CLEEN
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Research Report nr D534
Helsinki 2014

Nicklas Nordbäck

Report on status and capacities of geological CO_2 storage in the surrounding regions to Finland

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Report Title: **Report on status and capacities of geological CO_2 storage in the surrounding regions to Finland**

Key words: CO_2 storage, Finland

Abstract

Geological storage of CO_2 (CGS) is currently seen as a potential option for mitigating CO_2 emissions and scientist believes the earth has extensive capacity to store injected CO_2. Storage capacity is regionally quite unevenly distributed and most capacity estimates are still only theoretical estimates, which might have insecurities regarding the possible total volumes and the injectivity rates.

Since Finland lacks any potential for geological CO_2 storage any CO_2 captured in Finland would need to be transported and stored outside of Finland's borders. The Baltic Sea has some theoretical capacities but the formations, so far studied, seem quite poor regarding injectivity. Areas of Latvia and Kaliningrad could be more potential, but more data and work is needed. Some limited capacity is available in Sweden and in the Baltic countries while Poland, Germany and Denmark have quite good CO_2 storage capacities. Norway has an exceptionally large CO_2 storage potential and currently both the highest theoretical and practical capacities, mainly in the North Sea but also some in the Norwegian and Barents Sea. Western Russia looks promising for geological CO_2 storage but has not been systematically investigated. For Denmark and Sweden, new information on storage potential and possible practical capacities will be published in 2015 as part of a Nordic CO_2 storage atlas.

The distances from Finnish point sources to potential storage sites is quite long, but in comparison to the rest of Europe, the offshore storage potential is very large in areas surrounding Finland.

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1 Introduction

1.1 General

Geological storage of CO_2 (CGS) is the only storage method, which has been demonstrated in industrial scale and is currently seen as the most potential option. Scientist believes the earth has extensive capacity to store injected CO_2 and the U.N. special report on CCS (IPCC, 2005) estimates the global CO_2 storage capacity in oil and gas fields, unmineable coal seams and in deep saline aquifers to be at least 2 Tt in total. There is still however a high insecurity regarding the capacity of deep saline aquifers, which alone could have a capacity of up to 10 Tt. This insecurity is due to the fact that saline aquifers are much less explored, compared to the sedimentary formations that have been found to hold oil and gas accumulations. Potential storage sites are present on all continents but are regionally quite unevenly distributed (Figure 1-1). For assessing the storage potential and comparing potential reservoirs, only theoretical estimates are available for many regions. To allow more precise estimates; more data, dynamic simulations and injection experience is needed.

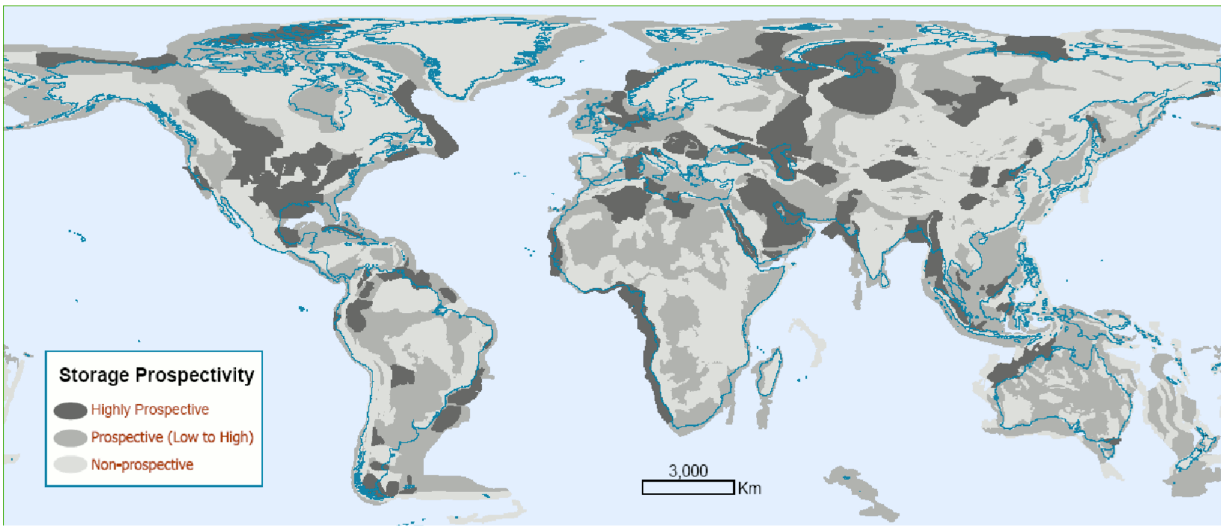

Figure 1-1. Map of global geological CO_2 storage prospectivity (IPPC, 2005).

From Finnish point of view CGS means transportation of CO_2 abroad because no potential storage sites have been identified inside the borders of Finland. The nearest identified and demonstrated geological storage sites are located in the North Sea.

The aim of this report is to compile information on the current status and capacities of CGS in the surrounding regions to Finland. Large parts of this region were estimated in the EU GeoCapacity project (Vankilde-Pedersen et al. 2009). The so called CO2StoP project (2013) has also since then gathered some additional data and harmonised most European data into a common database. Some countries have also recently published results from further national studies on CO_2 storage capacity. To characterise potential storage sites and to get accurate estimates of actual practical capacity, much work is still needed. One important issue is to get more information on possible injectivity rates.

One of the upcoming studies, especially interesting from Finnish point of view, is the Nordic CO_2 storage atlas compromising potential storage sites in all the Nordic countries. This atlas, created by the NORDICCS project, will be publicly available in 2015 as a web-based geographical information system (GIS), allowing visual overview of CO_2 storage options and access to data connected to the storage site e.g. storage capacity. Characterisation of the storage sites will lead to identification of the most prospective sites for safe storage of CO_2 in the Nordic region.

1.2 Geological CO2 storage criteria

To store CO_2 a porous, permeable formation with a caprock usually at a depth below 800 m is needed. Porosity is required for the space to store, permeability for the ability to inject large quantities of CO_2, caprock to ensure that the CO_2 stays inside the formation and sufficient depth to maximise the quantities stored. Critical parameters that are considered for geological storage are gathered in Table 1-1.

Table 1-1. Requirements on CO_2 geological storage (based on Chadwick et al. 2008)

Parameter	Requirement	Comments
Capacity	**> 100 Mt CO_2**	Equivalent production of about 2 Mt of carbon dioxide per year from a source under 50 years. Storage capacity should generally be much larger than what the nearby source produces during its lifetime.
Depth	**800-2500 m**	At around 800 m depth CO_2 enters supercritical state. Below 2500 m depth the rock (aquifer) is generally too dense. Shallower aquifers may be interesting if the carbon dioxide can be injected under positive pressure and still be in supercritical state.
Thickness of formation	**20-50 m**	Net thickness. Can thus be divided into one or more sandstone levels separated by dense rocks.
Porosity	**>10%**	Preferably above 15%.
Temperature	**>31.1°C**	For the CO_2 to enter supercritical state.
Salinity	**>30g/l**	Preferably above 100g/l
Pressure	**>73.9 bars**	For the CO_2 to enter supercritical state.
Permeability	**>200 mD**	Different numbers reported.
Caprock	**Site specific**	Layers of low permeability rock that overlay the storage formation, ensuring that buoyant dense or vapour-phase CO_2 does not leak into overlying strata.

1.3 Evaluation of geological storage capacity

The evaluation of geological volumes suitable for injecting and storing CO_2 can be viewed as a step-wise approximation, as shown in the maturation pyramid in Figure 1-2 (NPD, 2014).

The lowest level (blue) is the volume calculated on average porosity and thickness. This is done in a screening phase that identifies possible aquifers suitable for storage of CO_2. The theoretical volume is based on depositional environment, diagenesis, bulk volume from area and thickness, average porosity, permeability and net/gross values. A large part of the world's estimates on CO_2 storage capacity are at this theoretical level.

The second level (green) is the storage volume calculated when areas with possible conflicts of interest (i.e. petroleum industry, nature reserves) have been removed. Only aquifers and prospects of reasonable size and quality are evaluated. Evaluation is based on relevant available data.

The third (yellow) level refers to storage volumes where trap, reservoir and seal have been mapped and evaluated in terms of regulatory and technical criteria to ensure safe and effective storage. To achieve this stage a detailed static and dynamic modelling is required. Storage volumes in this level can be regarded as ready for injection and are often referred to as practical capacity.

The highest level (red) is when CO_2 is injected in the reservoir. Throughout the injection period, the injection history is closely evaluated and the experience gained provides further guidance on the reservoirs' ability and capacity to store CO_2. More data, detailed modelling and experience from subsurface activities contributes to the process of finding storage volumes as high up as possible in the pyramid.

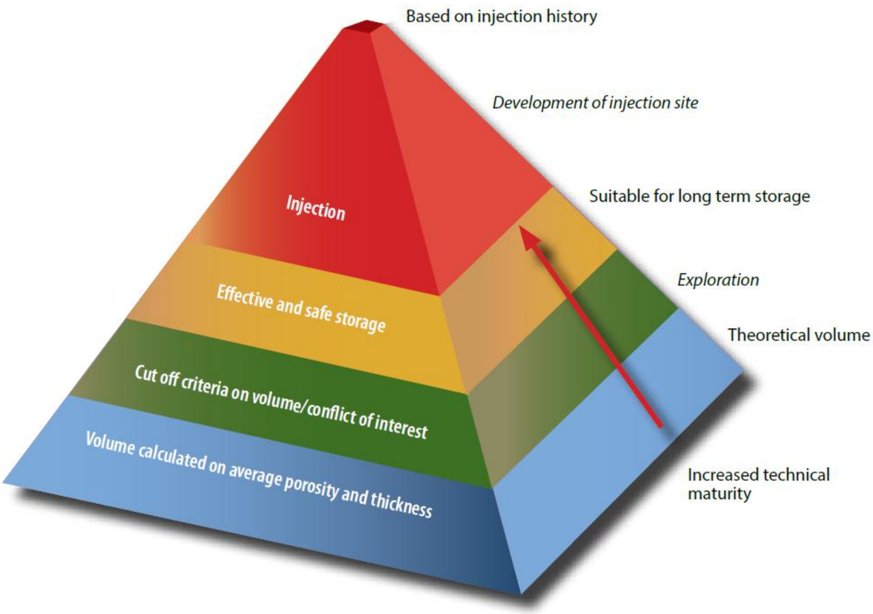

Figure 0-1. Maturation pyramid for CO_2 storage capacity (NPD, 2014).

2 Geology and storage potential of Finland

The bedrock in Finland is composed mainly by crystalline and low porosity rock types which lack a potential for CO_2 storage. The crystalline bedrock of Finland is a part of the Precambrian Fennoscandian Shield, which was eroded down almost to its present level prior to the beginning of the Cambrian (about 600 million years ago). Due to continental conditions and subsequent ongoing erosion it is almost totally lacking in sedimentary rocks younger than the Precambrian (Fig. 2-1).

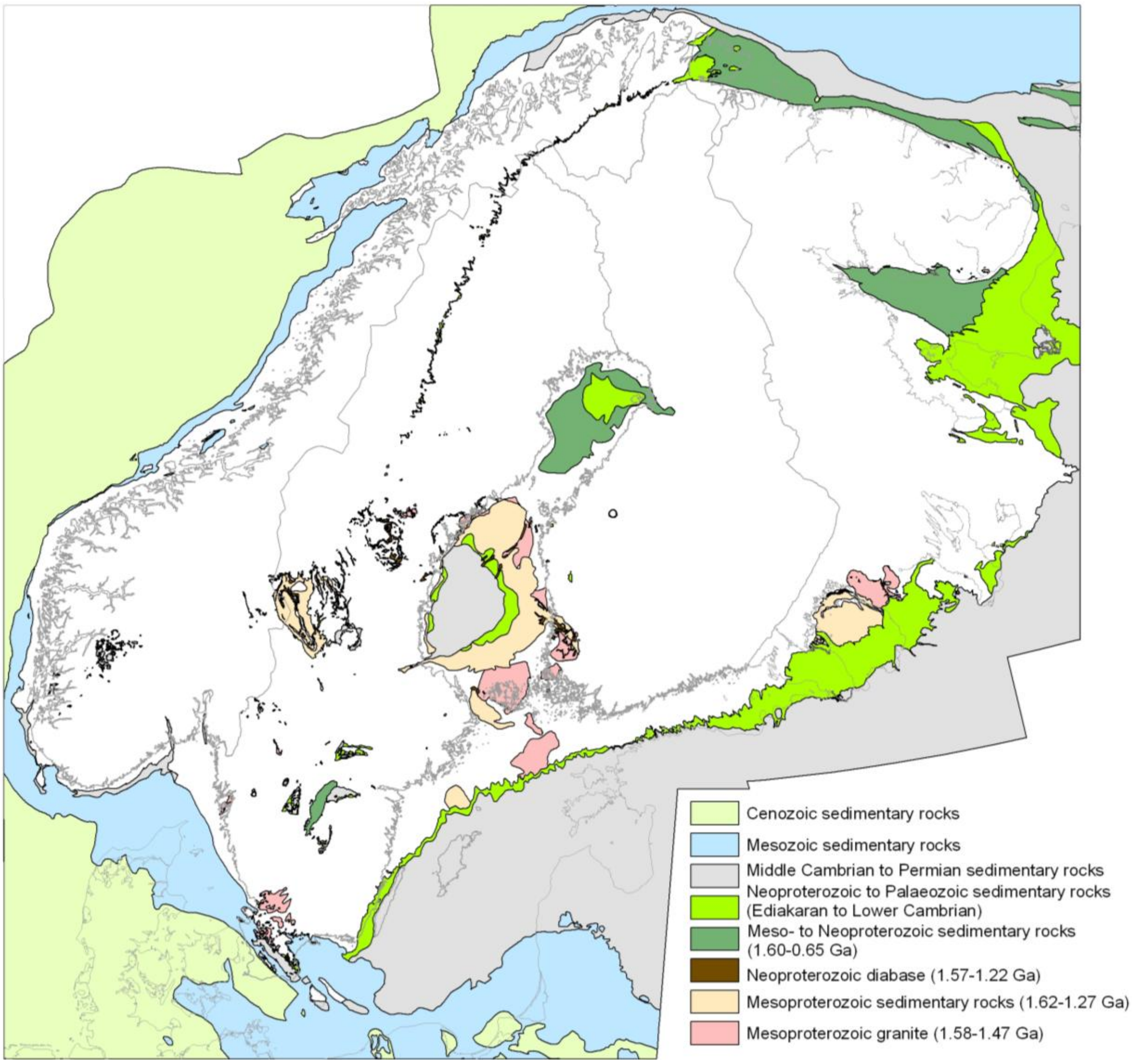

Figure 2-1. Sedimentary rocks on Fennoscandian shield and surrounding areas (Koistinen et al., 2001).

As sedimentary age increases, so does the likelihood that the porosity and permeability is reduced. Due to density and other geological characteristics the few and small existing Finnish sedimentary formations are unsuitable for CCS. Storage potential in a sufficiently deep (> 800 m) and porous sedimentary rock does not occur in Finland. Known sedimentary rocks are generally too shallow and the porosity is poor. The porosity is regularly higher (5-10 %) in the upper and younger layers of the Finnish sedimentary formations and gradually decreases towards the deeper and older layers. Porosity is generally < 5 % in sufficiently deep layers. Formations also usually lack possible cap rocks. Due to lack of geological data (especially from the Gulf of Bothnia), the possibility to store in geological formations in Finland cannot be totally excluded but it can be regarded very unlikely and theoretical volumes would probably be negligible (Solismaa 2009). Finnish basaltic volcanic rocks are also old and metamorphosed, thus lacking in porosity. The potential for storage increases in the Baltic Sea, southwards from the Åland Islands.

3 Status and capacities of geological CO_2 storage in the surrounding regions to Finland

3.1 Storage potential in the Baltic Sea

3.1.1 Status of investigations

The Baltic Sea was previously not studied in detail and therefore not included in the GeoCapacity project. Lately there have been some actions regarding CO_2 storage in this region.

In 1998 BASREC (the Baltic Sea Region Energy Cooperation) was founded by the ministers for energy of the region and the European Commission. As part of a CCS initiative of BASREC, a pre-study on transportation and storage solutions for CO_2 in the Baltic Sea region was published in 2012. A BASREC CCS network initiative is also currently ongoing.

In 2011 the BASTOR (Baltic Sea Storage of CO_2) project was initiated as collaboration between the Finnish CCSP research programme and the Swedish CCS project consortium. This study was based on analysis of previously measured available data, with focus on the southern part of the Baltic Sea region. The final report from this project was published in 2014.

3.1.2 Storage capacity

The Cambrian sandstone of the Baltic Sea could be suitable for storage (Figure 3-1). The knowledge of the Cambrian layer sequence in the southern Baltic Sea is largely based on information from the hydrocarbon prospecting in the 1970s by OPAB (Oljeprospektering AB), partly in collaboration with other stakeholders.

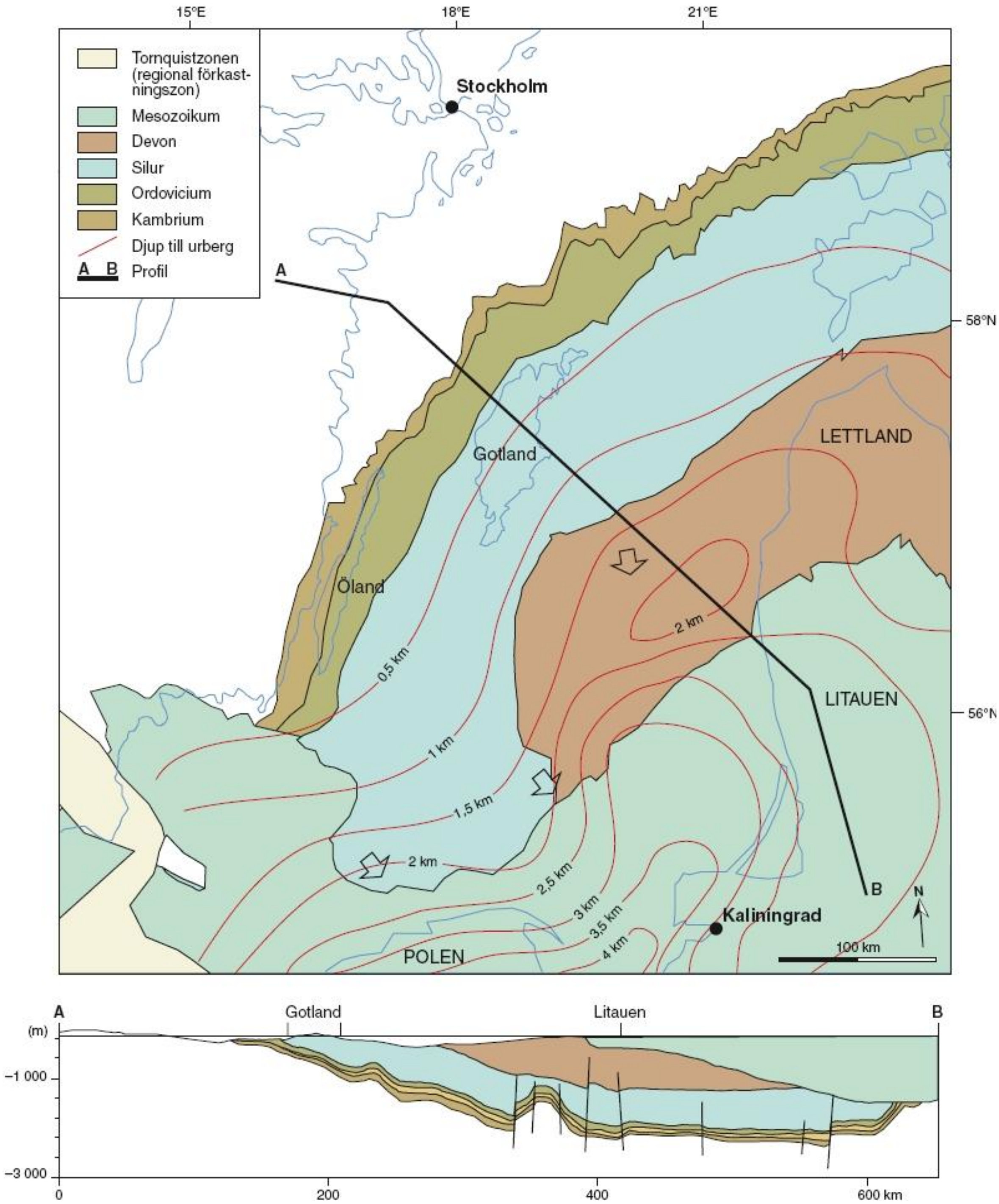

Figure 3-1. Map showing bedrock surface age in the southern Baltic. The profile of the lower part of the figure shows a vertical section of the rock from northwest to southeast (Erlström et al. 2011).

The Cambrian sandstone sequence is overlain by a thick sequence of Middle Cambrian, Ordovician and Silurian rocks. In the south-eastern part of the Baltic the Silurian rocks are overlain by Devonian sandstones. The presence of the contained oil and gas in the Cambrian sandstone on the Baltic side of the Baltic Sea is a good indication that the overlying layers, at least in these parts of the Baltic Sea, is sufficiently dense (Erlström et al. 2011).

The BASTOR study determined that there is a theoretical regional capacity to store some 16Gt of CO_2 in the Middle Cambrian sandstone beneath 900 metres of caprock and 1.9Gt in the Dalders Monocline. There is theoretical storage capacity of some 743Mt CO_2 in hydrocarbon and saline structures, which are located mainly offshore Latvia. On the basis of the data available, there is no effective capacity proven within these totals, although the Dalders Structure, with 128Mt, could be considered better defined, albeit still within the theoretical category range. Thus the study has established a relatively large theoretical storage capacity for captured CO_2.

The southern Swedish sector of the Baltic Sea, where dynamic modelling was undertaken has relatively poor permeability and porosity characteristics. Maintaining a reservoir pressure at a reasonable level limits the injection rate to about 0.5Mt per well per annum over a 50 year period, resulting in a relatively low practical capacity. Areas in Latvia and Kaliningrad are thought to have better reservoir properties but more data and investigations would be needed.

3.2 Storage potential in Baltics

3.2.1 Status

The Baltic countries has been studied and assessed and their storage capacity is included in the GeoCapacity and CO2StoP database.

3.2.2 Capacity

The Baltic countries are situated in the eastern part of the Baltic sedimentary basin that overlies the western periphery of the East European Craton. The basin contains the Ediacaran (Upper Vendian) and all of the Phanerozoic systems. The thickness of the sediments is less than 100 m in northern Estonia, increasing to 1900 m in south-western Latvia and 2300 m in western Lithuania (Figure 3-2). Cambrian sandstones are the most prospective reservoir rocks for CO_2 storage in the Baltic region (Shogenova et al. 2011).

The storage potential of the Baltic countries has been reported by Sliaupa et al. in 2009. According to this report the storage possibilities in Estonia are virtually nonexistent since the potential aquifers are too shallow. In Latvia the Cambrian sandstone aquifers contain 15 structural traps suitable for CO_2 storage. The assessed total storage capacity in Latvia is 0.4 $GtCO_2$, 0.3 $GtCO_2$ onshore and 0.1 $GtCO_2$ offshore. In Lithuania, a comprehensive survey of potential aquifers and their suitability for carbon storage has been carried out. Two aquifers in Cambrian and Devonian formations were identified as suitable. The theoretically possible regional storage capacity of the two aquifers is very large (1-2 $GtCO_2$), but assessments are focused on closed structures (Sliaupa et al 2009). A number of structural traps, which theoretically can store up to 200 $MtCO_2$ have been identified and a practical capacity of 37$MtCO_2$ has been calculated.

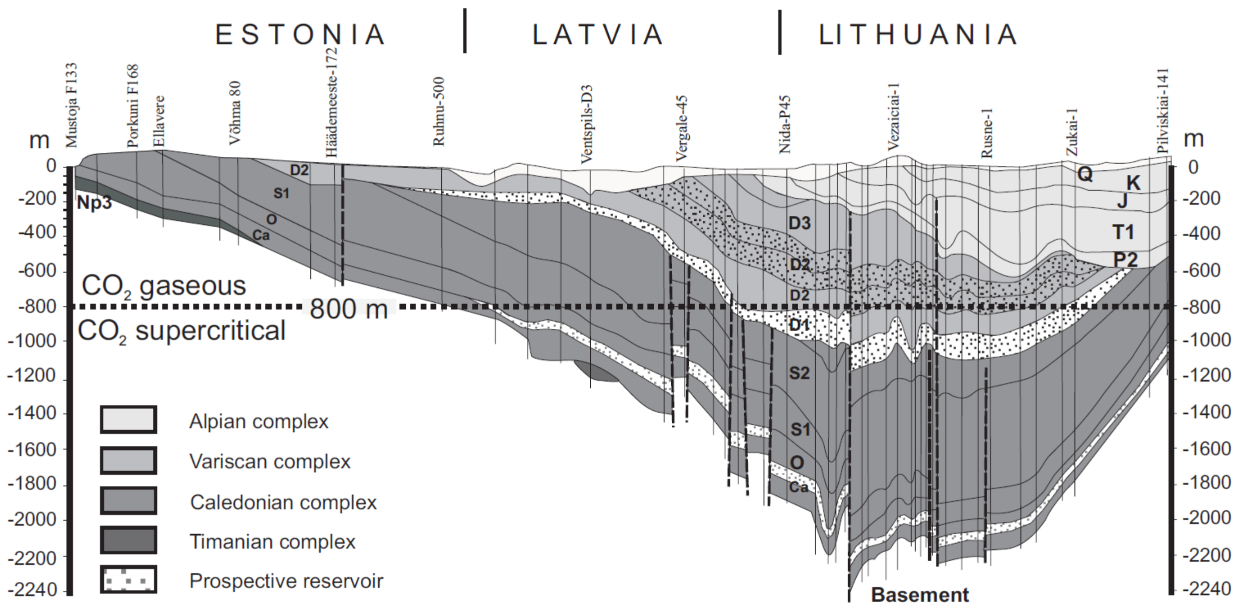

Figure 3-2. Geological cross section across Estonia, Latvia, and Lithuania (modified after Sliaupa et al. 2008). Major aquifers are indicated by dots. Np3, Ediacaran (Vendian); Ca, Cambrian; O, Ordovician; S1, Lower Silurian (Llandovery and Wenlock series); S2, Upper Silurian (Ludlow and Pridoli series); D1, D2, and D3, Lower, Middle, and Upper Devonian; P2, Middle Permian; T1, Lower Triassic; J, Jurassic; K, Cretaceous; Q, Quaternary (Shogenova et al. 2009).

3.3 Storage potential in Russia

3.3.1 Status

During 1980-1990 large scale pilot tests were carried out in the southern Ural area, where CO_2 formed at petrochemical plants was used for EOR (Enhanced Oil Recovery) testing. Recent government-organized scientific research has been aimed at the development of advanced and economically attractive solutions for the future. Issues looked at include advanced capture technologies, CCS potential, identification of large point pollution sources and links to potential storage sites. In addition, the Russian State University of Oil and Gas has been looking into EOR and ECBM (Enhanced Coal Bed Methane) opportunities. At this stage it seems that most CCS research in Russia has been suspended. This is likely because Russia's CO_2 obligations have been met with no action (D506).

3.3.2 Capacity

The potential for storage in Russia has not yet been systematically studied. The Russian Federation is however extremely rich in oil and gas deposits with high potential for storage. Storage in aquifers probably has even a greater potential but has not been investigated. Areas with likely storage potential in western Russia include: Barents Sea, Timan Pechora, Volga Ural, Moscow basin and the Baltic Sea (D506) (Figure 3-3). The prospective areas for CO_2 storage in western Russia, presented below, were identified in the CLEEN CCSP research report D518.

Mezen and Moscow basins have not been drilled and explored as much as the more potential hydrocarbon areas of Russia. However, some prospective Vendian layers seem to exist in both regions and especially the Devonian sequence of Moscow basin looks promising from a CO_2 storage perspective.

In Volga-Ural and Timan Pechora basins potential for geological CO_2 storage most likely exists, both in aquifers and in depleted oil and gas fields. The Paleozoic strata looks highly potential for CO_2 storage in both regions and in Timan Pechora a high storage potential should also exist in the overlying Mesozoic sequence. These regions have for a long time both been active in oil and gas production and exploration and have therefore reached a high level of maturity regarding the availability of data.

The arctic offshore location of the East Barent Sea basin makes it a challenging area for exploration. Although not very well studied, there is a huge hydrocarbon potential in this region and CO_2 storage has already been demonstrated in sediments of Mesozoic age on the Norwegian part of Barents Sea. In addition to the Mesozoic sequence, some parts of the Paleozoic might also offer possibilities for CO_2 storage in the East Barents Sea basin.

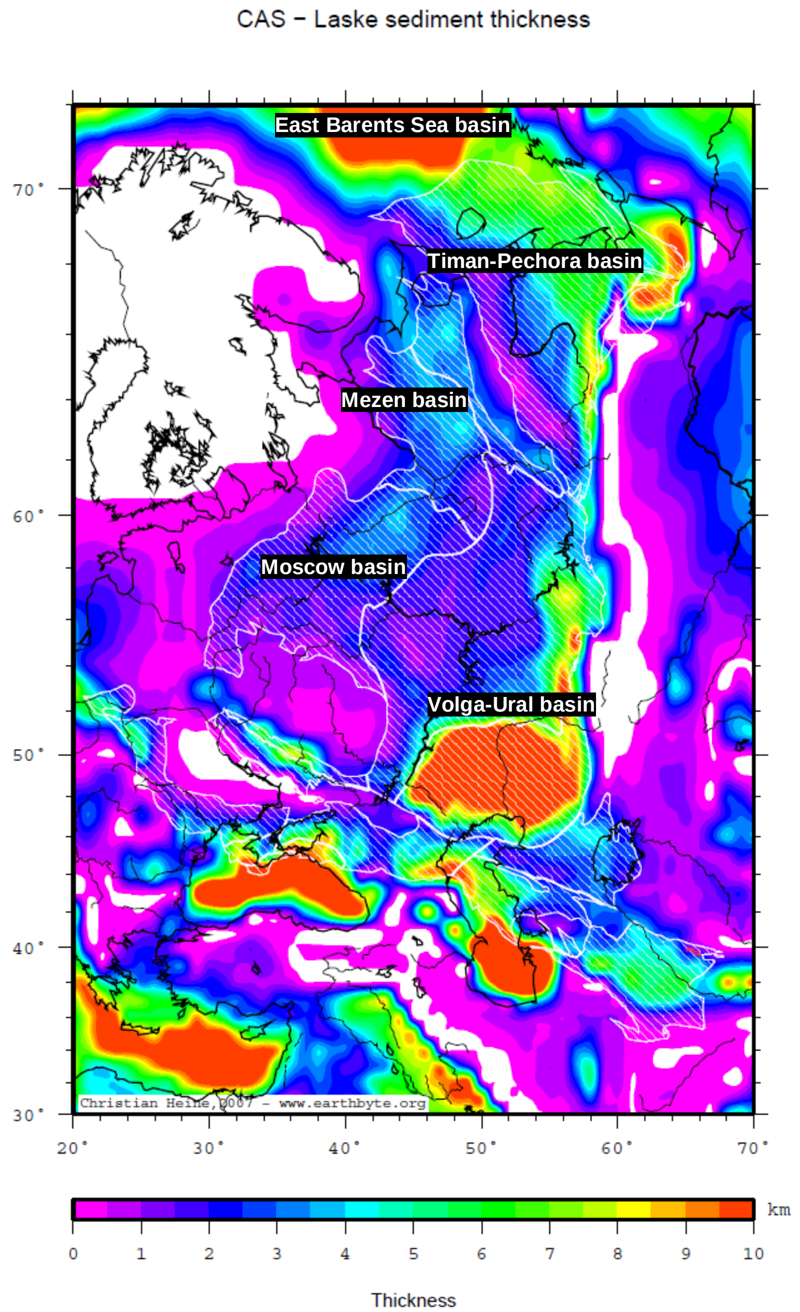

Figure 3-3. Laske sediment thickness map with sedimentary basins of western Russia outlined.

3.4 Storage potential in Poland

3.4.1 Status

Poland has been systematically exploring its capacity for CO_2 storage already since the beginning of this century. First storage capacity estimates were made as part of the RECOPOL project (2001-2005) which studied the feasibility of CO_2 underground storage in unmineable coal seams in combination with the production of coal bed methane (CBM). First systematic calculations on Polands total CO_2 storage capacity were made as part of the CASTOR and following GeoCapacity projects. Since then a project called "Assessment of formations and structures for safe CO_2 geological storage including monitoring plans" (2008-2012) has made more detailed studies and calculations. Currently, a new project has started in Poland called "A detailed assessment of areas perspective for CO_2 storage on the area of Polish economic zone of Baltic Sea" (2014-2016).

3.4.2 Capacity

In Poland Mesozoic saline aquifers have the largest capacity to store CO_2 but there is also a small potential in hydrocarbon fields and coal seams (Figure 3-4). Paleozoic successions also seem to have some additional storage capacity, including the Cambrian offshore in the Baltic Sea. The Castor and GeoCapacity projects, which only focussed on the Mesozoic, reported a theoretical total of around 90 Gt CO_2 and a conservative capacity of 5 Gt. Following studies however shows that the realistic theoretical storage capacity in Poland is probably around 15 Gt CO_2 (Wójcicki, 2013). The rate of onshore versus offshore potential is likely 90 % to 10 %.

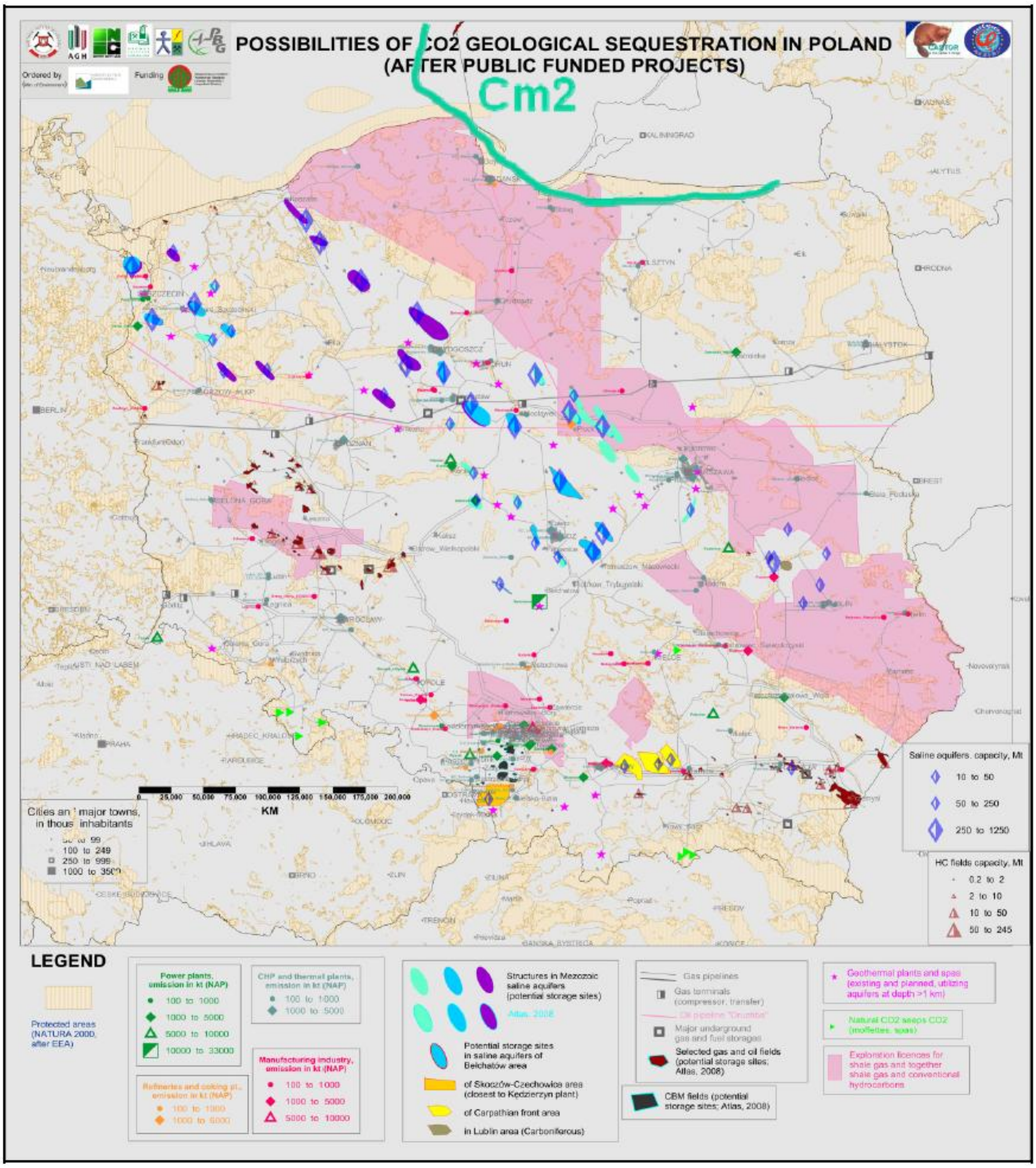

Figure 3-4. Results of ongoing regional studies on assessment of realistic CO_2 storage capacity for Poland (Wójcicki, 2011).

3.5 Storage potential in Germany

3.5.1 Status

Germany has assessed its CO_2 storage potential as parts of the European GESTCO (1999-2003), GeoCapacity and CO2Stop projects. The Federal Institute for Geosciences and Natural Resources in Germany in currently actively involved in several R&D projects on geological CO_2 storage.

3.5.2 Capacity

The most suitable sites for CO_2 storage in Germany would be depleted and active gas fields in Permian and Triassic sandstones of the North and Middle German Sedimentary Basin (Figure 3-5). The storage capacity of depleted gas fields in Germany is about 2.75 Gt (billion tons). Depleted oil reservoirs in Germany are too small to make a substantial contribution to CO_2 storage. Their storage potential is only about 130 Mt. Deep saline aquifers have the largest potential for CO_2 storage in Germany and their storage potential is currently estimated to be up to about 13 Gt (Knopf et al. 2010).

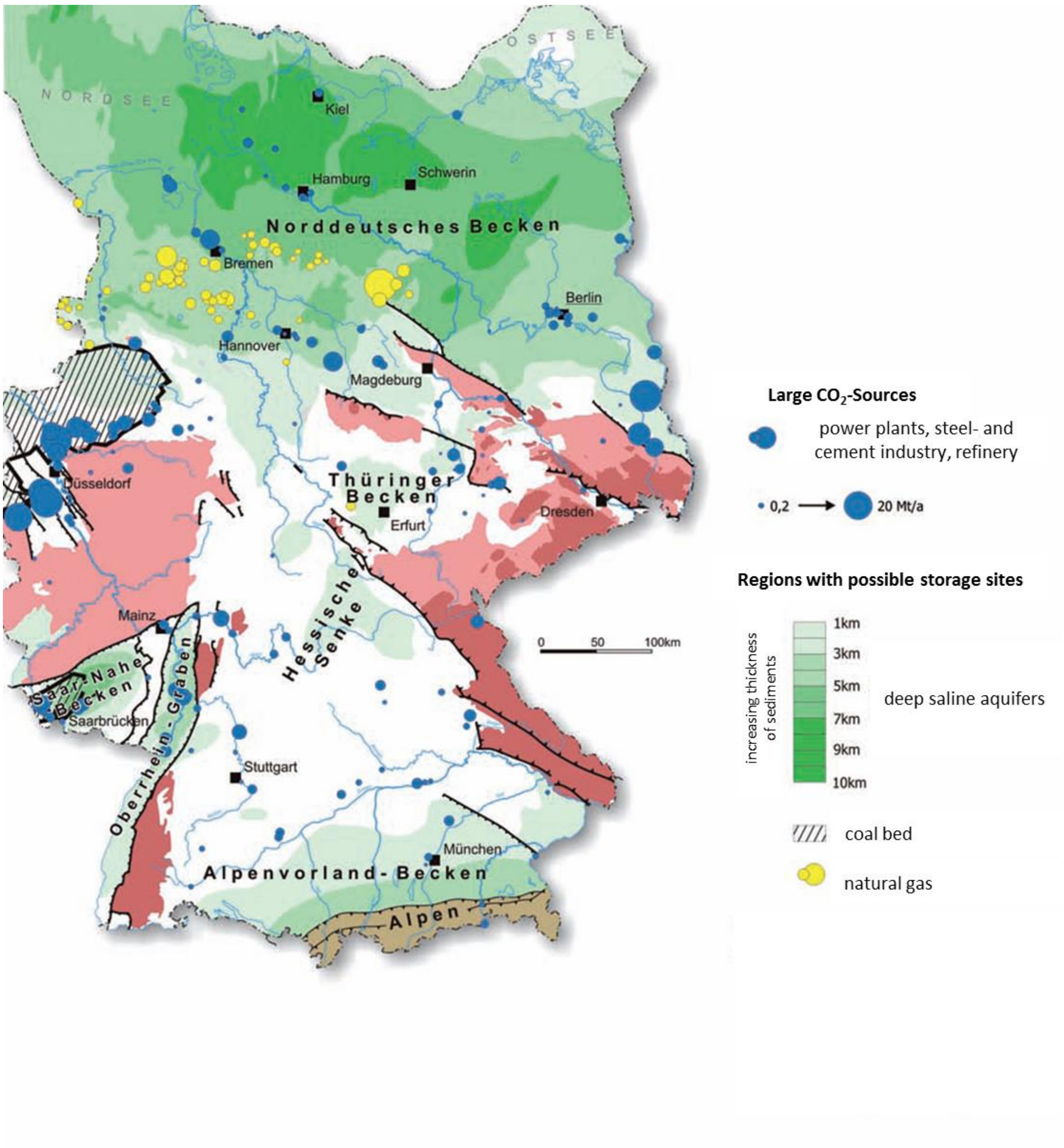

Figure 3-5. Large CO_2 sources and potential CO_2 storage reservoirs in Germany (Ketzin webpage, 2014).

3.6 Storage potential in Sweden

3.6.1 Status

The potential for storage in Sweden has not been systematically assessed yet. Erlström et al. published in 2011 a report on the possibilities for CO_2 storage in Sweden, containing results from screening for potential sedimentary formations in Sweden for CO_2 storage. Currently Sweden is participating in the NORDICCS project which is aiming to create a Nordic CO_2 storage atlas compromising potential storage sites in all the Nordic countries. This atlas will be publicly available in 2015 as a web-based geographical information system (GIS), allowing visual overview of CO_2 storage options and access to data connected to the storage site e.g. storage capacity.

3.6.2 Capacity

Screenings for CO_2 storage capacity in the Swedish territory indicates three potential areas for CO_2 storage in southern Sweden. Suitable aquifers are present in the Cambrian sandstone in the southern Baltic Sea (adjacent to Polish, Russian, Lithuanian and Latvian waters), sandstones from older Cretaceous, older Jurassic and older Triassic, present at a 1200-2500 m depth in SW Skåne and sandstone layers in the Skagerrak and Gassum formations (younger Triassic – older Jurassic) in SW Kattegatt (adjacent to Danish waters) (Erlström et al. 2011) (Fig. 3-6).

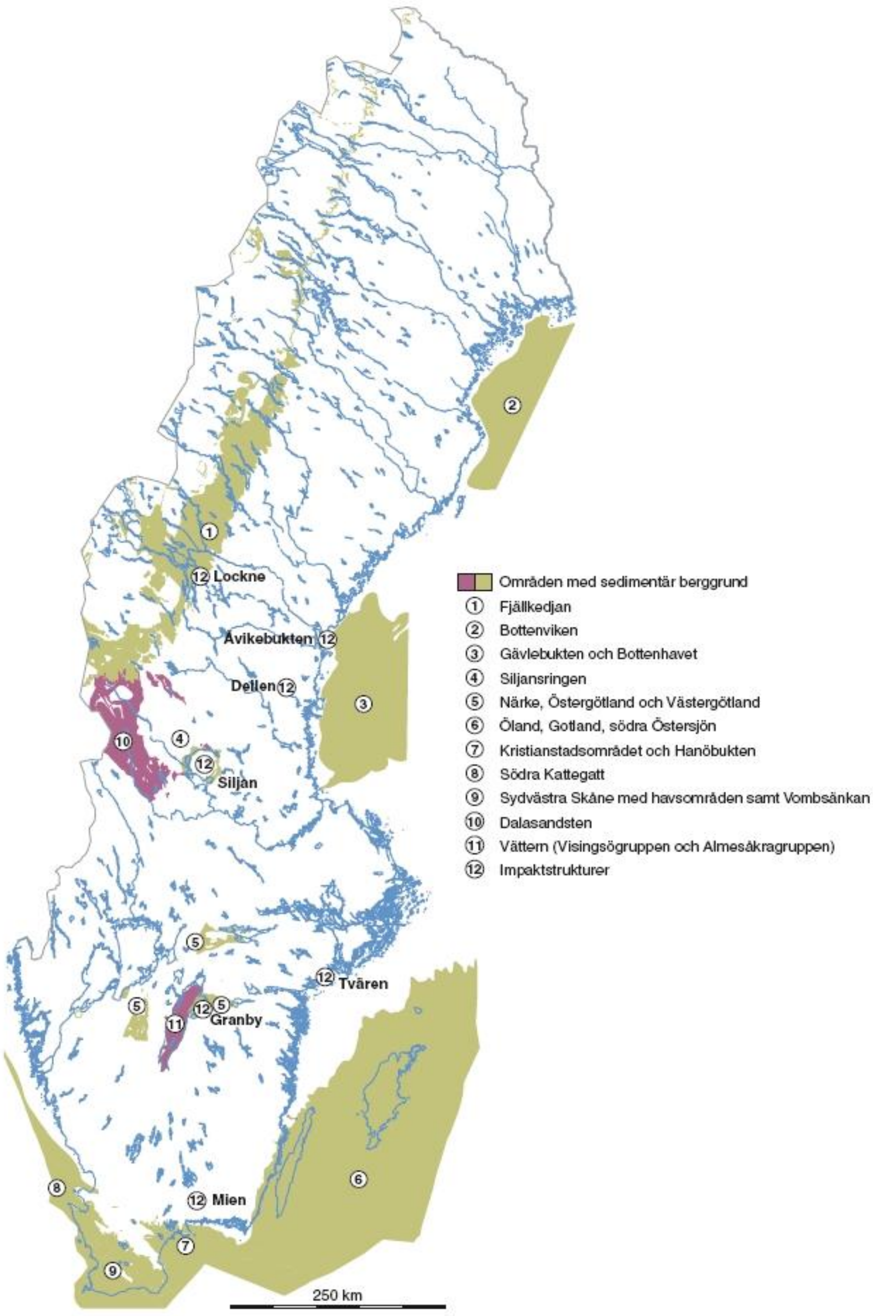

Figure 3-6. Sedimentary bedrock of Sweden (Erlström et al. 2011).

3.7 Storage potential in Denmark

3.7.1 Status

Denmark has been actively involved in geological CO_2 storage investigations and GEUS has coordinated several R&D projects such as GeoCapacity and CO_2StoP. Together with Sweden and Norway, Denmark (GEUS) is currently participating and coordinating the work on the Nordic CO_2 storage atlas.

3.7.2 Capacity

According to GeoCapacity conservative estimates the storage potential in Denmark is 2.6 GtCO_2 in deep saline aquifers and 0.2 GtCO_2 in hydrocarbon fields. Denmark has through international cooperation purposefully studied the structures of the bedrock. The depth of the top of Early Jurassic–Lower Triassic reservoir sandstones of the Gassum, Bunter and Skagerrak formations structures is usually between 1000–1900 m, permeability 75–1000 mD, porosity 10–25% and the thickness of sandstones between 100–760 m (Shogenova et al. 2011). In Denmark salt domes has produced anticlines that would be very good reservoirs. A number of closed structures have been identified in close proximity to emission sources and the total estimated storage volume in the Danish structures could cope with a storage corresponding annual production from major point sources for several hundred years. In addition to carbon storage the identified aquifers are also interesting for geothermal energy production, hydrocarbon prospecting and energy storage. This means that in some cases there could be conflicts of interest (Erlström et al. 2011).

Updated information and more precise numbers on storage capacity are expected when the NORDICCS project delivers its Nordic CO_2 storage atlas in 2015.

3.8 Storage potential in Norway

3.8.1 Status

Norway is committed to promoting and developing the CCS technology. CLIMIT is Norway's public programme aimed at accelerating commercialisation (R&D) of carbon capture and storage (CCS). The state enterprise Gassnova contributes to finding solutions to ensure that technology for capture and storage of CO_2 can be implemented (Demo) and become an effective climate measure.

The Norwegian Petroleum Directorate (NPD) has mapped areas suited for geological storage and are also assessing the use of CO_2 to enhance oil recovery. The NPD published in April 2014 a CO_2 Storage Atlas over all the Norwegian continental shelf that has been opened for production

(NPD, 2014). Data from this atlas will also be included in the forthcoming Nordic CO_2 storage atlas.

3.8.2 Capacity

Norway has over 40 years of experience of petroleum activity on the Norwegian continental shelf (Fig. 3-7) and the Norwegian Petroleum Directorate (NPD) has access to a huge amount of data collected by the petroleum industry. According the NPD Atlas there is a storage capacity of 85 GtCO2 in Norway of which 1.27 Gt can be regarded as practical capacity. The capacity in the North Sea is 72.1 Gt (1.1 Gt practical), 5.6 Gt in the Norwegian Sea (0.15 Gt practical) and 7.49 Gt in the Barents Sea (0.02 Gt practical). Of the total practical capacity in Norway 1 Gt is in the Miocene and Pliocene Utsira formation in the North Sea where CO2 injections have already been ongoing since 1996.

Figure 3-7. Area status on the Norwegian continental shelf. Areas open for production have been assessed for CO2 storage potential (NPD, 2014).

4 Summary

Finland is situated in the middle of the Precambrian Fennoscandian Shield where sedimentary rocks younger than the Precambrian are almost totally lacking. However, most of the surrounding countries to Finland have at least some theoretical potential for CO_2 storage (Table 4-1). A large portion of the theoretical potential is in deep saline aquifers, which normally are not so well studied. Consequently, practical capacities are quite low in all countries. Norway has both the highest theoretical and practical capacity, mainly in the North Sea.

For Denmark and Sweden, new information on storage potential and possible practical capacities will be published in 2015.

The distances from Finnish point sources to potential storage sites is quite long, but in comparison to the rest of Europe, the offshore storage potential is very large in some areas surrounding Finland.

Table 4-1. Current geological CO_2 storage capacity in the surrounding regions to Finland

Name	Theoretical capacity ($GtCO_2$)	Practical capacity ($GtCO_2$)	Reference
Baltic Sea	16	0	SLR, 2014
Baltics	11	0.037	Sliaupa et al. 2009
Russia	?	0	CCSP, D518
Poland	15	0.15	Wójcicki, A. 2011.
Germany	16	0	Knopf et al. 2010
Sweden	?	0	In prep. NORDICCS
Denmark	17	0	GeoCapacity
Norway	85	1.27	NPD, 2014

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