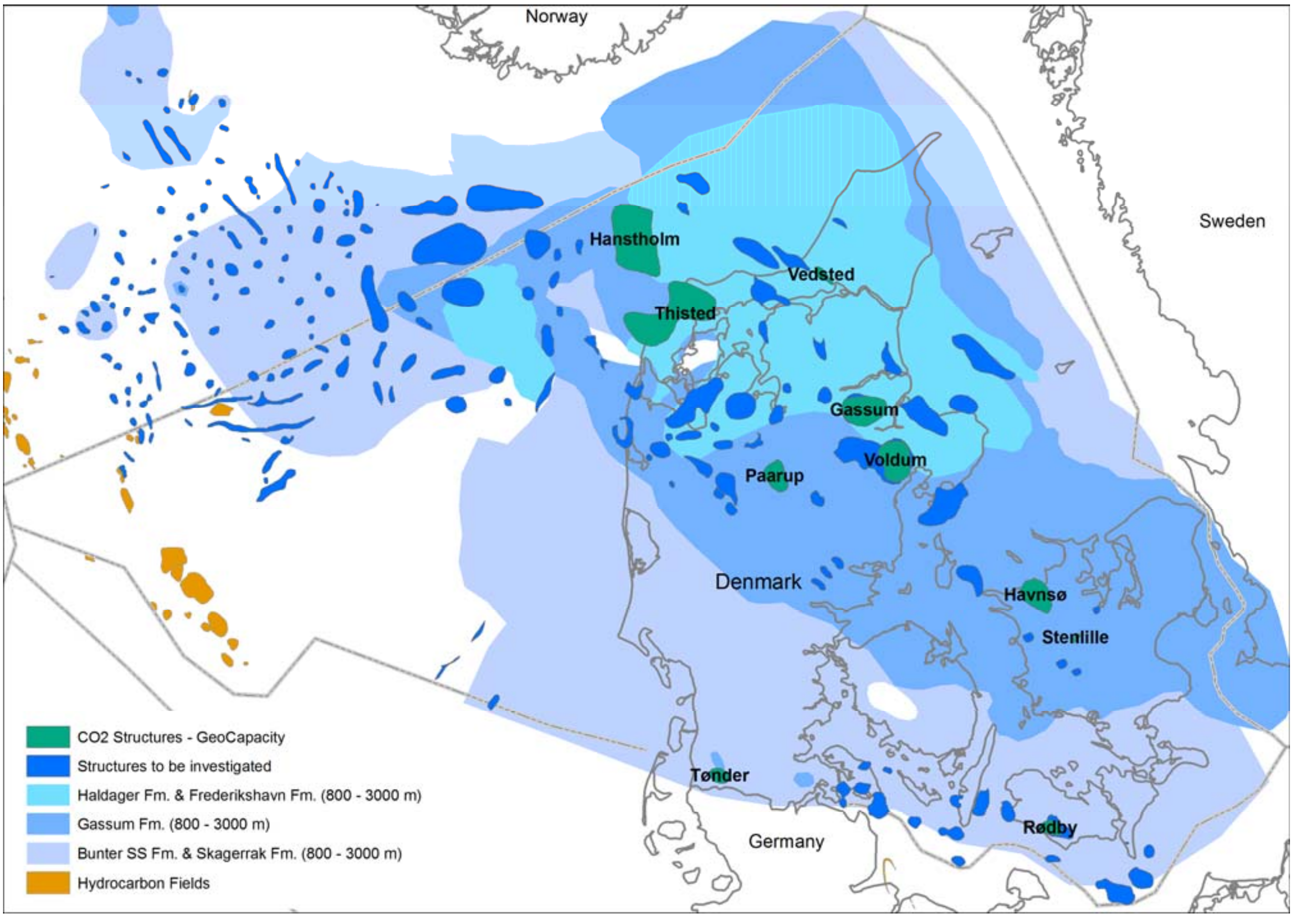

Figure 10.2: *Distribution of formations relevant for CO_2 injection in depth interval 800 – 3000 meter, together with geological structures and hydrocarbon fields.*

10.1.3 *Hydrocarbon fields*

Access to hydrocarbon data are restricted because of commercial interest. Data needed to calculate CO_2 storage capacity for hydrocarbon fields are available at GEUS. A modified outline of the hydrocarbon field locations exists as digital data and can after permission from the Danish Energy Agency (DEA) be added to the NORDICCS GIS database.

10.1.4 *Mineral trapping sites*

Denmark has no formations suitable for mineral trapping of carbon dioxide.

10.1.5 *Sealing formations*

The extension of formations with sealing properties have not been systematically mapped in Denmark only the outline of the lower Jurassic Fjerritslev Formation is well known (fig. 10.3)(Nielsen 2003). The Fjerritslev formation is the primary sealing formation for the most prospective Danish CO_2 storage formation, the Upper Triassic-Lowe Jurassic Gassum Formation. Outline of the Fjerritslev Formation is available in digital format at GEUS.

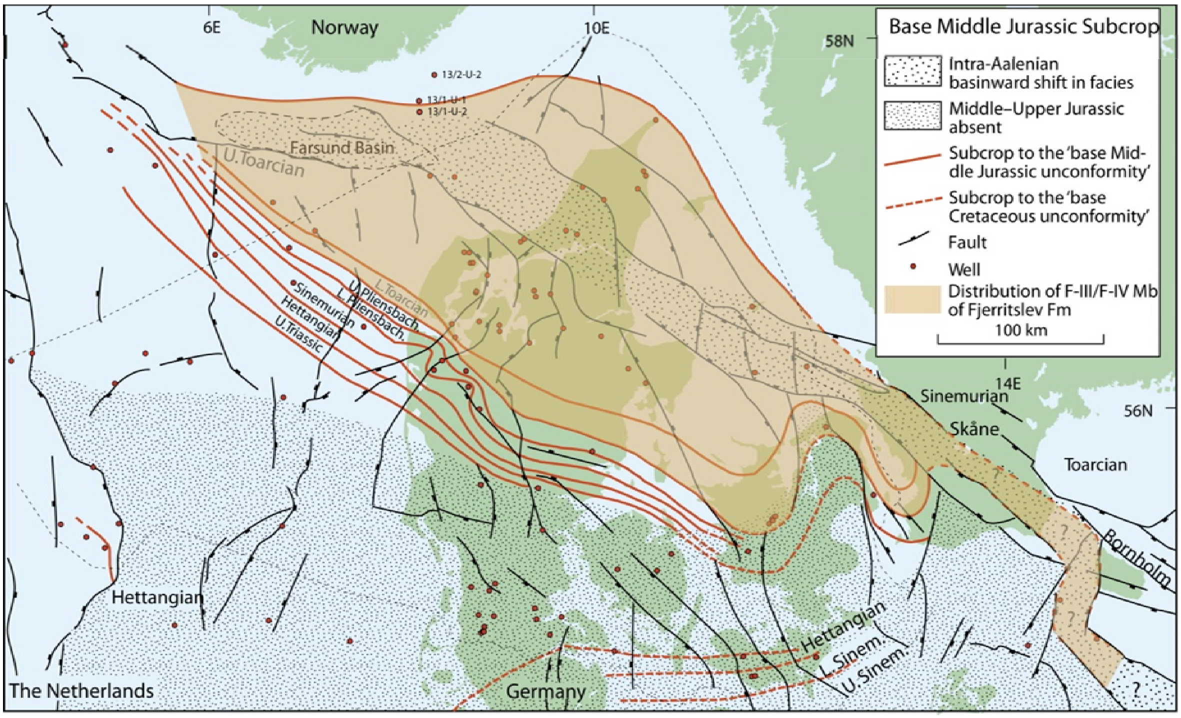

Figure 10.3: *Map showing the subcrop of the Base Middle Jurassic Unconformity and the distribution of the two upper units (F-III & F-IV mb) of the Lower Jurassic Fjerritslev Fm. (modified from Nielsen 2003).*

10.1.6 *Exploration wells*

Public information is available from the website of the Danish Energy Agency (DEA). Digital data in GIS-format can be downloaded from:
www.ens.dk/en-US/OilAndGas/Data/GISMap/Sider/Forside.aspx

10.1.7 *Pipelines*

Both pipelines transporting gas and oil are included in the Geocapacity GIS database, and therefore these data are available as digital data, ready to transfer to the NORDICCS GIS database.

10.1.8 *Pipeline terminals*

Data on pipeline terminals are also included in the GeoCapacity GIS database and can without difficulties be transferred to the NORDICCS GIS database.

10.1.9 *CO2 emission sources*

Emission source data from all Danish stationary sources with emission above 0, 1 Mt are included in the GeoCapacity database. Data can be transferred to the NORDICCS GIS database but data will need to be updated with current figures for emission.

10.1.10 Commercial, demonstration or pilot CCS activities

Denmark has presently no pilot or demo CCS projects. The Danish energy company DONG Energy have recently had a pilot project in Esbjerg on CO_2 capture focused on post-combustion technology, but this facility is in the process of being dismounted.

10.2 Summary for Danish data

Denmark	Availability	Data format	Copyright holder	Public	Comments
Saline aquifers	Partly	Digital	GEUS	no	Distribution of saline aquifers
Sedimentary geological structures	Partly	Digital	GEUS	no	Most structures are mapped, but needs evaluation regarding CO_2 storage relevance
Hydrocarbon fields	All	Digital	Danish Energy Agency	no	Name and location can be public, but detailed data are restricted
Mineral trapping sites	-	-	-	-	Not relevant for Denmark
Sealing formations	Partly	Digital	GEUS	no	Draft data for one sealing formation exist
Exploration wells	All	Digital	Danish Energy Agency/GEUS	yes	Name, location and well logs are available from GEUS website for most Danish wells
Licence areas	All	Digital	Danish Energy Agency	yes	Data available from DEA website
Pipelines	Partly	Digital	GEUS	yes	Main pipeline data exist, as a digital version of public map
Pipeline terminals	All	Digital	GEUS	no	Data can most properly be public
Commercial, demonstration or pilot CCS activities	Data do not exist	-	-	-	Data can be generated

11. Summary for all Nordic countries

Most data on CO_2 storage sites relevant for a Nordic storage atlas exist in all Nordic countries, but there is a variation in level of detail and in what format data exists, which to some extent reflects the nature of national and international Carbon, Capture and Storage (CCS) research projects each country have participated in through the years. Norway and Denmark have participated in previous European CO_2 assessment projects and consequently Norway and Denmark have most CO_2 storage data available in a GIS (Geographical Information system) format ready to transfer to a new Nordic storage atlas. Nevertheless is Norway lacking detailed mapping of prospective CO_2 storage sits, because the “Norwegian Storage Atlas - Northern North sea” realised by the Norwegian Petroleum Directorate only contains maps of potential storage formations. The opposite is the case for the Danish data since mapping of the storage formations are insufficient whereas mapping of detailed geological structures exists. Sweden has all CO_2 storage relevant data available but only few data are digital or in a GIS ready format. In Iceland most of the data needed for the storage atlas are digital and can very likely be integrated into the webGIS atlas without major complications.

Geological data and maps such as the extension of sedimentary basins, storage or sealing formations, geological structures and mineral trapping sites and their geological properties are recorded at the national geological surveys or energy/exploration authorities. The national geological surveys or energy/exploration authorities also have access to or owns seismic data and well data essential for mapping the subsurface where data coverage are insufficient and new data are needed to be generated.

Data essential for CO_2 storage capacity estimates of hydrocarbon field are not public, but data exist and national energy/exploration authorities keep record of these data. Hopefully NORDICCS will get permission from the authorities to make estimated CO_2 storage capacities values public and available in the storage atlas.

Apart from the essential storage site data, data on CO_2 emission and infrastructure will add to the value of the atlas e.g. large stationary emission sources, existing pipelines, pipeline terminals and well data. Pipeline and pipeline terminal data are in most cases owned by governmental companies and exist in digital format, but it will need permission from these companies to publish data. Location of deep well are general public data and recorded at the national geological surveys or energy authorities for the respective countries. Digital well data are available from Iceland, Norway and Denmark.

National authorities have for several years claimed report on CO_2 emission from large CO_2 emitters and as a result are these data public available. Emission data have already 2010 been complied for the Nordic countries in connection within the pre-study report “Potential for carbon capture and storage (CCS) in the Nordic region” (Teir et al., 2010) and can easily be included in the storage atlas.

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Appendix

NORDICCS

Task 6.1 The Nordic CO_2 storage Atlas

Overview of existing data

Swedish sector

Compiled by

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29 May 2012

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Deep aquifers in Sweden that may be suitable for storage of CO2

There are three areas suitable for CO_2 storage. The most interesting is the Cambrian sandstones in the Central and Southern Baltic, the Triassic–Cenomanian sequence in the Southwest Skåne and adjacent offshore areas and probably also the Triassic–Cretaceous sequence in the Kattegat area.

The Cambrian sandstone aquifer

In the Swedish Baltic sector, in the Central and Southern Baltic there are sandstone horizons in the Lower and Middle Cambrian exhibiting suitable porosity and permeability values for CO_2 storing. The sandstone horizons have an areal distribution of several thousands of square kilometres. In most of the distribution area the sandstone units are found on depths more than 800 m. A stratigraphic scheme of the Lower and Middle Cambrian is shown in figure 1.

The Cambrian sequence dips gently to the south-east. The Cambrian sequence crops out at the island of Öland. In the south-eastern part of the South Baltic the sandstone sequences are found on depths exceeding 1 000 m.

The up to 50 m thick Faludden Sandstone exhibits the best reservoir properties. In the distal parts of the Swedish sector (south-eastern part of the Southern Baltic) the Faludden Sandstone occurs at depth of more than 1 000 m. Other less suitable sandstone units, the När and Viklau sandstones are found on depths exceeding 1 200 m in the same area.

The Faludden Sandstone is interpreted as a closed aquifer since it wedges out up dip and is overlain by alum shale and several hundred metres of Ordovician and Silurian limestone layers with bentonite clays acting as a significant seals.

A cross section from the Yoldia-1 in the west to the B9 well in the east is demonstrated in figure 2

Triassic to Cenomanian aquifers

In the Mesozoic sequence there are three intervals suitable for CO_2 storage, the Triassic Ljunghusen and Hammar sandstones, the uppermost Triassic–Lower Jurasic (Rät–Hettange) Höganäs Formation and the Cenomanian–Lower Cretaceous sandstone.

The most interesting area for CO_2 storage is the South-west Skåne and adjacent offshore areas. In this area the Triassic to Cenomanian sequence is well known and the interval top is found on depth more than 1 200 m. In the Kattegat area, a Triassic–Cenomanian sequence is identified but the data is insufficient to draw any conclusion according its storage potential. The situation is the same for the Jurassic–Cenomanian sequence in the Hanö Bay.

The Triassic aquifers are the Lower Triassic (Buntsandstein) including the Ljunghusen and Hammar formations. These formations are only found in the south-westernmost part of Southwest Skåne and in adjacent offshore area (Fig. 3) at 1 950–2 400 m depth. The formations have a total thickness of 100–200 m and a pay sand of 30–50 %. The porosity is 20–25 % in the sandstone interval. The sequence covers an area of ca 850 km^2 in Sweden.

In the south-westernmost part of Southwest Skåne and adjacent offshore area (Fig. 3) the Höganäs Formation top is found at 1 300–1 900 m depth. The formation has a total thickness of 100 m and a pay sand of 40–60 %. The porosity is 20–35 % in the sandstone interval. The sequence covers an area of ca 2 900 km^2 in Sweden.

In the south-westernmost part of Southwest Skåne and adjacent offshore area (Fig. 3) the Cenomanian Arnager Greensand top is found at 1 200–1 700 m depth. The formation has a total thickness of 20–60 m and a pay sand of 40–60 %. The porosity is 20–30 % in the sandstone interval. The sequence covers an area of ca 9 500 km^2 in Sweden.

There is a very thick sequence of argillaceous limestone, siltstone, claystone and chalk acting as a seal above the discussed Triassic–Cenomanian sequence. There are also clay layers in between the discussed aquifers acting as secondary seals.

Areas of interest included in the CO_2 atlas work

Sedimentary rocks cover most of the Swedish offshore area, the island of Öland, Gotland and Öland and Skåne. Sedimentary rocks occur also in minor areas on the Swedish mainland, however these areas are out of focus for CO_2 storage. Based on different sedimentary basins, and also the different seismic surveys and drilling campaigns, the following areal division have been made.

The Skagerakk area, area A

Includes the easternmost part of Skagerakk.

The Kattegat, area B

Includes the Skälderviken Bay, the Laholm Bay and the southeast parts of the Kattegat.

North-west Skåne, area C

The area is restricted to the onshore areas of northwest Skåne.

The Öresund area "the Sound" including the Höllviken Halfgraben, area D

The Sound and the offshore area south of Skåne and east of the Svedala Fault are included.

SW Skåne, area E

The area is limited by the Romeleåsen Fault and Flexurezone in the northeast, the Svedala Fault in the east and the coast line in south and west.

South-western Baltic – Skurup Platform, area F

The area is limited by the Romeleåsen Fault- and Flexurezone in the northeast, the Svedala Fault in the west and the German border in the south.

Inner Hanö Bay, area G

The Hanö Bay. The area is neighbouring area H, to the south by the Danish boarder and a line running from the southwest part of Scania in direction to the southern part of Bornholm. The Swedish mainland forms the western boarder.

Outer Hanö Bay, area H

Corresponds to the eastern part of the South Baltic Sea. The area is bordered in the east by area I, to the south by the Danish border, in the north by the Swedish mainland and to the west by a line drawn west-south-west from the south-east part of Blekinge to the Danish border.

Southern Baltic, area I

The area includes the Central and Southern Baltic.

Review of existing data useful for characterization

Seismic surveys

Several regional seismic surveys in the Swedish offshore sector as well as in Skåne and on the islands of Öland and Gotland have been performed during the 1970s and 1980s (Figs 4 & 5). The surveys were performed during commercial prospecting campaigns for hydrocarbon by the Swedish Oil Prospecting Company (OPAB) and the Swedish Exploration Consortium (SECAB). Data and results from these investigations are public and stored at SGU (Tables 1–3).

Borehole information

In the 1940s–1960s SGU drilled five deep prospecting wells for salt and hydrocarbon in Skåne. In the late 1960s OPAB continued the prospecting campaign for hydrocarbon and drilled 9 deep wells in Skåne and 14 off shore wells in the Baltic Sea and the Hanö Bay. Data, such as geophysical logs and reports from these wells are stored at SGU.

Some core material and cuttings are also available. All the data and material are public at the geological survey of Sweden.

Additional wells have been drilled by other companies. For instance have more than 300 prospecting wells been drilled on the island of Gotland. All these wells are also accessible and public available at the geological survey.

Publications and reports

Erlström, M. & Sivhed, U., 2001: Intra-cratonic dextral transtension and inversion of the southern Kattegat on the southwest margin of Baltica – Seismostratigraphy and structural development. *Sveriges geologiska undersökning Research Paper, C 832*, 1-33.

Erlström, M. & Sivhed, U., 2012: Pre-Rhaetian Triassic strata in Scania and adjacent offshore areas – stratigraphy, petrology and subsurface characteristics. *Sveriges geologiska undersökning Rapporter och Meddelanden, 132*, 1-74.

Erlström, M., Fredriksson, D., Juhojuntti, N., Sivhed, U. & Wickström. L., 2011: Lagring av koldioxid i berggrunden – krav, förutsättningar och möjligheter. *Sveriges Geologiska Undersökning Rapporter och Meddelanden, 131*, 1-96.

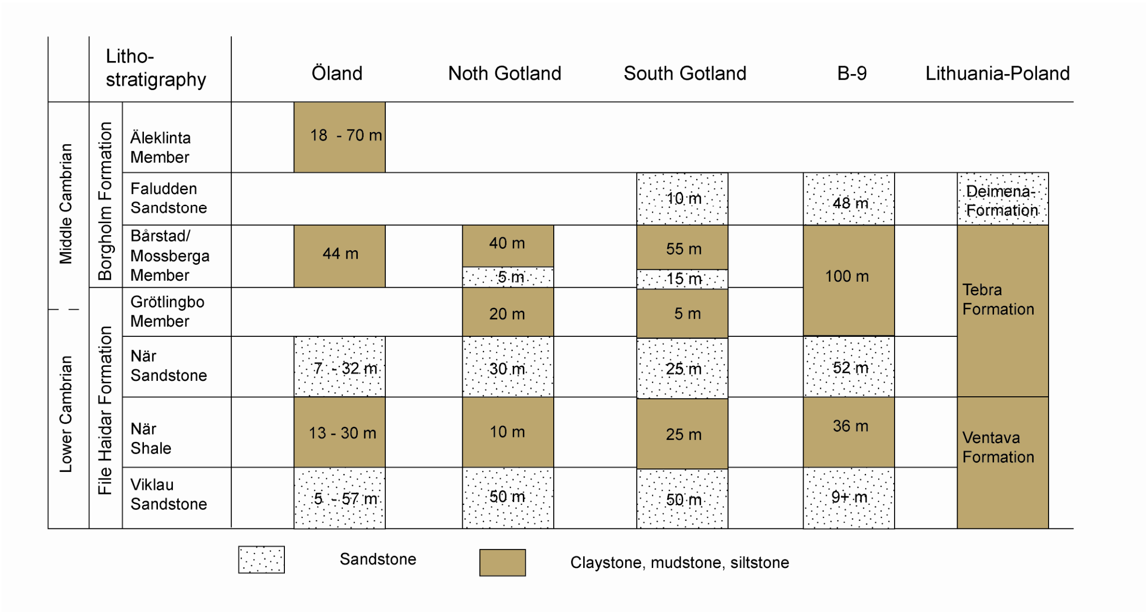

Figure 1. *Stratigraphic subdivision of the Lower and Middle Cambrian sequence in the Southern and Central Baltic Sea*

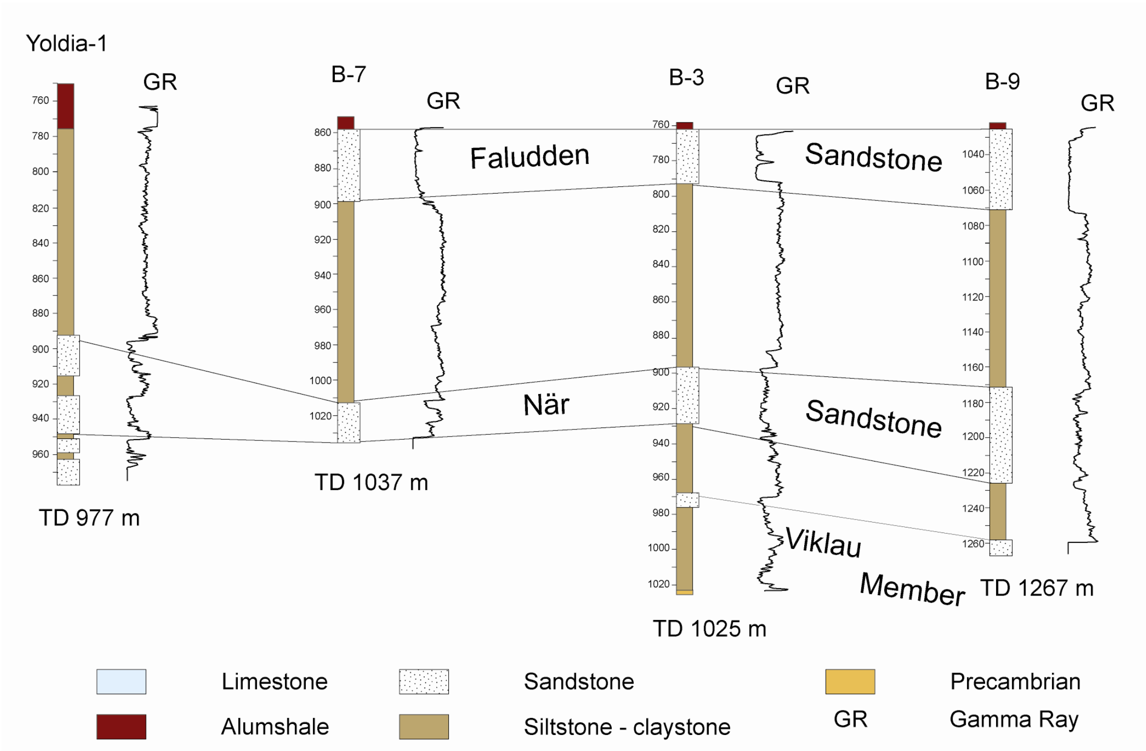

Figure 2. *Geological profile showing the Cambrian sequence in the Southern Baltic Sea.*

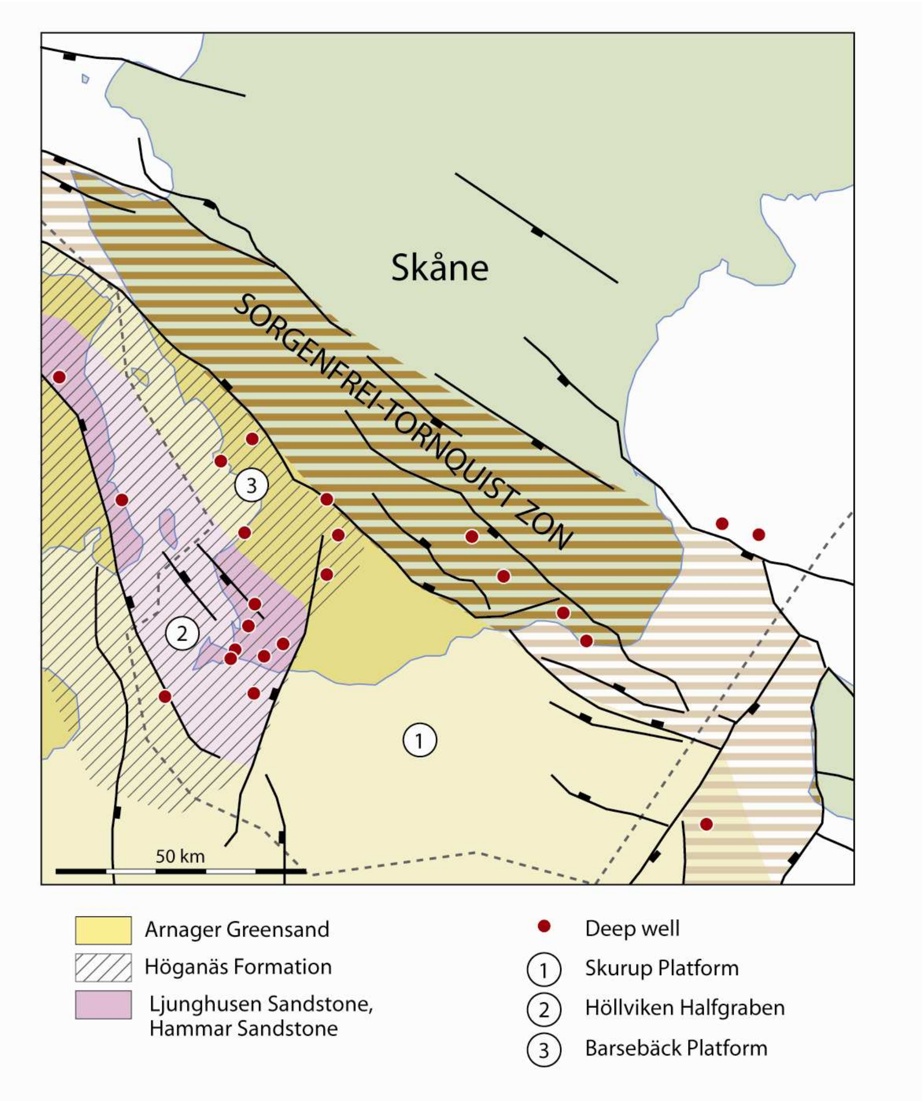

Figure 3. *Distribution of different aquifers in Southwest Skåne and adjacent offshore areas.*

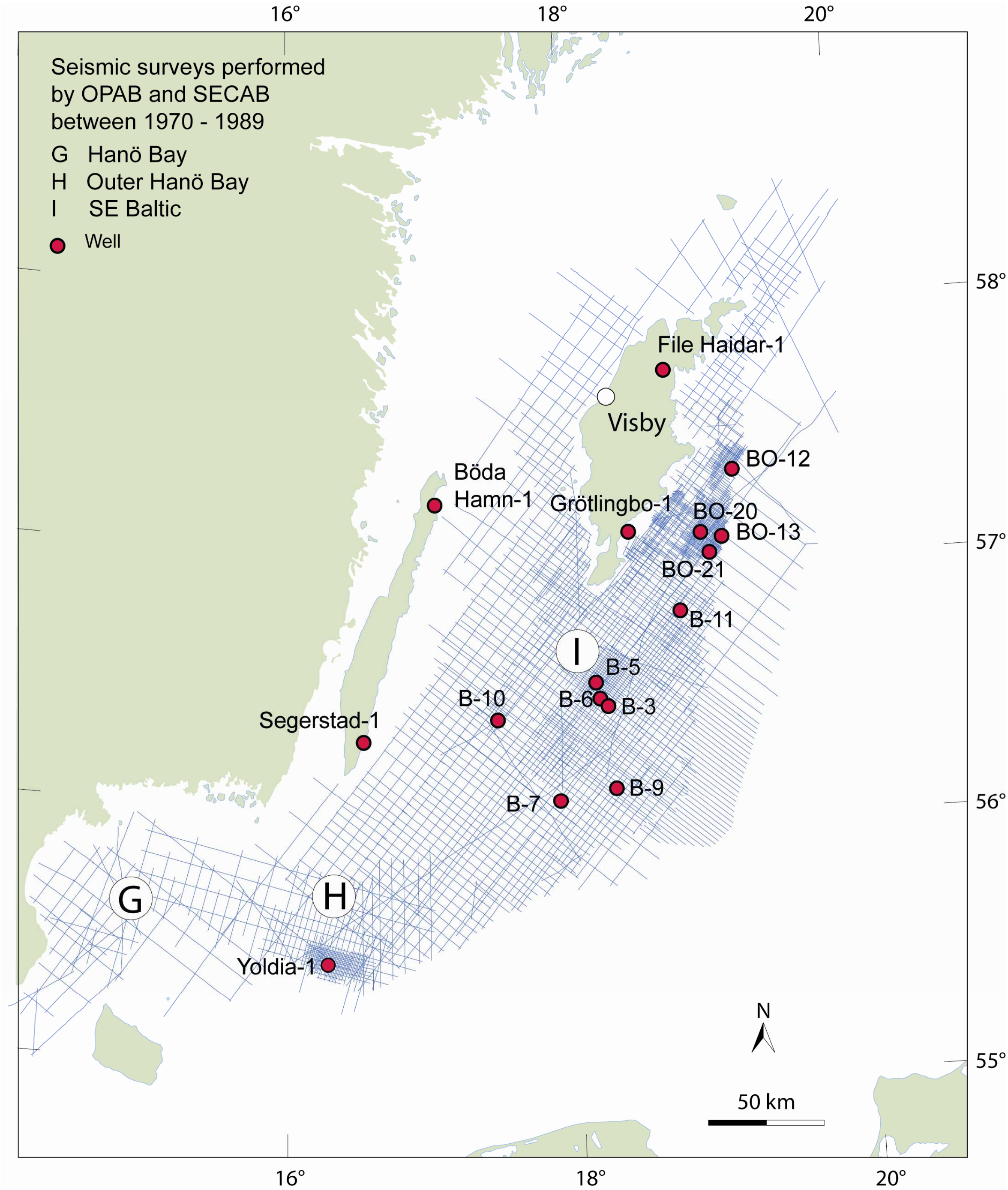

Figure 4. *Map showing the locations of seismic investigations performed by OPAB in the Central and Southern Baltic and the Hanö Bay.*

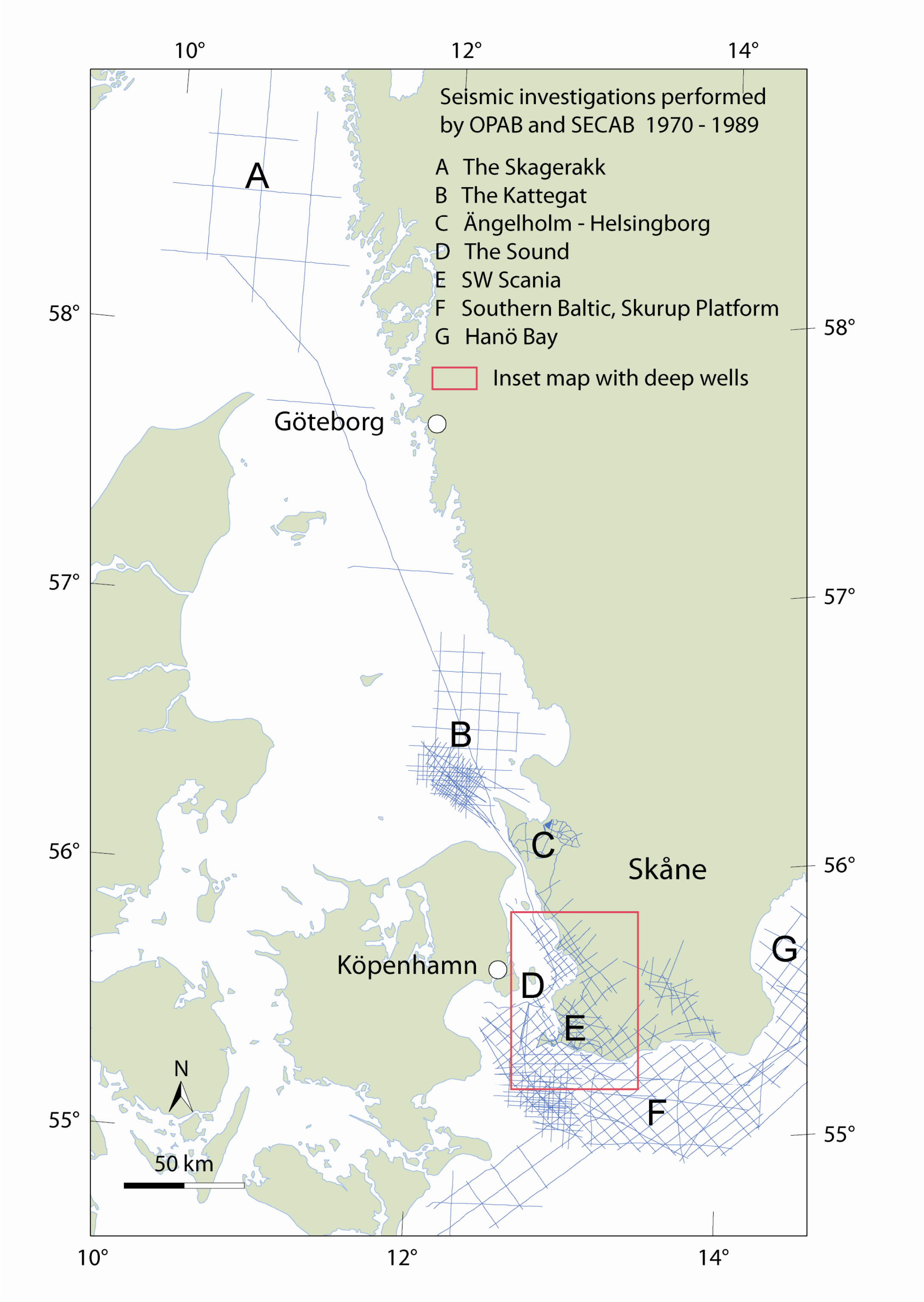

Figure 5. *Map showing locations of seismic investigations performed by OPAB in the Hanö Bay, the Southern Baltic, the Sound, Kattegat, Skagerakk, Southwest Skåne and in the Ängelholm-Helsingborg area.*

Table 1. Summary of boreholes drilled through or into Triassic – Cenomanian in Skåne and adjacent offshore areas. All depths are related to mean sea level in metres. TD= total depth.

Well	**Operator**	**Year**	**Reservoir unit**		**TD**
			Cenomanian-Triassic	Cambrian	m
Barsebäck-1	OPAB	1972	x		2255
Eskilstorp-1	OPAB	1971	x	x	2463
Falsterborev-1	OPAB	1973	x	x	1396
Granvik-1	Nordstjärnan	1947	x		1250
Hammarlöv-1	OPAB	1971	x	x	2369
Håslöv-1	OPAB	1972	x	x	2554
Höllviken-1	SGU	1941-1943	x		1415
Höllviken-2	SGU	1943-1947	x		1197
Höllviksnäs-1	OPAB	1971-1972	x	x	2606
Kungstorp-1	OPAB	1973	x		2064
Ljunghusen-1	SGU	1954-1955	x		2276
Maglarp-1	OPAB	1971	x		1938
Mossheddinge-1	OPAB	1973	x		1785
Norrevång-1	OPAB	1971	x		2127
Smygehuk-1	OPAB	1973	x		1659
Svedala-1	SGU	1948-1951	x		1628
Trelleborg-1	SGU	1947-1948	x		1201

Table 2. Boreholes drilled through or into Cambrian sequence on the islands of Öland, Gotland and in the Baltic. All depths are related to mean sea level in metres. TD = total depth.

Well	**Operator**	**Year**	**Reservoir unit**		**TD**
			Cenomanian-Triassic	Cambrian	m
Yoldia-1	OPAB	1987		x	952
B3	OPAB	1973		x	1006
B5	OPAB	1973		x	751
B6	OPAB	1974		x	839
B7	OPAB	1974		x	1009
B9	OPAB	1974		x	1240
B10	OPAB	1976		x	509
B11	OPAB	1976		x	1015
B12	OPAB	1976		x	794
B13	OPAB	1976		x	933
B20	OPAB	1976		x	665
B21	OPAB	1976		x	956
Faludden-1	OPAB	1972		x	792
Grötlingbo-1	SGU	1968		x	666
När-1	SGU	1967		x	652
File Haidar-1	Skånska Cement AB	1935		x	446
Segerstad-1	SGU	1968		x	256
Böda hamn-1	Pal. Inst. Uppsala	1948		x	162

Table 3. Seismic lines, available data, operators and datahost for the surveys carried out in the off shore area and in Skåne.

Region	Line	Year	No. of Sections available for re-processing of total	Operator	Datahost
The Skagerakk	W-70	1970		Western	
The Kattegat	W-70	1970		Western	
	D-72	1972	46/62	Delta	SGU
	E-73	1973		SEI	
	E-74	1974		GSI	
	Na-79	1979	59/68	GECO	SGU
	SKB-89	1989		Delft	
Ängelholm - Helsingborg	MCA-78	1978		Seis Geocode	
	MSA-78	1978		Seis Geocode	
The Sound	W-70	1970		Western	
	WS-71	1971		Western	
	C-71	1970		CGG	
	SKB-89	1989		Delft	
SW Scania	L-70	1970		CGG	
	1971	1971		Delta	
	C-71	1971		CGG	
South Baltic	W-70	1970		Western	
	WS-71	1971		Western	
	D-72	1972	46/62	Delta	SGU
	Ga-74	1974	142/165	GSI	SGU
	Na-79	1979	59/68	GECO	SGU
	SKB-89	1989		Delft	
Hanö Bay	W-70	1970		Western	
	WS-71	1971		Western	
	S-71	1971		SSL	
	D-72	1972	46/62	Delta	SGU
	Ea-73	1973	29/34	SEI	SGU
	Na-79	1979	59/68	GECO	SGU
Outer Hanö Bay	S-71	1971		SSL	
	Ga-74	1974	142/165	GSI	SGU
	RW-84	1984	44/45	RACAL	SGU
SE Baltic	IAOJ	?		?	
	S-71D				
	D-72	1972	46/62	Delta	SGU
	EA-73	1973	29/34	SEI	SGU
	ES-73		21/22		
	CV-74	1974		CGG	
	Ga-74	1974	142/165	GSI	SGU
	HR-74	1974		GSI	
	DS-75		139/169		SGU