The potential for large-scale, subsurface geological CO_2 storage in Denmark

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Carbon capture and storage (CCS) is increasingly considered to be a tool that can significantly reduce the emission of CO_2. It is viewed as a technology that can contribute to a substantial, global reduction of emitted CO_2 within the timeframe that seems available for mitigating the effects of present and continued emission. In order to develop the CCS method the European Union (EU) has supported research programmes for more than a decade, which focus on capture techniques, transport and geological storage. The results of the numerous research projects on geological storage are summarised in a comprehensive best practice manual outlining guidelines for storage in saline aquifers (Chadwick *et al.* 2008). A detailed directive for geological storage is under implementation (European Commission 2009), and the EU has furthermore established a programme for supporting the development of more than ten large-scale demonstration plants throughout Europe. Geological investigations show that suitable storage sites are present in most European countries. In Denmark initial investigations conducted by the Geological Survey of Denmark and Greenland and private companies indicate that there is significant storage potential at several locations in the subsurface.

The Danish perspective in storage capacity

The ten largest point sources of CO_2 emission in Denmark account for 21 mega-tonnes per year (Mt/year). From preliminary investigations of the Danish subsurface the CO_2 storage capacity in selected subsurface structures is estimated to 2500 Mt (GeoCapacity 2009a). This corresponds to more than 100 years of storage from the ten largest emission point sources. The critical parameters of this analysis are the size of the structure, thickness, continuity and quality of the reservoir and the amount of formation water that may be displaced by the injected CO_2. The estimate is calculated assuming a surrounding aquifer volume displacement of formation water, which is limited to 50 times the trap volume (GeoCapacity 2009b).

These estimates of storage capacity are uncertain and have not yet been tested in real physical storage operation. Therefore it is difficult to evaluate to what degree the volume calculations are realistic. When a specific structure is selected for storage, a number of investigative steps are necessary, including acquisition and interpretation of new 2-D or 3-D seismic data, drilling of new wells, geological and reservoir modelling and flow simulation studies. For each step of incorporating new geological data, the site model of the reservoir is updated in the process of maturing the structure towards a storage site. This stepwise approach to site characterisation gradually leads to a research-based and relatively certain capacity estimate and an evaluation of the safety and behaviour of the site under simulated conditions, including the uncertainties of the estimates.

Assessment of geological and environmental risks can be carried out at various stages in the process. Similarly, establishment of baseline studies and monitoring strategies need to be considered along with the progress of the characterisa-

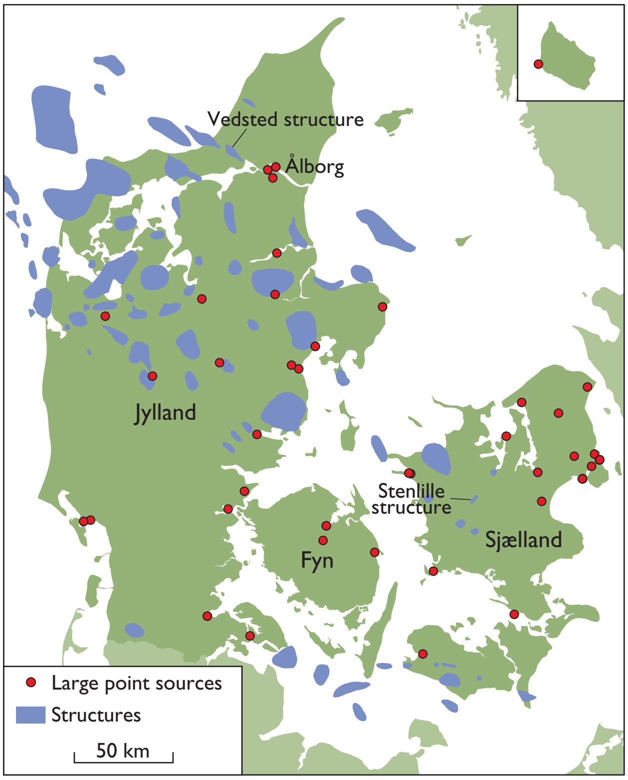

Fig. 1. Map of Denmark showing the most important point sources of CO_2 emission and prospective structures for geological storage of CO_2. The Stenlille structure is presently used for storage of natural gas; it serves to moderate seasonal fluctuations in consumption. The Vedsted structure is currently investigated for possible storage of CO_2.

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tion of the storage site in order to make sure that the necessary background information is obtained before storage is initiated. In order to be reliable and operational, the baseline studies should preferably focus on measurement of conditions and properties that are stable and only show limited seasonal variations. Such studies may include groundwater-flow models and groundwater chemistry, pore water and pore gas analyses from deep wells, surface topography and natural seismicity.

A site study

Site investigations have recently been initiated of the Vedsted structure by Vattenfall A/S, with the intention of using the structure for storage of CO_2 from a nearby coal-fired power plant in Ålborg (Fig. 1; Sørensen *et al.* 2009). Existing data from oil exploration activities in the 1950s include one well in the centre of the structure and sparse 2-D seismic line data. The main target layer is the Triassic–Jurassic Gassum Formation at around 1800 m depth. The formation is widely distributed in the Danish Basin and has good reservoir properties (Fig. 2). It is currently used for storage of natural gas in the Stenlille structure on Sjælland and for geothermal energy in the Thisted area in northern Jylland.

Detailed sedimentological and sequence stratigraphic interpretations and correlations of the well logs and cores have established a robust stratigraphic framework for the Upper Triassic – Jurassic succession (Nielsen 2003). This framework forms the basis for the interpretation of the Vedsted-1 well section as well as predictions regarding the lithology of the potential reservoirs and seals in the Vedsted area (Fig. 3). The process has also underlined the necessity of acquisition of new data and more detailed modelling at several different scales.

At site scale, the optimal positioning of injection wells, as well as injectivity and capacity can be modelled and analysed, and the coupling between the operation of the power plant and the capture facility can be studied. The specific geological properties of the storage reservoir layers have consequences for the propagation and distribution of the injected CO_2 and for the storage mechanisms in the specific reservoir. Most reservoirs show both vertical and horizontal heterogeneities that will influence the distribution of the CO_2.

The preliminary reservoir model for the Vedsted structure has been investigated by simulating an injection well on its south-eastern flank and using injection rates realistic for power-plant supply rates (Frykman *et al.* 2009). After ten years of constant injection, the CO_2 distribution is as seen in Fig. 4, which clearly shows the subdivision of the migrating front into several sub-layers due to intraformational sealing layers with low permeability that also have high capillary entry pressures. The layering in the model has maximum lateral continuity, which probably overestimates the segregation to be found in real cases, but any intra-reservoir sealing layers will have such an effect on the distribution. Since this filling pattern influences the capacity, it is necessary to analyse further the properties and the continuity of the intraformational sealing layers.

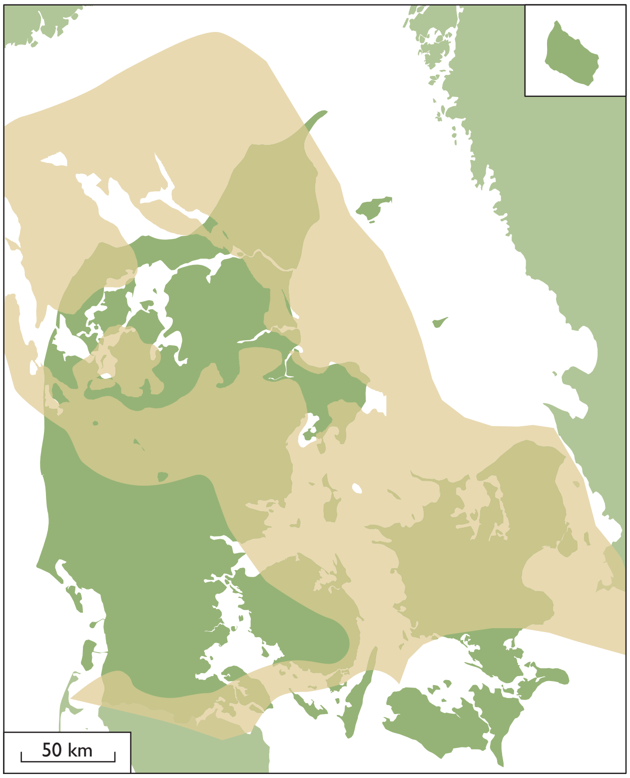

Fig. 2. Distribution of the Triassic–Jurassic Gassum Formation in the subsurface at depths between 800 m and 2400 m (yellow), the depth interval in which CO_2 exists as a supercritical phase and where burial diagenesis has not yet provoked significantly lowered porosity. At the supercritical phase the volume of CO_2 is much less than that of the CO_2 gas at the surface.

CO_2 can be trapped by several mechanisms, including structural trapping under an overlying sealing formation, dissolution of CO_2 in formation water, capillary trapping in the pore network and mineral trapping by reactions between CO_2 and mineral phases in the reservoir rock. These trapping mechanisms work on different scales both in space and time and need to be studied by designing appropriate models and experiments.

For large-scale injection of CO_2 displacing saline porewater, the propagation of the pressure field during injection outside the immediate site area is of interest. Modelling of this pressure distribution will serve to predict the amount of overpressure building up locally within the storage site, and can be used to suggest possible means of management.

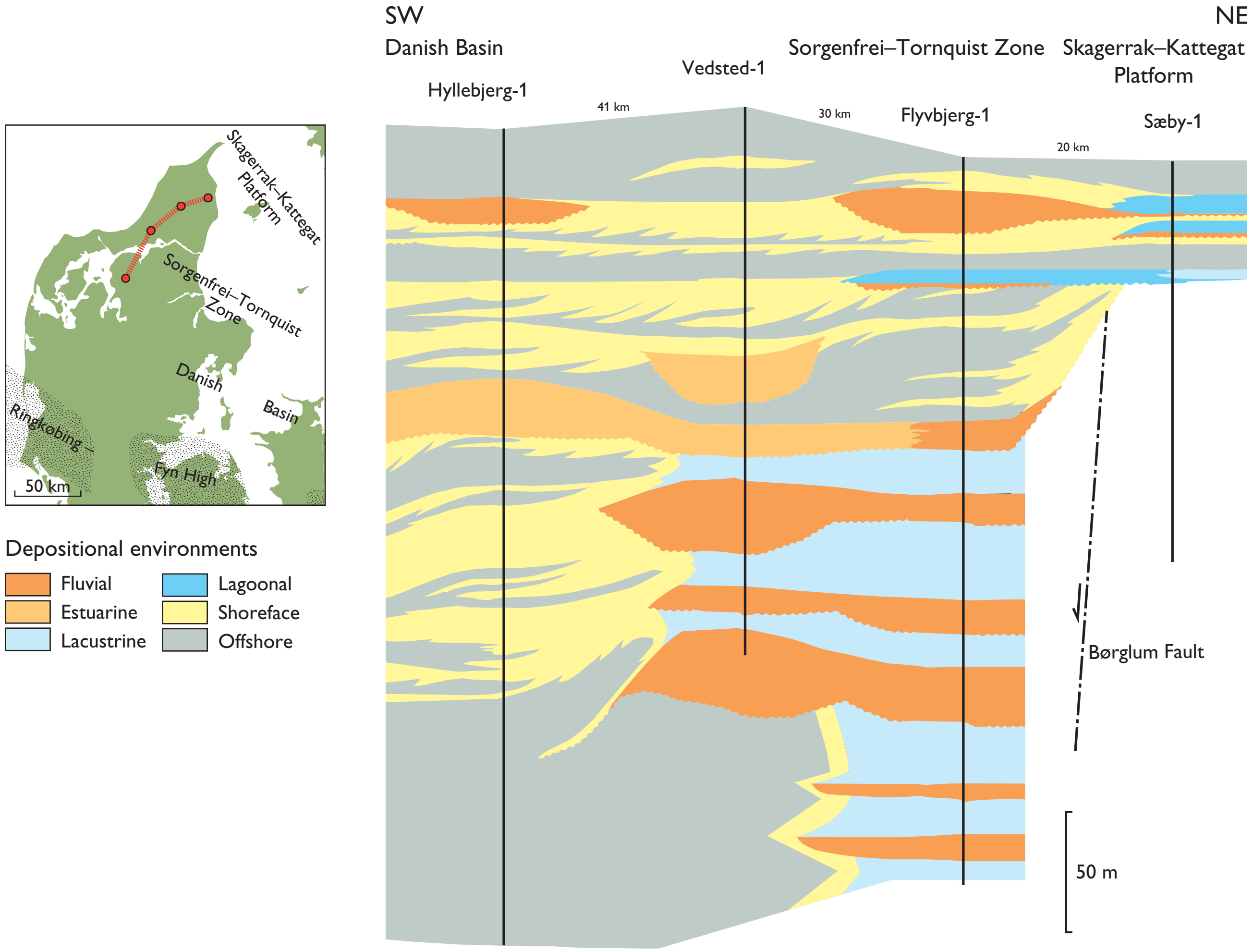

Fig. 3. SW–NE-oriented cross-section across the Danish Basin, the Sorgenfrei–Tornquist Zone and the Skagerrak–Kattegat Platform (red line on the index map). The panel shows the lower part of the Gassum reservoir which comprises fluvial, estuarine and shallow-marine deposits interbedded with offshore mudstones and some lacustrine mudstones. Shoreline fluctuations have caused interfingering of these different facies types and given rise to pronounced vertical variability. Informations from the four wells in the section about sedimentary facies have been interpreted and correlated into a sequence-stratigraphic framework. At a local site, this framework must be confirmed from detailed investigations of material from new wells drilled, and supplemented with new seismic data. Modified from Nielsen (2003).

The scale of the challenge and future perspective

The first detailed pan-European assessment of CO_2 storage capacity in the framework of the EU research project GeoCapacity has resulted in a geographic information system (GIS) database of CO_2 emissions, storage capacity estimates and geological information. The database includes information on reservoirs with a total storage capacity of 360 000 Mt CO_2, with 326 000 Mt in deep saline aquifers, 32 000 Mt in depleted hydrocarbon fields and 2000 Mt in unmineable coal beds: 116 000 Mt are onshore, and 244 000 Mt offshore (GeoCapacity 2009a). Some of the estimated storage capacity is associated with structural traps, but a very large part is in regional deep saline aquifers without identified specific traps. Almost 200 000 Mt of the total storage capacity in the database are located offshore Norway. These estimates date back to 2003 and have not been updated within the GeoCapacity project. An attempt to provide a more cautious and conservative European estimate has yielded a storage capacity of 117 000 Mt with 96 000 Mt in deep saline aquifers, 20 000 Mt in depleted hydrocarbon fields and 1000 Mt in coal beds, and with approximately 25% located offshore Norway. This must be compared to a total of 2000 Mt of CO_2 emission from large point sources, i.e. point sources emitting more than 0.1 Mt/year within Europe.

In order to illustrate the scale of the technology and infrastructure that has to be established if CCS is to become an active industry, we can look at the amount of CO_2 produced by the ten largest point sources in Denmark. There are 43 large point sources emitting 28 Mt CO_2/year, the ten largest of which are responsible for 21 Mt/year. At surface condi-

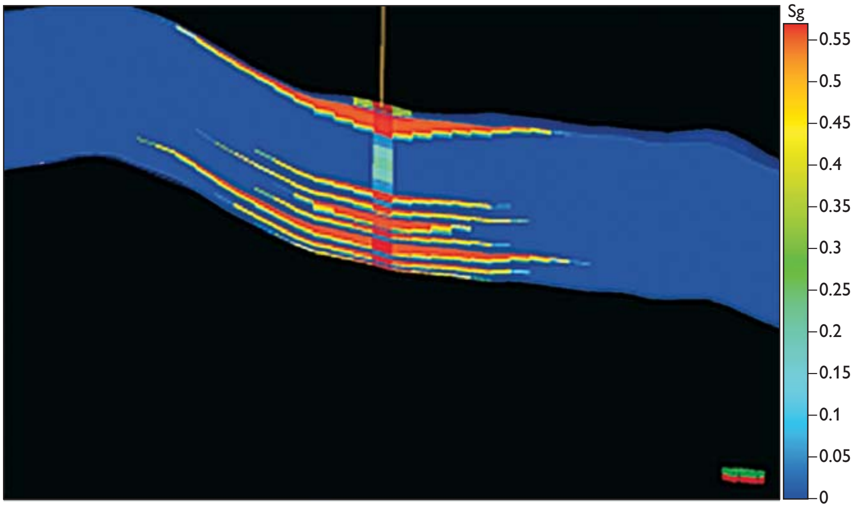

Fig. 4. Vertical NW–SE section in the Gassum reservoir model through the injection well, showing CO_2 saturation Sg (free gas-phase supercritical CO_2) after 10 years of injection. Although the model is constructed in a fairly coarse grid, the intra-reservoir sealing layers are clearly reflected and influence the spatial distribution of the injected CO_2. The sedimentary layering causes filling of the individual layers of porous sand with the injected CO_2, whereas the interbedded mudstone layers with much lower reservoir quality are not filled and also limit the vertical movement of CO_2. Model thickness 300 m, length 4800 m, vertical exaggeration 5 times. (Modified from Frykman *et al.* 2008).

tions this corresponds to 11 billion (11×10^9) m^3 CO_2 gas. The annual production of natural gas from the Danish part of the North Sea amounts to 10 billion (10×10^9) m^3 (Danish Energy Agency 2008), which is transported in pipelines and tankers and processed at plants and refineries. The comparable size of the potential volume of CO_2, to be moved around at surface and injected into the subsurface (although compressed to smaller volumes at depth), points to the large scale at which a CCS-related processing and transporting industry has to be established.

Concluding remarks

The CCS activities described here related to large-scale storage operations will involve significant physical resources and manpower. Fortunately, the work with storage-related items does not have to begin from first principles, because much of the experience already exists in the oil and gas industry, which can provide methods and tools for immediate use. The skills of geoscientists and engineers are needed in the investigation and characterisation of the sites and the subsurface conditions for storage of CO_2, and a whole new infrastructure and industry may be established. Geoscience and geo-engineering will play a major role in the analysis of the geological foundation, the assessment of site performance, and will be critical in securing the safety of the operations.

Initial investigations of the Danish subsurface indicate that suitable structural traps with a significant storage potential are present at several locations, and that the structures can accommodate the CO_2 produced from several or most of the large Danish point sources. Thus, geological storage of CO_2 may contribute considerably to the reduction of the Danish CO_2 emission, if we can be assured about safety issues, and if political and public acceptance can be obtained.

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