



# Final report on prospective sites for the geological storage of CO<sub>2</sub> in the southern Baltic Sea

Elforsk report 14:53



SLR Consulting & Uppsala University

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**ELFORSK**



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## 1.0 EXECUTIVE SUMMARY

SLR was commissioned by Elforsk to identify and characterise the potential CO<sub>2</sub> storage sites in the southern Baltic Sea, in a project sponsored by the Swedish Energy Agency, the Global Carbon Capture and Storage Institute and Swedish industrial partners.<sup>1</sup> The project cooperates with the Finnish program CCSP under the management of the VTT Technical Research Centre

The study determined that there is a theoretical regional capacity to store some 16Gt of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>.

The southern Swedish sector, where dynamic modelling was undertaken by Uppsala University, has relatively poor permeability and porosity characteristics. Maintaining the reservoir pressure at 50% above the hydrostatic pressure, limits the injection rate to 0.5Mt per well per annum over a 50 year period if five wells were to be used. The preliminary and indicative dynamic modelling for this area suggests that with 5 injection wells, a total injection capacity of 2.5 Mt per annum could be achieved. Reducing the injection period to say 25 years and increasing the number of wells could increase the total injection rate somewhat above this level. There may also be reservoir intervals with higher porosity and permeability where higher injection rates could be safely achieved. Thus it is possible that this area, including the Dalders structure, could be suitable as a storage site for CO<sub>2</sub> captured from a limited number of industrial facilities.

Other areas to the north east of the Monocline, such as the eastern Swedish sector and offshore Latvia where limited data is available, may have better reservoir qualities and where a higher rate of injection could be achieved, and thus be more suitable for regional industrial CO<sub>2</sub> storage. Furthermore, the regional storage capacity assessment demonstrated that there are sweet spots in the Cambrian reservoir such as onshore Latvia, where there is commercial gas storage, and both onshore and offshore Kaliningrad, where there is ongoing hydrocarbon production.

Three possible modes of seal failure have been identified. These include top seal failure, migration up the bounding fault planes and leakage across fault planes. All three possible modes of potential failure were investigated. The risk associated with all of these is considered low, based on currently available data. However the sealing integrity will require further investigation once new data becomes available and an injection site is selected. This will characterise small, site specific fault structures.

A test injection methodology has been designed with the objective of assessing the viability of CO<sub>2</sub> injection in the Baltic Sea region. This includes the characterisation of reservoir, caprock and hydraulic properties, pump testing as well as CO<sub>2</sub> migration and trapping using a phased approach methodology.

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<sup>1</sup> SSAB, Jernkontoret, Svenska Petroleum Exploration, Cementsa, Nordkalk, SMA Mineral, Minfo, Vattenfall, Fortum and Preem

An outline MMV programme has been developed based on the results of the dynamic modelling and the development phases of a CO<sub>2</sub> injection site. However, the details of this will be subject to site specific conditions and will need to be updated once new data is available.

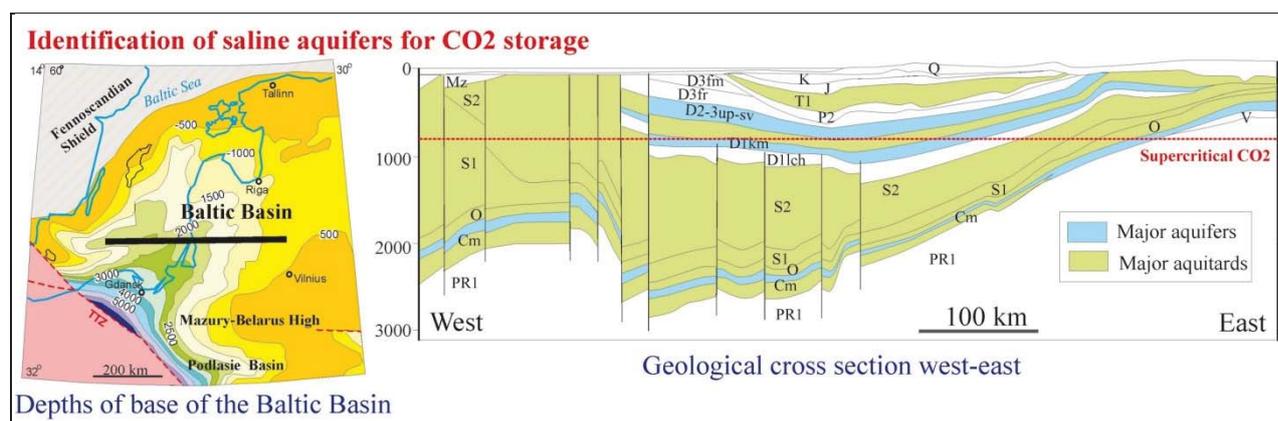
Since the potential of the Swedish part of the Dalders Monocline to act as a regional storage site for significant quantities of CO<sub>2</sub> appears to be limited based on the present information, exploration efforts should be focused on areas where the best reservoir quality and regional storage potential are likely to be found. As offshore and onshore well data indicate that the north eastern portion of the Dalders Monocline appears to have better reservoir qualities than the current study area, new well data covering this area, in particular offshore Latvia would help to identify more suitable sites for CO<sub>2</sub> storage. Regional reservoir quality maps based on the limited data available indicate that onshore and offshore Kaliningrad would also appear to have better reservoir qualities.

Recommendations for further work include a study of the Cambrian sandstone interval to better understand the heterogeneity and distribution of good quality reservoir; a seismic attribute study to investigate the porosity trends in the Cambrian reservoir; a structural geology study to understand the influence of faulting on diagenesis and fracture porosity within the Cambrian; and a fracture gradient study of the Cambrian interval.

## 2.0 DEFINITION OF THE STUDY AREA

The study area is defined as previously mapped Palaeozoic sedimentary basins in the Baltic Sea Area, as described in the document *Geology and hydrocarbon prospects of the Paleozoic in the Baltic region*, 1993 by Brangulis, Kanev, Margulis and Pomerantseva. This assessment by SLR is searching for a geological formation that is ultimately capable of storing 50 million tonnes of dense phase CO<sub>2</sub> per year for a minimum of 25 years. This is based on calculations that show carbon dioxide emissions from stationary sources of up to a gross volume of some 100 million tonnes per year in the Baltic Sea region (Nilsson, 2011).

The report assesses the potential for geological storage of carbon dioxide (CO<sub>2</sub>) in sedimentary basins in the Baltic Sea area. Storage potential may exist in depleted oil and gas fields or saline aquifer formations at depths greater than 800m, the minimum depth for CO<sub>2</sub> stability. The Precambrian crystalline basement of the Baltic Sea Basin lacks porosity and permeability for CO<sub>2</sub> storage. The principal stage of basin development was during deposition of a thick Middle Cambrian-Lower Devonian (Caledonian) sequence. This sequence contains sandstone and limestone aquifers that could store CO<sub>2</sub> that are sealed by shale and claystone aquifers (see Figure 1 below). Mesozoic rocks that unconformably overlie the Paleozoic are not deeply buried enough for CO<sub>2</sub> storage and are confined to the south and southwest of the Baltic Sea area.



**Figure 1 Map showing depth in metres of the Caledonian Baltic Sea Basin with a geological cross section indicating the aquifers that could store CO<sub>2</sub> in supercritical state below 800m<sup>2</sup>**

The Baltic Sea Basin is a marginal platform depression, deepening from 1 km in the northwest to more than 4km in the southwest, containing un-deformed Palaeozoic rocks underlain by Proterozoic crystalline basement (Figure 1). The area of the basin is about 200,000km<sup>2</sup> with the long axis being approximately 700 km and the maximum width in the southwest being 400-500 km (A.P. Brangulis, 1993). The structural elements with Caledonian sedimentary deposits are the Slupsk-Latvian-Estonian Border Zone (or Gotland Monocline), the Lithuanian Border Zone, the Liepaja Depression, and the Gdansk-Kura Depression (Plate 1). The sub-basins are separated by the Leba High and Liepaya-Saldus Ridge where structural traps are abundant. Palaeozoic terrigenous and volcanic rocks overlie the crystalline basement. There is a 100-150m thick Lower to Middle Cambrian sandstone that is the main hydrocarbon bearing reservoir of the Baltic region (Figure 3). The overlying Ordovician rocks comprise interbedded sand and shale members including the

<sup>2</sup> Cm, 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 (after Sliupa S., 2009).

Alum Shale. This is followed by interbedded shale and limestone including shallow shelf carbonate rocks. Further limestone and shale was deposited in the Silurian. In the south west graptolitic shales are found. The shales grade to the northeast into marls, limestone, clays and shoal carbonates facies with barrier reefs. The upper part of the Caledonian sedimentary sequence is composed of lagoonal, continental deposits. Within this sequence the Cambrian and Devonian sandstones and the Ordovician and Silurian carbonates have the reservoir potential to store CO<sub>2</sub>.

The main targets for CO<sub>2</sub> storage sites are faulted anticlines, step and nose features associated with the monoclines that occur on the northwest margin of the Baltic Basin. These structures contain the Lower to Middle Cambrian sandstone (Deimena Formation in Latvia, Faludden Sandstone in Sweden) that is the main hydrocarbon bearing reservoir of the Baltic region. There is also the possibility of stratigraphic traps, particularly in the Ordovician shelf carbonate rocks that are porous but not very permeable. There are indications on seismic sections offshore Latvia (A.P. Brangulis, 1993) of possible Ordovician shelf carbonates offshore (see L&OG Report) but poor reservoir quality and small size makes them inappropriate for CO<sub>2</sub> storage (Sweden Baltic Sea OPAB Farmout Prospectivity Appraisal, 1990).

The offshore Dalders Prospect Structure (Figure 2), which straddles Swedish, Lithuanian and Latvian territory, has been identified as a potential site for storage (Svenska Petroleum Exploration OPAB, 2010). Associated with the Dalders structure is the Dalders Monocline that extends NW to Gotland in Sweden. While storage in confined aquifers and closed structures is the preferred CO<sub>2</sub> sequestration mechanism ( e.g. in the CCS-directive from the EC), it would significantly increase the potential of aquifers offshore Sweden if it can be shown theoretically and by demonstration and monitoring projects that CO<sub>2</sub> can be trapped in monoclinal structures (Erlstrom, 2008).

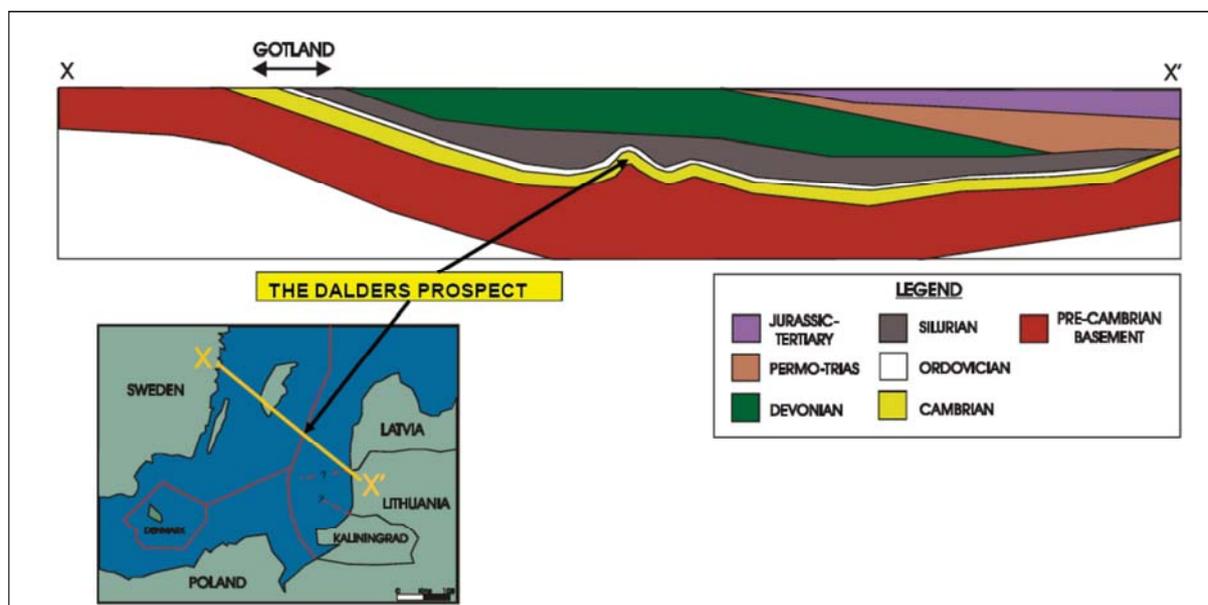


Figure 2 Location of the Dalders Prospect and the Dalders Monocline (from OPAB)

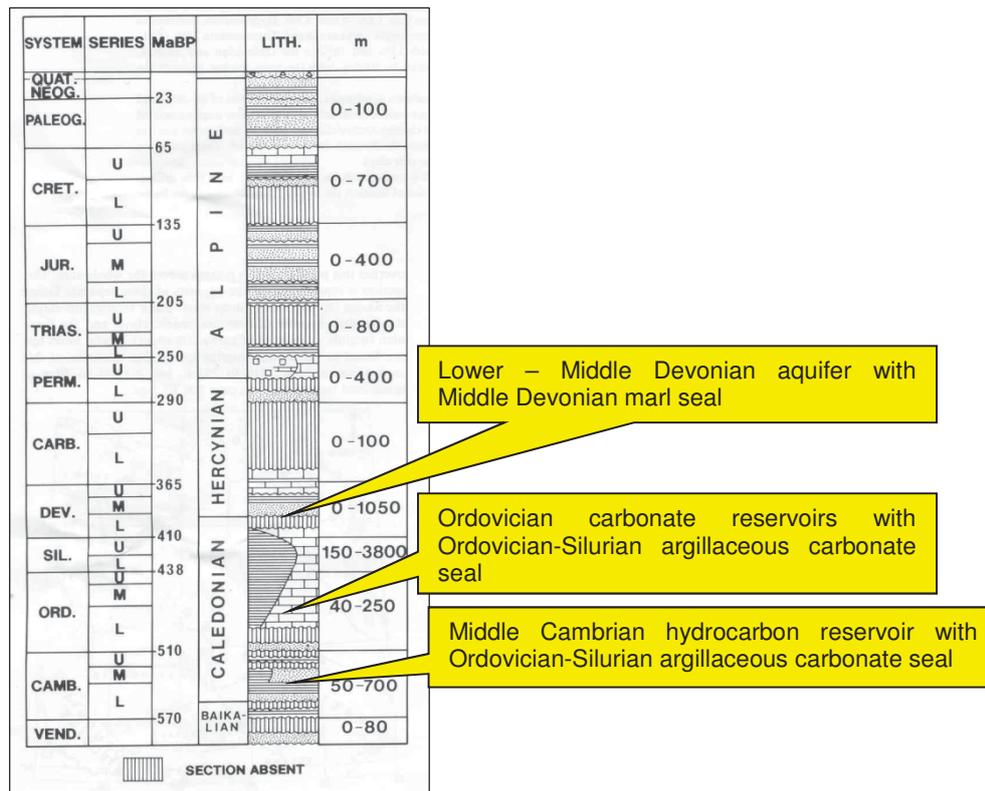


Figure 3 Geological section of the sedimentary basins in the Baltic Sea area<sup>3</sup>

<sup>3</sup> From Brangulis, A.P., Kanev, L.S., Margulis, L.S. and Pomerantseva, R. A., 1993 *Geology and hydrocarbon prospects of the Paleozoic in the Baltic region*. Geology of Northwest Europe: Proceedings of the 4<sup>th</sup> Conference edited by J.R. Parker, Geol. Soc. Lon.

## 3.0 GEOLOGICAL OVERVIEW

### 3.1 Introduction

Within the East Baltic region the main area for hydrocarbon exploration is the Baltic Depression. The Baltic Basin has an approximate latitude of 56° 30' N and longitude of 19° 00' E. The Baltic Basin is a large synclinal structure located in the south-western part of the East European Craton (EEC). The area of the basin is about 200,000km<sup>2</sup>. The synclinal structure is approximately 700km long and 500km wide. The axis of the syncline plunges to the southwest. Towards the north, east and southeast the syncline is bounded by the Baltic Shield, the Latvian Saddle and Byelorussian Anticline, respectively, (Brangulis, A.P. et al 1993). The basin is bounded to the south west by the Trans-European Suture Zone that strikes north-west to south-south-east. The area of interest covers parts of onshore Latvia, Lithuania, Kaliningrad and northern Poland, as well as the Baltic Sea. The central Baltic Sea is located in a transitional zone between an area of present day uplift to the north and an area of slight subsidence to the south. Four principal sub-basins (Plate ) are considered as part of this study:

- **Slupsk Border Zone (SBZ)** located in the South-western Baltic Sea between Poland and Sweden, has an approximate surface area 2500km<sup>2</sup>.
- **Gdansk-Kura Depression (GKD)** located in the south-eastern Baltic Sea, covers parts of Poland Russian and Lithuania and has an approximate surface area of 8000km<sup>2</sup>.
- **Liepaja Saldus Ridge (LSR)** located in the southern part of the Baltic Sea and extends southwest to northeast across the Baltic Sea into Latvia. The Liepaja Saldus Ridge has a surface area of 2500 km<sup>2</sup>.
- **Latvian, Estonian, Lithuanian Border Zone (LEL)** is located in the mid Baltic Sea and extends southeast to northwest covering parts of Estonia, Latvia and Gotland Island. The border zone has an approximate surface area of 2500 km<sup>2</sup>.

### 3.2 General Geology

The Baltic Sea Basin contains a full sedimentary sequence from the Archean to the Cenozoic. The general geology of the Baltic Sea Area can be broken down into four major complexes (Brangulis et al, 1993):

- The Baikalian Complex
- The Caledonian Complex
- The Variscan Complex
- The Alpine Complex

#### 3.2.1 The Baikalian Complex

The Baikalian Complex made up of a sequence of sandstones, siltstones and claystones up to 200m in thickness and includes up to 120m of early Cambrian claystones. This complex varies across the Basin and fills two northeast trending depressions.

#### 3.2.2 The Caledonian Complex

The Caledonian Complex covers the four main sub-basins that contain the identified CO<sub>2</sub> storage targets. It is made up of the Middle and Upper Cambrian succession of up to 170m of sandstone, siltstone and shale. The upper part of the complex is characterised by between 40m and 250m of Ordovician shaly carbonates, approximately 1,000m Silurian shales, as well as lower Devonian claystone, sandstone and marlstone.

### 3.2.3 The Variscan Complex

The Variscan Complex contains the rest of the Devonian sequence of about 1100m of interbedded marly-carbonates and sandstones. The upper part of the complex is characterised by Lower Carboniferous siliciclastic carbonates. There were no CO<sub>2</sub> storage sites identified in the Variscan Complex.

### 3.2.4 The Alpine Complex

The Alpine Complex contains rocks in age from the Middle to Upper Carboniferous up to the Quaternary. The Permo-Triassic part of the complex includes 100m of Upper Permian carbonates and evaporates and approximately 250m of Lower Triassic mudstones, 120m of Jurassic sandstones, claystones and limestones as well as 140m Cretaceous glauconitic sand and chalky marl. The Cenozoic sequence is characterised by 80m of siliciclastic lithologies and confined to the south western part of Lithuania. There were no CO<sub>2</sub> storage targets identified in the Alpine Complex.

## 3.3 Structural History

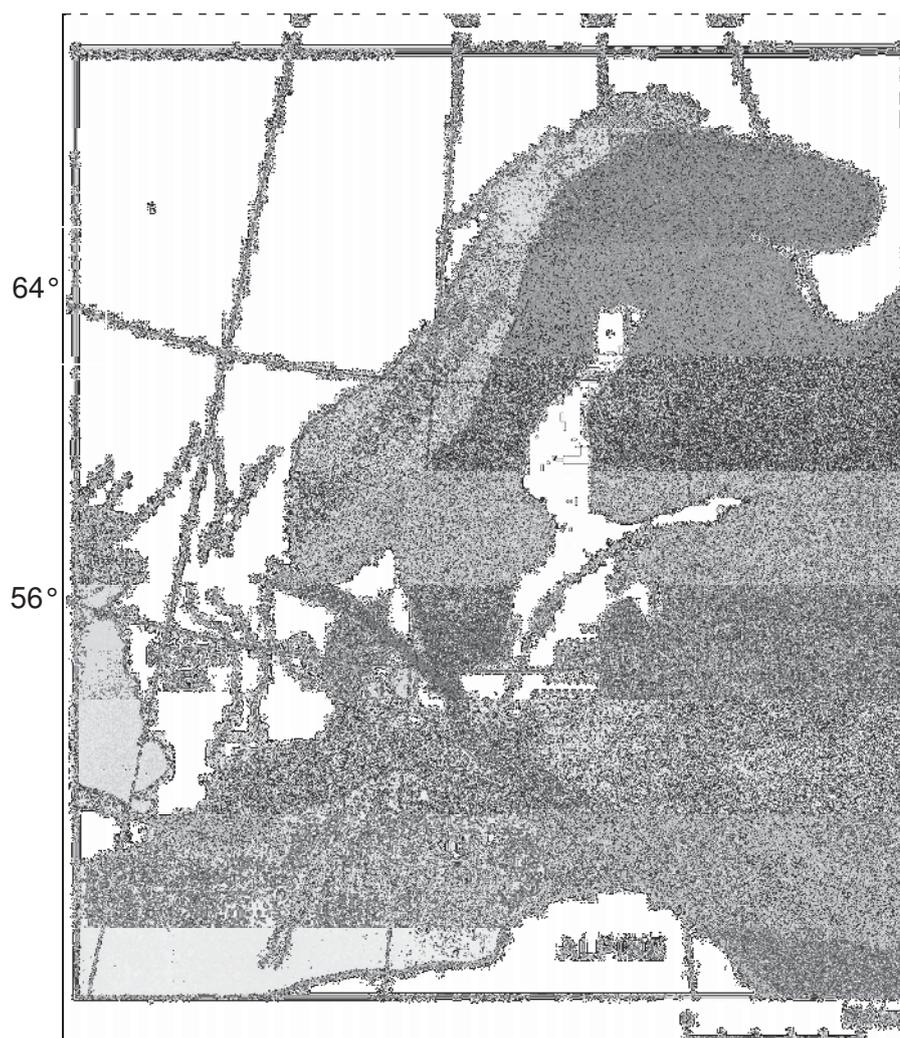
The Baltic Sea Basin has a long and complex structural history. The Precambrian East European Continent (EEC) comprises several continental and arc-related terranes developed during a sequence of orogenic cycles spanning Archean, Early Proterozoic and Riphean times. The Baltica terrane forms the core of the EEC. During the Late Riphean and Vendian, Baltica formed part of a supercontinent from which it was separated at the end of the Vendian. During Cambrian to Late Silurian times, Baltica was an independent plate. During the Caledonian orogeny, it formed part of the Laurussian plate which was integrated into Permo-Triassic Pangea during the Variscan-Appalachian orogenic cycles. The EEC has remained geologically stable since late pre-Cambrian times.

**Table 1 List of events which directly affected Baltica (Cocks et al 2005)**

<b>Events on Baltica</b>	<b>Millions of Years Ago (Ma)</b>
Start of Rodinia break-up	<b>c. 800</b>
Timanian Orogeny end	<b>c. 555</b>
Completion of Iapetus Ocean opening	<b>c. 560</b>
Tornquist Ocean closure	<b>c. 445</b>
Iapetus Ocean closure	<b>c. 420</b>
Pangea assembly	<b>om 330</b>

The Baltic Depression is a large marginal synclinal structure in the south-western part of the EEC and formed during a period of extensions associated with the breakup of the Rodinia supercontinent (Poprawa et al, 1999). The basin developed as a flexural foreland basin during the Silurian collision of Baltica and Eastern Avalonia.

The structural elements of the Baltic Depression are mainly associated with the movements of the basement blocks. The throws of the largest faults reach 200-500m and the lengths of the fault zones can be up to a few hundred kilometres. The majority of faults have accompanying fold structures; most of these interestingly do not cut the Variscan and Alpine complexes.



**Figure 4: Major Tectonic structures and orogenic belts surrounding the Baltic Basin<sup>4</sup>**

The main stage in the evolution of the Baltic Sea Basin was the Caledonian period. Rapid subsidence in the Silurian followed by deformation in the early Devonian produced the major structural features of the basin. The Hercynian and Alpine tectonic cycles modified the regional basin geometry only slightly.

### **3.4 Sub-Basin Structure**

#### **3.4.1 Slupsk Border Zone (SBZ)**

The Slupsk Border Zone is a gently sloping monocline at the West northwest margin of the Baltic Basin.

#### **3.4.2 Gdansk – Kura Depression (GKD)**

The Gdansk-Kura Depression is affected by Caledonian minor faulting and folding that creates the best structural closures for hydrocarbon and CO<sub>2</sub> storage.

#### **3.4.3 Liepaja Saldus Ridge (LSR)**

The Liepaja-Saldus Ridge is a complex zone of faulted highs striking West-southwest/East-northeast. It traverses from the central part of the Baltic Sea onshore to central Latvia over a

<sup>4</sup>Poprawa et al, 1999

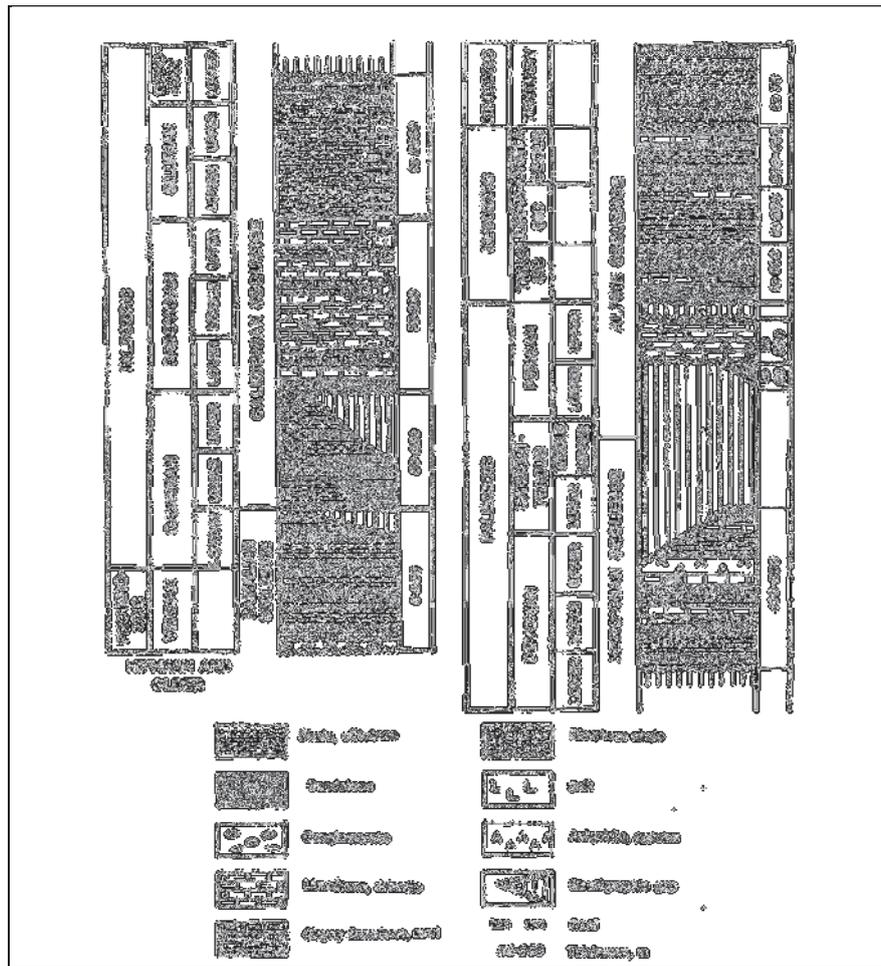
distance of more than 300 km. The Liepaja-Saldus Ridge is bounded by major faults, with a displacement of Caledonian sediments up to 600 m. The southern border of the ridge is particularly distinct. The ridge contains several untested potential CO<sub>2</sub> storage structures offshore Sweden and Latvian including the Dalders structure.

#### **3.4.4 *Latvian, Estonian, Lithuanian Border Zone (LEL)***

The Latvian-Estonian and the Lithuanian Border Zones are stable areas of gently dipping crystalline basement overlain by a thin sedimentary succession. The surface of the basement rocks is buried to depths ranging from 500 to 1200-1400 m, and the monoclines have small anticlinal structures. An example is the significant structure that contains the Inčukalns underground gas storage facility.

### **3.5 Depositional Setting and Stratigraphy**

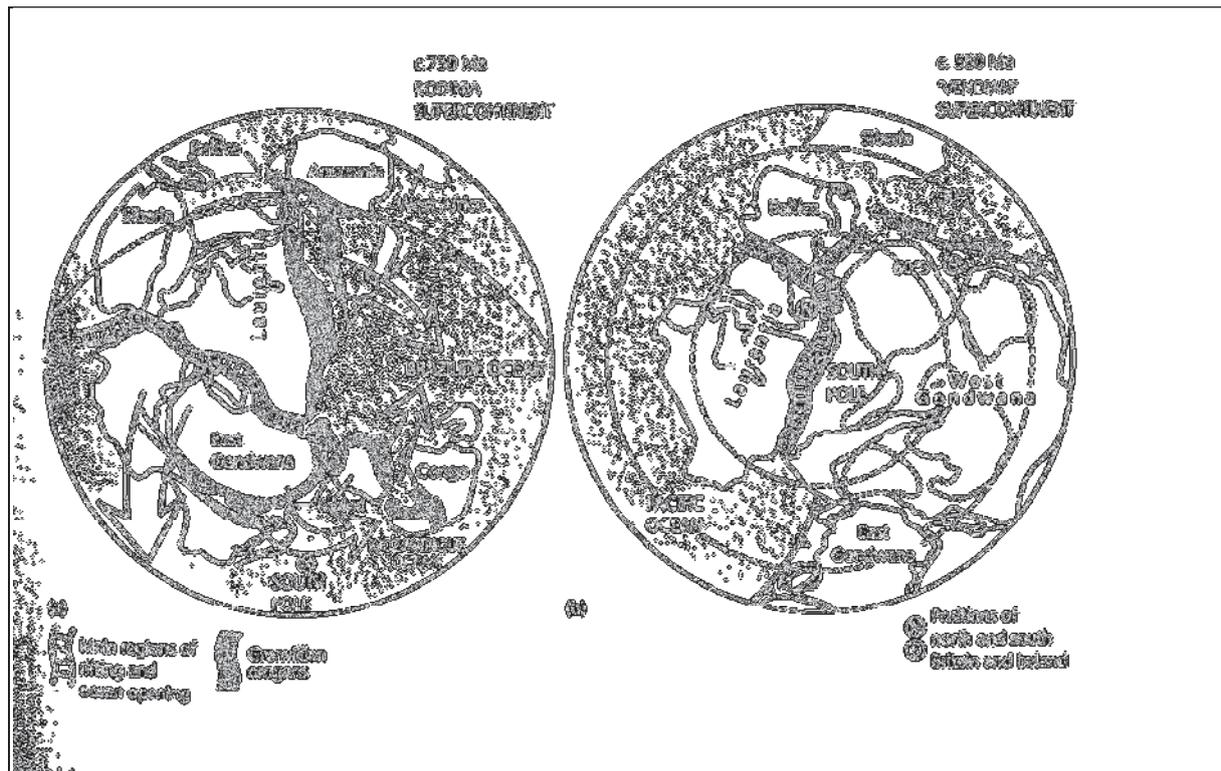
The continental crust of the Baltic region was formed between 3.5 and 1.5 Ga. during four periods of orogenic activity. After its formation the crust underwent major reworking during the Sveconorwegian – Grenvillian and Caledonian orogenies (1.2 - 0.9 Ga). The Variscan and Alpine orogenies (about 300 and 100Ma respectively) influenced the south-western parts of the EEC. The anorogenic periods succeeding the orogenies saw erosion, sedimentation and a moderate amount of igneous activity. The Baltic Basin includes the Vendian at the base and most Phanerozoic systems. Four separate successions, the Baikalian, Caledonian, Hercynian and Alpine, can be distinguished and are separated by angular unconformities.



**Figure 5 Stratigraphic Column of the Baltic Sea Basin showing the main depositional sequences<sup>5</sup>.**

The basement structures of the Baltic basin formed part of Baltica. Baltica consisted of three terranes, Fennoscandia, Sarmatia and Volgo-Uralia. They consolidated to form the supercontinent of Rodinia (c1300-1000Ma) during the Sveconorwegian Orogeny. At about 770-750 Ma, Rodinia broke up with the opening of the proto-Pacific, separating East Gondwana from the western margin of Laurentia. Subduction of the Mozambique and Brazilide oceans led to the collision of East Gondwana, and several continental blocks forming West Gondwana and produced the Pan African-Baikalian-Brasiliano orogens about 620Ma. This orogen formed a second, Late Proterozoic 'Vendian' supercontinent comprising Gondwana, Laurentia and Baltica (Woodcock and Stracken, 2000).

<sup>5</sup> Ulmishek G, 1990



**Figure 6 Global Palecontinent reconstruction from the Neoproterozoic.**

### **3.5.1 Proterozoic**

The Proterozoic resulted in the deposition of a considerable thickness of the Jotnian red quartzites, aleurolites and conglomerates that make up the oldest non-metamorphosed cover of the Baltic Shield. Mid Riphean sandstones (c.1.3Ga), were uniformly deposited but can only be observed in a few tectonic depressions as a result of post depositional erosion forming the sub-Cambrian peneplain. This erosion continued into the Late Vendian as the Baltic Region remained uplifted. Late Vendian arkose sedimentation occurred in the narrow basins located along the future Baltica continental margin.

### **3.5.2 Cambrian**

The Cambrian contains the best candidate reservoirs for CO<sub>2</sub> storage. The transgressive Cambrian sea created an embayment in the Baltic region and resulted in both near shore and open marine depositional sequences. Open marine conditions prevailed in the western and offshore area during the Early Cambrian whilst shallow marine conditions prevailed to the east. The oldest rocks in the Baltic Basin are found in Estonia. They are represented by the Rovno and Lontova regional stage (the Baltoji group) of the Manykayan stage. (Usaityte,D, 2000.) The Rovono stage comprises of greenish grey clays with interbedded silt and sand with glauconite grains.

The Lontova regional stage in the NW of the Baltic Basin is approximately 90m thick. The sequence is comprised of greenish, grey, violet, brown fine-laminated clay with beds of glauconitic sandstone and silt. Clay occurs in the lower parts of the upper units to the east whilst silt and sandstone replace the clay in the western regions.

Regional stages can be distinguished in the Lower, Middle and Upper Cambrian.

### 3.5.3 Lower Cambrian

The Lower Cambrian is characterised by mainly deep marine sequences with sediment sourced from land to the northwest and southeast of the Baltic Basin. Most of Latvia and Lithuania were covered in a shallow sea environment at this time.

The lower unit is the Talsi Formation, consisting of mainly sandstone with some pyroclastic rocks towards the northwest of the basin. This indicates a marine environment to the south, with some volcanic activity on the north western border of Baltica, possibly on the Baltic Continent, (Figure 7). The volcanism is consistent with rifting that was taking place during the Cambrian period. The thickest sandstones in the Cambrian are in this lower unit with a thickness of approximately 157m (Grigelis, 2011).

The middle unit is the Vergale Formation characterised by mainly sandstone in the south and interbedded sandstone, limestone, siltstone and argillite in the northwest. This is still a marine sequence with some quiet water conditions, as well as reef build up.

The upper formation is the Raus Formation. This sequence is fairly compact and consists of interbedded sandstone siltstone, argillite and limestone across the Baltic Basin. This indicates the continuing marine paleoenvironment during the Cambrian. There was a reduction in the sedimentation at this time.

The end of the Lower Cambrian is represented by a widespread unconformity.

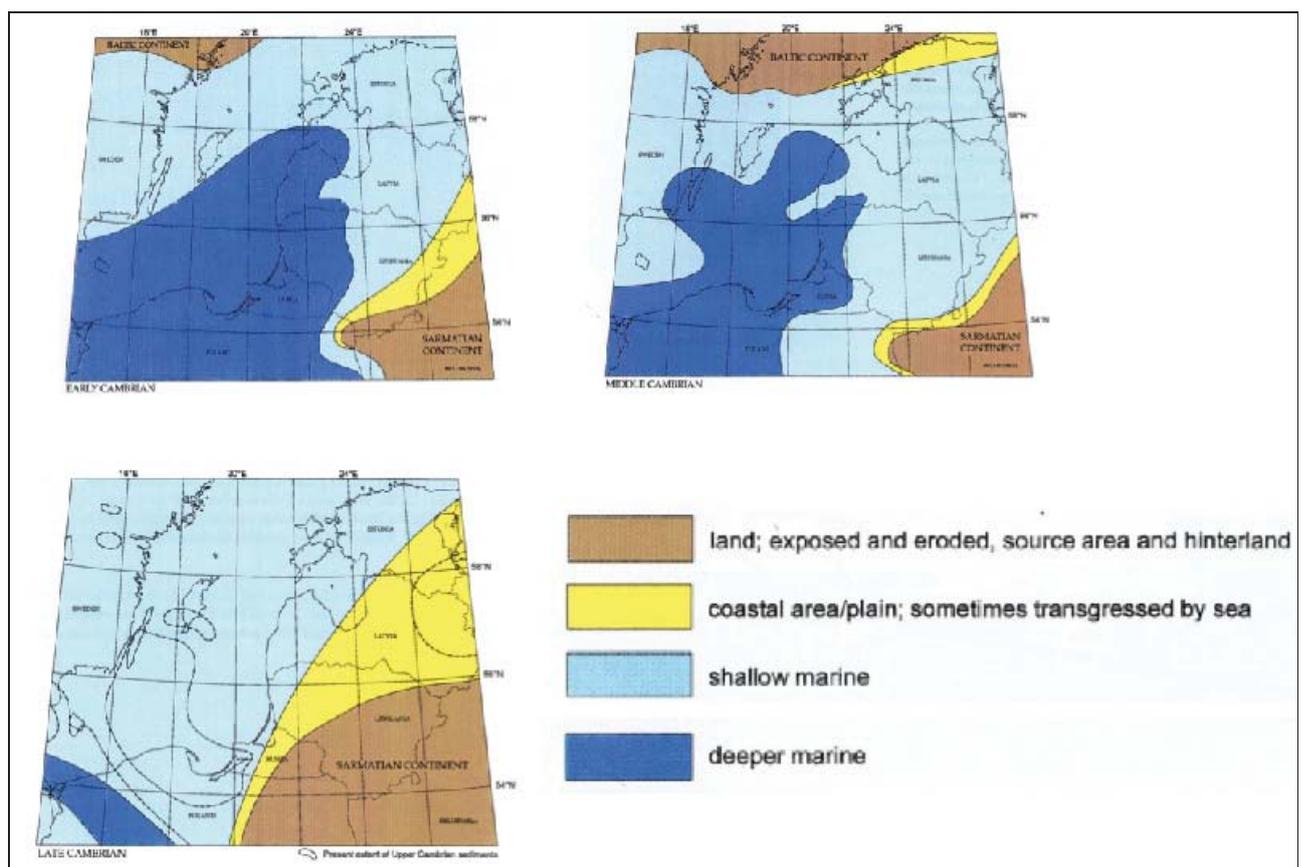


Figure 7 Reconstruction of the Cambrian paleoenvironment, separated into Early, Middle and Late Cambrian<sup>6</sup>

<sup>6</sup> Tarvis, T. 2007

### **3.5.4 Middle Cambrian**

There was a marine transgression in the middle Cambrian with an increase in sedimentation. Subsidence occurred to the east of the Baltic Basin. Parts of Russia, Lithuania and Latvia were subsiding at this time and continued to subside into the Upper Cambrian period.

The Middle Cambrian is split into the Upper and Lower units.

The lower unit consists of the Kybartai Formation comprising argillite and siltstone lithologies, with thin interbedded sandstone and limestone in the north of the basin. This argillite shale dominance indicates quiet water, deep marine depositional conditions, with the basin shallowing towards the north with the introduction of sandstone and limestone.

The upper sequence is made up of the Deimena Group consisting of 82m thick sequence sandstones in the north of the Basin with the introduction of interbedded siltstones and argillite in the south. Marine conditions prevail throughout the upper-Middle Cambrian.

### **3.5.5 Upper Cambrian**

During the Upper Cambrian there was a vast reduction in the number of deep marine deposits as the basin dramatically shallowed. Shallow marine sequences were widespread across the Baltic Basin. Terrigenous sediments were deposited in the Lithuanian region during this period and extensive coastal deposits were also formed.

The Upper Cambrian is not very well constrained. It is found mainly in the south of the Baltic Basin and consists of argillites and a thin bed of limestone.

The bituminous organic rich Alum Shales make up most of the argillites in the Upper Cambrian sequence.

### **3.5.6 Ordovician**

The Ordovician contains argillaceous limestone deposits associated with algal reefs on the northern and north eastern flanks of the Baltic Basin. The reef structures are relatively shallow, small in size and therefore unsuitable for CO<sub>2</sub> storage.

### **3.5.7 Silurian**

Thick Silurian argillaceous carbonates act as an effective seal to Cambrian reservoirs. The Silurian also contains barrier reef build ups with secondary dolomites but the size of individual structures is likely to be too small for matched CO<sub>2</sub> storage.

### **3.5.8 Devonian & Carboniferous**

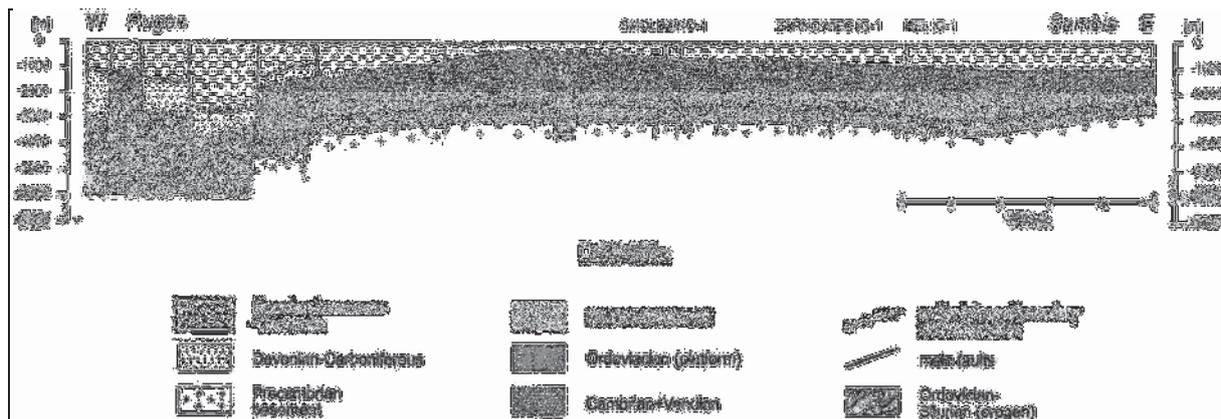
Devonian and Carboniferous terrigenous and carbonate deposits up to 800m thick are found in the east of the Baltic Basin.

### **3.5.9 Permian**

Lower Permian continental sandstones, conglomerates and siltstones are up to 70m thick but are too shallow to be considered for CO<sub>2</sub> storage. The upper Permian is made up of carbonate and evaporitic deposits.

### **3.5.10 Mesozoic & Cenozoic**

Mesozoic and Cenozoic terrigenous rocks unconformably overly the Caledonian sequence (Figure 8).



**Figure 8 Sambia-Rügen Cross Section Through the Central Western Part of the Baltic Basin and the Caledonides.**

### 3.6 Reservoir and Seal Pairs

The first oil field in the Baltic basin was discovered in 1962. It was located in the Middle-Late Cambrian sandstones. Several gas shows were encountered in the Devonian and older rocks. (Ulmishek, G. 1990) The Middle-Upper Cambrian sandstones form the major CO<sub>2</sub> storage reservoir of interest in the Baltic Sea Basin. The Cambrian reservoirs are sealed by thick Ordovician-Silurian carbonates and a 20m thick Upper Cambrian – Lower Ordovician shale horizon.

#### 3.6.1 Reservoir Rocks

The best reservoir rocks in the Baltic Sea Basin are the Middle-Upper Cambrian sandstones that alternate with shales and siltstones. Diagenetic alteration controls the properties of the sandstones. Quartz grains went into dissolution and reprecipitation occurred between the grains in open pore spaces. This controls the porosity and to a lesser extent the permeability of the sandstones. The sandstones are well sorted with porosities of up to 25% and permeabilities of several hundred millidarcies in places. Below 2km the porosity deteriorates to values of 5% to 7%. The Middle Cambrian Deimena sandstones contain Skolithos ichnofossils that locally increase the vertical porosity and permeability (Brangulis et al 1993).

The Ordovician has little potential as a CO<sub>2</sub> storage reservoir due to the variability of carbonate porosity and permeability as well as size of individual reef structures (Ulmishek, G. 1990).

#### 3.6.2 Cap Rocks

The upper Cambrian and Lower Ordovician shales and the thick Ordovician marls and argillaceous carbonates form the cap rock for most of the reservoirs in the Baltic Basin. A thick sequence of Silurian mudstones, shales and siltstones overlie the Ordovician lithologies. The overall cap rock thickness across the Baltic Basin exceeds 800m in many areas (Modliński, 2010).

#### 3.6.3 Mod

In the southeast part of the Baltic Sea Basin most of the known hydrocarbon fields are located in a narrow area east of the basin axis in the Mid-Upper Cambrian sequence. The Ordovician carbonates and marls form the cap. The traps are controlled by local structures intersected by reverse faults. These structures are relatively small in area with vertical closures between 30-70m in height (Ulmishek, G. 1990).

### **3.7 Geological Targets for CO<sub>2</sub> Storage**

The conclusion of the geological overview is that the only workable reservoir seal pair for CO<sub>2</sub> storage is the Cambrian sandstones sealed by the Ordovician Silurian argillaceous carbonates and shales.

In the Baltic Basin four sub-basins of interest have been identified, Slupsk Border Zone (SBZ), Gdansk-Kura Depression (GKD), Liepaja-Saldus Ridge (LSR) and the Latvian, Estonian Lithuanian Border Zone (LEL). These areas contain almost all of the oil and gas fields in the Baltic Basin (Plate 1).

The basin screening in Section 4.0 concentrates on the assessment of these sub-basins for CO<sub>2</sub> storage.

#### 4.0 BASIN SCREENING

Bachu (2003) developed a quantitative evaluation of a sedimentary basin's suitability for CO<sub>2</sub> storage. In the table below fifteen assessment criteria are shown with three to five classes defined from the least favourable to the most favourable.

**Table 2 Criteria for assessing sedimentary basins for CO<sub>2</sub> geological sequestration (Bachu 2003)**

Criterion	Classes				
	1	2	3	4	5
1 Tectonic setting	Convergent or stable	Convergent intracratonic	Dissevergent continental shelf	Dissevergent foredeep	Dissevergent orogenic
2 Size	Small	Medium	Large		
3 Depth	Shallow (<1000 m)	Intermediate (1000-3000 m)	Deep (>3000 m)		
4 Geology	Extensively folded and fractured	Modestly folded and fractured	Minimal folding and fracture, extensive shales		
5 Hydrogeology	Shallow, slow flow systems, or compaction flow	Intermediate flow systems	Regional, long-range flow systems, topography or orogenic flow		
6 Geothermal	Warm basin	Medium	Cold basin		
7 Hydrocarbon potential	None	Small	Medium	Large	Great
8 Maturity	Unexplored	Exploration	Developing	Minor	Over mature
9 Oil and GHI	None	Exp. (>500 m)	Shallow (<500 m)		
10 Salt	None	None	None		
11 Carbon Store	Depositional	Shallow offshore	Onshore		
12 Climate	Arctic	Sub-Arctic	Temperate	Tropical	Tropical
13 Accessibility	Inaccessible	Remote	Accessible	Very	Very
14 Infrastructure	None	Minor	Major	Major	Major
15 CO <sub>2</sub> sources	None	Low	Medium	High	High

Sedimentary basins were selected for their suitability for storage of CO<sub>2</sub> in depleted oil and gas fields or saline aquifers using a basin-by-basin approach applying the minimum criteria, secondary qualifiers and weightings as defined in Table 3 and Table 4 (modified from Bachu, 2003). Bachu's suitability criteria were broadly classified into three:

1. Basin characteristics, such as tectonism, geology, geothermal and hydrodynamic regimes (these are "hard" criteria because they do not change).
2. Basin resources (hydrocarbons, coal, salt), maturity and infrastructure (these "semi-hard" or "semi-soft" criteria because they may change with new discoveries, technological advances and/or economic development).
3. Societal, such as level of development, economy, political structure and stability, public education and attitude (these are "soft" criteria because they can rapidly change or vary from one region to another).

**Table 3 Minimum criteria for consideration of sedimentary basins for CO<sub>2</sub> storage**

<b>Suitability Criterion</b>		<b>Suitability threshold</b>	<b>Weight</b>
<b>1</b>	Depth	>800 m	0.07
<b>2</b>	Size at surface	>2500 km <sup>2</sup>	0.06
<b>3</b>	Seismicity	<High (i.e., not in subduction zones)	0.06
<b>4</b>	Reservoir/Seal	At least one major extensive and competent seal	0.08
<b>5</b>	Faulting and/or fracturing	Low to moderate	0.07
<b>6</b>	Pressure regime	Not overpressured	0.05
<b>7</b>	Regulatory status	Accessible	0.03
<b>TOTAL</b>			<b>0.42</b>

**Table 4 Proposed secondary qualifiers for assessing the potential of sedimentary basins for CO<sub>2</sub> storage**

<b>Potential Criterion</b>	<b>Poor Potential</b>	<b>Good Potential</b>	<b>Weight</b>	
<b>1</b>	CO <sub>2</sub> sources	At >500 km distance	At <500 km distance	0.08
<b>2</b>	Physical accessibility	Difficult	Good	0.03
<b>3</b>	Infrastructure	None or poor	Developed	0.05
<b>4</b>	Hydrogeology Flow systems	Shallow, short	Deep and/or long	0.08
<b>5</b>	Geothermal regime <sup>1</sup>	Warm	Cold	0.10
<b>6</b>	Hydrocarbon potential and industry maturity	None, poor	Large, mature	0.08
<b>7</b>	Coal	Too shallow or too deep	Between 400 and 1000 m depth	0.04
<b>8</b>	Coal value <sup>2</sup>	Economic	Uneconomic	0.04
<b>9</b>	Climate	Arctic and sub-arctic	Temperate	0.08
<b>TOTAL</b>			<b>0.58</b>	

The combined weights of Table 3 and Table 4 are equal to 1.0. Individual basins can be ranked according to these criteria to give a value between 0 and 1.

The Baltic Sea Basin is potentially a good candidate for CO<sub>2</sub> storage because it is a stable divergent cratonic basin with limited faulting and extensive sealing shale (Plate 1 and Ulmishek, G. 1009). It has regional long range flow systems. The cold climate and geothermal gradient increase CO<sub>2</sub> storage capacity and decrease CO<sub>2</sub> buoyancy. There is a proven hydrocarbon system with oil and gas production. However the monoclines around the margins are relatively shallow. In the relatively shallow monocline structures where the target saline aquifer storage reservoirs are less than 800m deep, CO<sub>2</sub> sequestration and storage is inefficient (low CO<sub>2</sub> density) and unsafe because of very high CO<sub>2</sub> buoyancy (Chadwick, A. 2008). The Baltic Sea sub-basins are all of suitable size but the structures within them are not. The monoclines that form the boundary to the basin may be candidates for CO<sub>2</sub> storage in saline aquifers but further reservoir engineering studies are required to establish the integrity of CO<sub>2</sub> trapping in monoclines where no structural closure exists. This applies in to the Dalders Monocline in Sweden.

With respect to physical accessibility and regulatory status the Baltic sub basins were ranked from the point of view of transporting CO<sub>2</sub> from point sources surrounding the Baltic Sea. Both pipeline and shipping transport are considered. In Table 4, Table 6, Table 8 and Table 10 the distance is calculated for point sources in Finland which are the furthest away from the potential storage sites in the Baltic Sea sub basins. Clearly distances from other countries will be much less. The Baltic Sea sub-basins could provide accessible CO<sub>2</sub> storage sites below 800m onshore and offshore in shallow water. There are major CO<sub>2</sub> sources surrounding the Baltic Sea Basin and there is a moderate level of pipeline and hydrocarbon production infrastructure. The regulatory status refers to legal and commercial access by Finland and Sweden to CO<sub>2</sub> sinks in the host country.

The results of the screening exercise for sedimentary basins of the Baltic Sea are shown below with additional weightings applied by SLR using a variation of Bachu's methodology (Bachu, 2003).

#### 4.1 Slupsk Border Zone

The Slupsk Border Zone (Plate 1) is a monocline at the WNW margin of the Baltic Basin. It contains part of the Dalders Monocline.

**Table 5 Criteria for consideration of Slupsk (including Dalders) Monocline for CO<sub>2</sub> storage**

<i>Criterion</i>	<i>Threshold</i>	<i>Slupsk Monocline</i>	<i>Weight</i>
1 Depth	>800 m	Deep (1000+ m)	0.07
2 Size at surface	>2500 km <sup>2</sup>	Moderate size structures	0.06
3 Seismicity	Low (i.e., not in subduction zones)	Low (intracratonic)	0.06
4 Reservoir/Seals	At least one major extensive and competent seal	Excellent	0.08
5 Faulting/fracturing	Low to moderate	Low	0.07
6 Pressure regime	Not overpressured	Normal	0.03
7 Regulatory status	Accessible	Moderately accessible	0.03

**Table 6 Secondary qualifiers for assessing the potential of Slupsk for CO<sub>2</sub> storage**

<i>Potential Criterion</i>	<i>Poor Potential</i>	<i>Good Potential</i>	<i>Weight</i>
1 CO <sub>2</sub> sources	--	~300 km distance	0.04
2 Physical accessibility	--	Good	0.03
3 Infrastructure	--	No developed pipelines	0.01
4 Flow systems	--	Deep but untested	0.03
5 Geothermal regime	--	Cold	0.10
6 Hydrocarbon potential and industry maturity	--	Good data	0.08
7 Coal	N/A	N/A	0.00
8 Coal value	N/A	N/A	0.00
9 Climate	--	maritime, sub arctic	0.08

**Total weightings of Table 4 and Table 5 for Slupsk Monocline = 0.76**

#### COMMENTS:

- A potential siliciclastic saline aquifer is present in the Cambrian.
- A significant structure closure (161 km<sup>2</sup>) has been mapped at the storage reservoir level at the Dalders Prospect.
- Oilfields in Poland, Lithuania and Russia are producing from the Middle Cambrian sandstone reservoir and therefore the Cambrian has proven capacity to store CO<sub>2</sub>.
- A significant part of the Dalders monocline is accessible in Swedish territory.
- When the Latvia/Lithuania border is agreed, all of the Dalders structure could be accessible for oil field development with CO<sub>2</sub> Enhanced Oil Recovery (EOR).

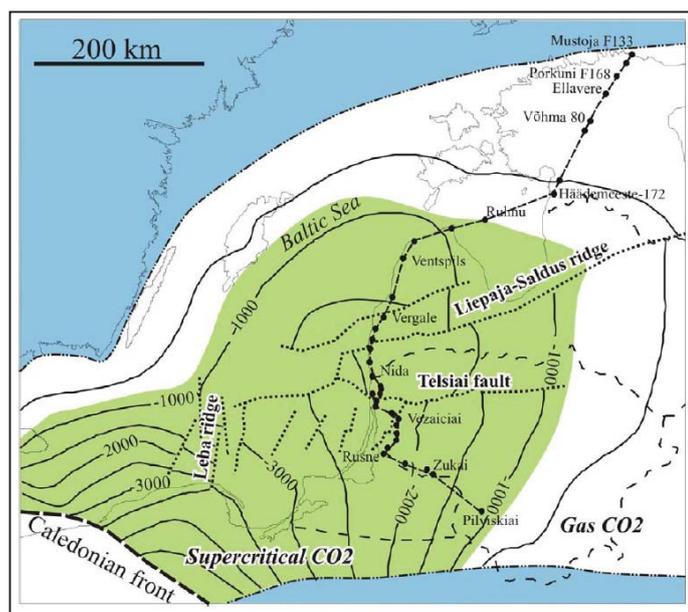


Figure 9 Depth of top of the Cambrian aquifer.<sup>7</sup>

The score of 0.76 for the Slupsk Border Zone makes it a potential candidate for CO<sub>2</sub> storage. The Dalders Prospect anticline structure (Figure 2) is located in water depth of 120m in the central Baltic across Swedish, Latvian and Lithuanian territory. It has a volume estimate of about 300 million barrels of recoverable oil in Cambrian sandstone (Petrosweide Svenska Petroleum Exploration, 2010). Structurally it lies on the SE edge of the Slupsk-Latvian-Estonian Monocline on the Liepaya-Saldus High. The Dalders structure and associated monocline is a potential candidate for CO<sub>2</sub> storage based on its favourable depth, size, low seismicity, limited faulting, accessibility and good reservoir seal pair.

#### 4.2 Latvian Estonian and Lithuanian Border Zone (LEL)

The Latvian Estonian and Lithuanian Border Zone (Plate 1) is a monoclonal structure that surrounds the margins of the Baltic Basin. The Latvian Estonian Monocline is largely offshore and the Lithuanian Monocline is largely onshore. There are a number of oilfields onshore Latvia and Lithuania producing from Cambrian sandstone reservoirs in small anticline traps (e.g. Kuldiga Field). The Devonian aquifer is not buried sufficiently deep to act as a reservoir for CO<sub>2</sub> storage (Figure 9). There is onshore pipeline infrastructure in Latvia and an underground gas storage facility at Inčukalns which proves the CO<sub>2</sub> storage capacity of the Cambrian sandstone reservoirs and the physical accessibility. The area is also less than 400kms from CO<sub>2</sub> point sources in Finland.

<sup>7</sup> The line of the geological cross-section shown in Figure 10 is indicated. The green area indicates the pressure temperature field for supercritical CO<sub>2</sub> (after Sliupa S., 2009).

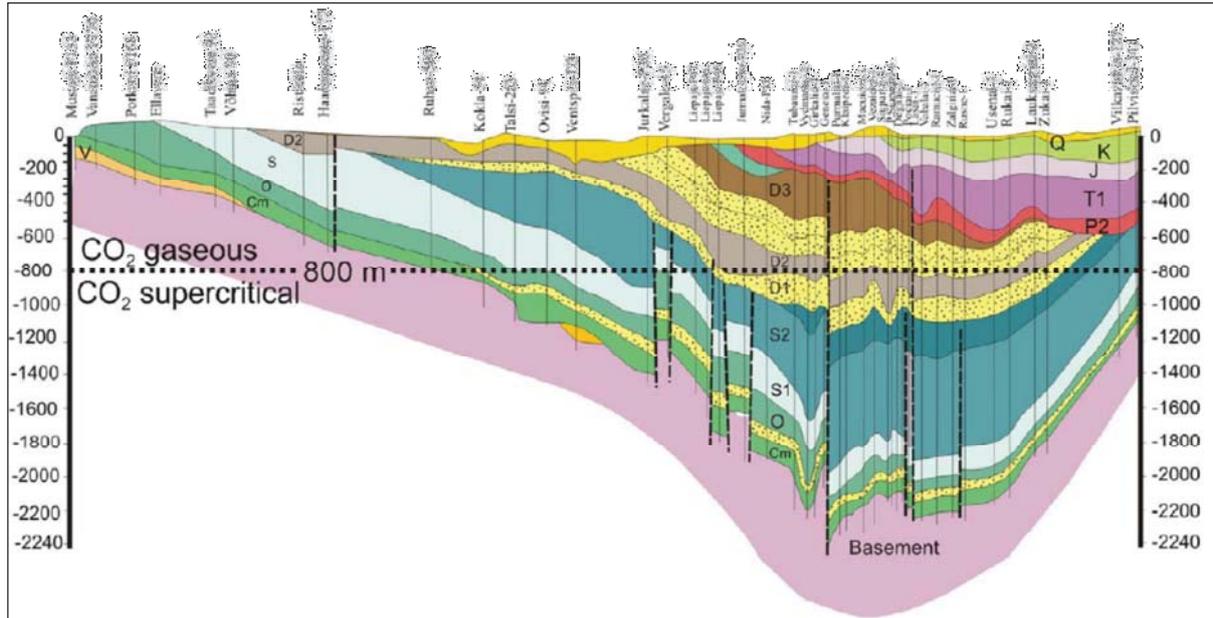


Figure 10 Geological cross section across Estonia, Latvia, and Lithuania<sup>8</sup>

Table 7 Criteria for consideration of Latvian Estonian and Lithuanian Monocline for CO<sub>2</sub> storage

Criterion	Threshold	Latvian Estonian Lithuanian Monocline	Weight
1 Depth	>1000 m	Deep (1000+ m)	0.07
2 Size at surface	>2500 km <sup>2</sup>	Small structures	0.02
3 Seismicity	Low (i.e., not in subduction zones)	Low (cratonic)	0.06
4 Reservoir/Seals	At least one major extensive and competent seal	Excellent	0.08
5 Faulting/fracturing	Low to moderate	Low	0.07
6 Pressure regime	Not overpressured	Normal	0.03
7 Regulatory status	Accessible	Moderately accessible	0.07

<sup>8</sup> Modified after Sliupa et al. 2008

**Table 8 Secondary qualifiers for assessing the potential of Latvian Estonian and Lithuanian Monocline for CO<sub>2</sub> storage**

	<i>Potential Criterion</i>	<i>Poor Potential</i>	<i>Good Potential</i>	<i>Weight</i>
1	CO <sub>2</sub> sources	--	~400 km distance	0.08
2	Physical accessibility	--	Good	0.01
3	Infrastructure	--	Some pipelines onshore	0.03
4	Flow systems	--	Deep and/or long	0.03
5	Geothermal regime	--	Cold	0.10
6	Hydrocarbon potential and industry maturity	--	Moderate, mature	0.05
7	Coal	N/A	N/A	0.00
8	Coal value	N/A	N/A	0.00
9	Climate	--	Maritime, sub arctic	0.08

**Total weightings of Table 6 and Table 7 for Latvian Estonian and Lithuanian Monocline = 0.71**

**COMMENTS:**

- Ten sources in Lithuania emit more than 0.1Mt of CO<sub>2</sub> per year from an oil refinery (Mazeikiai), an ammonia plant, two cement plants (Akmene) and power plants.
- Two prospective siliciclastic saline aquifers are present in the Cambrian and Lower Devonian. There are no significant structures in the Lower Devonian (Sliaupa S., 2009)
- Oil production onshore Gotland is from Ordovician reefs at shallow depths unsuitable for CO<sub>2</sub> storage.
- Ordovician and Upper Silurian carbonate reefs with storage potential are interpreted on seismic data acquired in the northern part of offshore Latvia.
- Eleven oilfields are producing from the Middle Cambrian sandstone reservoir in Lithuania, but the structures are small and enhanced oil recovery and storage potential is estimated to be negligible, about 5.6Mt (Sliaupa S., 2009).
- One of the 17 major West Latvian structures identified with Cambrian reservoirs, Inčukalns, has been used for underground gas storage since 1968, proving the stability of the sealing cap rock (Shogenova, A. 2009), (Latvijas Vides, Geolģijas, un Meteorolģijas Agentura, 2007).
- The storage capacity of the Lithuanian Monocline is limited by the size of structures with Cambrian sandstone reservoirs and the restricted area that is sufficiently deep for CO<sub>2</sub> storage.

The LEL, with a score of 0.71, is a possible candidate for CO<sub>2</sub> storage based on its favourable depth, low seismicity, good Cambrian and Devonian reservoir/seal pairs, onshore infrastructure and accessibility. Only two structures of capacity greater than 1 Mt CO<sub>2</sub> were identified in Lithuania. Ordovician algal reefs occur at shallow depths in small structures in Gotland and onshore Latvia. Thirty large structures (greater than 600Mt CO<sub>2</sub> storage capacity) are identified in Latvia, onshore and offshore (Sliaupa S., 2009).

**4.3 Liepaja-Saldus Ridge**

The Liepaja-Saldus Ridge (Plate 1) is a regional faulted zone with a complex structure, oriented SW-NE. It extends more than 300 km from the central part of the Baltic Sea to central Latvia onshore. It is bounded by major faults that displace Caledonian sediments up to 600m. The Liepaja-Saldus High has several structures with associated oil prospects offshore Latvia. The Dalders Prospect (Figure 2) extends onto the Liepaja-Saldus Ridge.

**Table 9 Minimum criteria for consideration of Liepaja-Saldus High for CO<sub>2</sub> storage**

<i>Criterion</i>	<i>Threshold</i>	<i>Liepaja-Saldus High</i>	<i>Weight</i>
1 Depth	>800 m	Deep (1000+ m)	0.07
2 Size at surface	>2500 km <sup>2</sup>	Medium size structures	0.06
3 Seismicity	Low (i.e., not in subduction zones)	Low (passive margin)	0.06
4 Reservoir/Seals	At least one major extensive and competent seal	Excellent	0.08
5 Faulting and/or fracturing	Low to moderate	Low	0.07
6 Pressure regime	Not overpressured	Normal	0.03
7 Regulatory status	Accessible	Accessible	0.02

**Table 10 Secondary qualifiers for assessing the potential of Liepaja-Saldus High for CO<sub>2</sub> storage**

<i>Potential Criterion</i>	<i>Poor Potential</i>	<i>Good Potential</i>	<i>Weight</i>
1 CO <sub>2</sub> sources	--	~400 km distant	0.08
2 Physical accessibility	--	Fair (marine)	0.02
3 Infrastructure	Limited	--	0.01
4 Flow systems	--	Deep and/or long	0.03
5 Geothermal regime	--	Cold	0.10
6 Hydrocarbon potential and industry maturity		Mature	0.05
7 Coal	N/A	N/A	0.00
8 Coal value	N/A	N/A	0.00
9 Climate	--	Maritime, sub-arctic	0.08

**Total weightings Table 8 and Table 9 for Liepaja-Saldus High = 0.75**

**COMMENTS:**

- Adjacent to Latvian coast.
- Two wells offshore Latvia, E6-1 and P6-1, proved a saline aquifer in Middle Cambrian sandstones and some oil production from Late Ordovician carbonates. No current production.
- A number of structures with prognosed Cambrian sandstone reservoirs have been identified offshore Latvia including the Dalders Structure.
- Good potential licence access given Svenska's licence holding in Latvia.

The Liepaja-Saldus Ridge, with a score of 0.75, is a potential candidate for CO<sub>2</sub> storage based on its favourable depth, low seismicity, excellent reservoir/seal pairs, and accessibility.

#### 4.4 Gdansk-Kura Depression

The Gdansk-Kura Depression is a large regional structure, extending SW-NE from Poland to the southern part of Western Latvia (Plate 1). There are oil discoveries in Poland, Lithuania and Kaliningrad District and several oil prospective structures offshore Latvia.

**Table 11 Minimum criteria for consideration of Gdansk-Kura Depression for CO<sub>2</sub> storage**

<i>Suitability Criterion</i>	<i>Gdansk-Kura Depression</i>	<i>Weight</i>
1 Depth	Deep (1000+ m)	0.07
2 Size at surface	Moderate size structures (in Poland ~8,000 km <sup>2</sup> )	0.03
3 Seismicity	Low	0.06
4 Reservoir/Seals	Proven excellent	0.05
5 Faulting and/or fracturing	Low to moderate	0.04
6 Pressure regime	Normal	0.05
7 Regulatory status	Reasonably accessible	0.02

**Table 12 Secondary qualifiers for assessing the potential of Gdansk-Kura Depression for CO<sub>2</sub> storage**

<i>Potential Criterion</i>	<i>Poor Potential</i>	<i>Good Potential</i>	<i>Weight</i>
1 CO <sub>2</sub> sources	--	~400 km distant	0.01
2 Physical accessibility		Good	0.03
3 Infrastructure		Present--	0.05
4 Flow systems	--	Deep and/or long	0.08
5 Geothermal regime	--	Cold - moderate	0.10
6 Hydrocarbon potential and industry maturity		Mature	0.08
7 Coal	N/A	N/A	0.00
8 Coal value	N/A	N/A	0.00
9 Climate	--	Maritime, sub-arctic	0.08

**Total weightings of Table 10 and Table 11 for Gdansk-Kura Depression = 0.75**

#### COMMENTS:

- Contains producing fields offshore Poland and Russia and onshore Russia and Lithuania.
- Existing platforms and pipelines.
- Potential access to storage offshore Poland.
- Possible access to storage offshore Kaliningrad.

The Gdansk-Kura Depression, with a score of 0.75, is a potential candidate for CO<sub>2</sub> storage based on its favourable depth, moderate size, low seismicity, proven reservoir/seal pairs and possible licence access through Poland.

#### 4.5 Liepaja Depression

The Liepaja Depression is located north of the Liepaja-Saldus High and extends onshore Latvia (Plate 1). The Liepaja Depression is not a candidate for CO<sub>2</sub> storage based on its unfavourable depth. The prospective reservoirs are less than 800m deep.

## 5.0 BASIN RANKING

In the previous section, a modified version of Bachu's criteria was used to score the sub-basins of the Baltic Sea Basin. Based on the weightings shown in Table 5 to Table 12 above the basins are ranked as follows Slupsk Border Zone (0.76), Gdansk-Kura Depression (0.75), Liepaja Saldus Ridge (0.75), and Latvian Estonian Lithuanian Border Zone (0.71).

**Table 13 Ranking of Baltic Sea sub-basins in terms of suitability for CO<sub>2</sub> geological sequestration**

<b>Rank</b>	<b>Basin</b>	<b>Characteristics</b>	<b>Score</b>
<b>1</b>	Slupsk Border Zone	Proven reservoir/seal pair, moderate size structures, offshore, large saline aquifer, limited faulting, good accessibility, <500kms to strategic CO <sub>2</sub> sources	0.76
<b>2</b>	Gdansk-Kura Depression	Existing oil and gas production infrastructure, moderate sized structures, offshore, fair accessibility, >500kms to some strategic CO <sub>2</sub> sources	0.75
<b>3</b>	Liepaja Saldus Ridge	Proven reservoir/seal pair, moderate size structures, offshore, fair accessibility, <500kms to strategic CO <sub>2</sub> sources	0.75
<b>4</b>	Latvian Estonian Lithuanian Border Zone	Proven reservoir/seal pairs, small structures, potential saline aquifer, only small area sufficiently deep for CO <sub>2</sub> storage, accessible, 250kms to strategic CO <sub>2</sub> sources	0.71

In this initial ranking the Slupsk Border Zone has the highest priority because it contains the Dalders Monocline which is a probable CO<sub>2</sub> storage structure that is accessible to Swedish CO<sub>2</sub> point sources. The Gdansk-Kura Depression is geologically suitable for CO<sub>2</sub> storage and has existing oil production infrastructure at PetroBaltic's B3 field and Lukoil's Kratsovskoye field. However access may be restricted depending on the storage capacity of the depleted oil and gas reservoirs when they become available. There are existing plans to use the offshore facilities in Poland to store CO<sub>2</sub> from the Lotos refinery in Gdansk. The Liepaja Saldus Ridge is closer to CO<sub>2</sub> sources in Finland and has potential CO<sub>2</sub> storage in saline aquifers offshore Latvia. The LEL Border Zone has the lowest rank because only a small area is sufficiently deep for CO<sub>2</sub> storage.

## 6.0 STORAGE CAPACITY CALCULATION METHODOLOGY & RESULTS

### 6.1 Introduction

Following the ranking of the Baltic Sea sub-basins, storage capacity calculations have been completed using the GeoCapacity (2009) methodology. Hydrocarbon exploration and production data obtained in the initial phases of the project was integrated into a GIS database and used to estimate the potential theoretical storage capacity for the Baltic Sea sub basins. The calculations were undertaken as regional estimates for both hydrocarbon fields and saline aquifers. The specific methodologies used for individual fields, the data origins and the results are discussed below.

### 6.2 Hydrocarbon Field Storage Capacity Estimates

#### 6.2.1 Generic Hydrocarbon Fields:

Based on the available data for specific hydrocarbon fields, two separate calculation methodologies were used. Where limited data is available the Generic Hydrocarbon Fields method is used. A simplified formula using the ultimate recoverable reserves (UR) and formation volume factors (FVF) for the oil and gas fields shown in Table 14 was used (Schuppers, *et al.*, 2003).

**Table 14 Oil and Gas Fields where Generic Hydrocarbon Fields method is used**

LITHUANIA	SUB-BASIN	POLAND	SUB-BASIN	KALININGRAD	SUB-BASIN
S. Blidinžiai	GKD	B34	LSR	Slavinsk	GKD
Lapgiriai	LEL			Gajevsk	GKD
Lauksargiai	GKD			Laduskino	GKD
Plunge	GKD			Veselovsk	GKD
Girkaliai	GKD			Slavsk	GKD
Ablinga	GKD			Gusevskij	GKD
Vezaiciai	GKD			Solnečnaja	GKD
Siupariai	GKD			Zverevskaja	GKD
P. Siupariai	GKD			Rjazanskaja	GKD
Degliai	GKD			Borokskaja	GKD
Silale	GKD			Dubravnaja	GKD
Pociai	GKD			D158	GKD
Vilkyciai	GKD			D30	GKD
Sakuciai	GKD			D160	GKD
Kybartai	LEL			C32	GKD
Kudirka	LEL			d21	GKD
				d22	GKD
				Kravtsovskoye (D-6)	GKD

$$M_{CO_2} = \rho_{CO_2} \times UR_p \times B$$

where:

$\rho_{CO_2}$  = CO<sub>2</sub> density at reservoir conditions

$UR_p$  = Proven Ultimate Recoverable Oil or Gas

$B$  = Oil or Gas Formation Volume Factor

The proven recoverable oil or gas data from the LO&G, 2007 report was used to estimate the CO<sub>2</sub> storage potential of the Lithuanian, Polish and some of the Kaliningrad fields. Zytner et al (2008), Otomas (2011) and Sliapiene and Sliupa (2011) provided the proven recoverable oil and gas reserve data for the other Kaliningrad fields. For the Lithuanian fields FVFs based on those reported for the Genciai, Nausodis and Kretinga fields by Svenska, 1996 were used. No FVF data was available for the Kaliningrad fields and a value of 1.08 similar to the onshore Lithuanian fields was assumed. In the case of the Polish fields, FVF data and CO<sub>2</sub> density was obtained from the data included in the LOTOS, 2010 presentation.

CO<sub>2</sub> density values based on published information and temperatures and pressures recorded for the Lithuanian fields as published by Streimikiene, 2010 was used in the calculations.

For the Kaliningrad fields a default CO<sub>2</sub> density value of 0.650t/m<sup>3</sup> was used due to the lack of specific formation data.

### 6.2.2 Detailed Hydrocarbon Fields:

Calculations of CO<sub>2</sub> storage capacity in hydrocarbon fields where detailed reservoir and formation data are available have been undertaken based on Bachu, *et al.*, 2007. The following formulae were applied:

$$\text{Gas Fields: } M_{CO_2} = \rho_{CO_2} \times R_f \times (1 - F_{ig}) \times OGIP \times B_g$$

$$\text{Oil Fields: } M_{CO_2} = \rho_{CO_2} \times (R_f \times OOIP \times B_o - V_{iw} + V_{pw})$$

where:

$\rho_{CO_2}$  = CO<sub>2</sub> density at reservoir conditions (best estimate based on available data & using the CO<sub>2</sub> State Equations for Pressure and Temperature Conditions; <http://webbook.nist.gov/chemistry/fluid/>)

$R_f$  = Recovery Factor

$F_{ig}$  = Fraction of Injected Gas

$OGIP$  = Original Gas in Place (at surface conditions)

$B_g$  = Gas Formation Volume Factor <<1

$OOIP$  = Original Oil in Place (at surface conditions)

$B_o$  = Oil Formation Volume Factor >1

$V_{iw}$  = Volume of Injected water

$V_{pw}$  = Volume of Produced water

Detailed information from a very limited number of hydrocarbon fields in the Baltic Sea region was available to perform a trap or structure specific theoretical storage capacity calculation. **Table 15** below summarises the fields where detailed Recovery Factor (RF) and FVF data was available to perform these detailed calculations. No information was available with regard to volumes of produced and injected water and these values were omitted from the calculations.

**Table 15 Hydrocarbon Fields with Detailed Reservoir Information**

POLAND	Trap / Structure Name	Sub-Basin	LITHUANIA	Trap / Structure Name	Sub-Basin
<b>B3</b>	Total	LSR	<b>Genciai</b>	Total	GKD
<b>B4</b>	B4-1	LSR	<b>Nausodis</b>	Total	GKD
<b>B6</b>	B6-1	LSR	<b>Kretinga</b>	Total	GKD
<b>B8</b>	B8-1	LSR			

The Polish field data was primarily based on data published in the LOTOS, 2010 presentation where more up to date information on the Middle Cambrian Zona Paradoxides Paradoxissimus formation reservoir conditions was available for the B3, B4, B6 and B8 fields.

A detailed assessment of the Genciai Lower and Upper Sand reservoirs was performed using this method based on the information compiled in the Svenska 1996 pre-development study report. For this field an average recovery factor of 47% was used.

Storage Capacity calculations for the A Upper and A Lower Sand were undertaken for both Nausodis and Kretinga as well as for the B Sand in the Kretinga field. Average RF values of 14% and 22% respectively were used for these calculations.

The OOIP values used were those published by Svenska in 1996. For all of the Lithuanian fields a FVF of 1.08 was used based on the published values from the Genciai field.

### 6.3 Saline Aquifer Storage Capacity Estimates:

#### 6.3.1 Regional, Bulk Volume Estimate:

A storage capacity calculation for the Cambrian below 900m and for the Dalders Monocline was performed using the modified formula by Bachu *et al.* (2007) as published in the GeoCapacity (2009) report:

$$M_{CO_2} = A \times h \times NG \times \phi \times \rho_{CO_2} \times S_{eff}$$

where:

$\rho_{CO_2}$  = CO<sub>2</sub> density at reservoir conditions (best estimate based on available data & using the CO<sub>2</sub> State Equations for Pressure and Temperature Conditions; <http://webbook.nist.gov/chemistry/fluid/>)

$A$  = Area of the regional trap of aquifer

$h$  = Height of the regional trap of aquifer

$NG$  = Net to Gross Ratio (NG)

$\phi$  = Average reservoir porosity of regional or trap aquifer (best estimate)

$S_{eff}$  = Storage Efficiency Factor (for bulk volume of regional aquifer or trap specific)

The outline of the Cambrian below 900m (LO&G, Enclosure 2, 2002) was digitised into GIS and an area of 193,192km<sup>2</sup> was calculated. The Dalders Monocline as outlined in the structural elements of the Baltic Syncline (Tarvis, 2007) and mapped below 900m (LO&G, Enclosure 2, 2002) was calculated as 19,634km<sup>2</sup>. An average height of the reservoir of 70m and average porosity of 13% were used based on data in Skirius, 1996 (Amoco report) and data for the Faludden sandstone from the B-9 and P6 wells.

A storage efficiency factor of 2% was used for all the bulk regional aquifer assessment whilst the CO<sub>2</sub> density was calculated based on reservoir temperature and pressure data from the B-9 well composite log.

#### 6.3.2 Trap Volume Estimate:

A trap specific theoretical storage capacity calculation was carried out for 8 offshore Latvia closures and for the Dalders Structure as presented in the Amoco 1996 report. The calculation was undertaken assuming the structures are open or semi-closed and assuming the Middle Cambrian Faludden sandstone is an unconfined aquifer. The structures modelled are listed in Table 16 below.

**Table 16 Closure specific Calculations for the Dalders Structure**

Structure Name	Sub-Basin
Dalders Structure	LSH
E5	LSR
E6	LSH
E7	LSH
E5	LSH
P1	LSH
E17	LSH
P4	LSH
E12-E13-E2-D10	LSH
E23	LSH

This conceptual model assumes that the storage space is generated by displacing existing fluids and distributing the pressure increase in the surrounding and connected aquifer. This approach therefore assumes that available space is essentially the pore volume and the storage efficiency factor is dependent on the connectivity of the surrounding aquifer (GeoCapacity, 2009).

Storage capacity calculations for the eight structures mapped in the Latvian offshore were completed using digital Top Cambrian depth structure isopach maps and fault outlines at a scale of 1:25,000 and 1:50,000 purchased from the Latvian Environment, Geology and Meteorology Centre (LEGMC). Outlines of the structures were digitised using the deepest closing contour and the fault structures.

Average reservoir height, average porosity values and CO<sub>2</sub> density values based on the observed reservoir formation data (including temperature and pressure) from the E6-1 and E7-1 wells were used in the storage capacity calculations for the E6 and E7 structure. Net to Gross (NG) ratio values published in the Amoco Enclosure 24 map were used.

The LEGMC Top Cambrian depth structure digital data was combined with fault structures and used to define the outlines of the E5, E17, P4 and E23 structures. Combined data from E12-E13-E2-D10 was used to determine overall area of the structure. An average reservoir thickness of 55m and average porosity of 15% was used based on the values from the E6-1 and E7-1 wells and an estimated CO<sub>2</sub> density of 0.603 t/m<sup>3</sup> was used in the calculation with the NG ratio values derived from the Amoco, Enclosure 24 map.

The P4 structure located within the area of the Dalders Monocline was also modelled based on the information available from the P6-1 well. An average reservoir thickness of 83m and a porosity value of 12% were used. However, it important to note that the digital Top Cambrian structure map coverage did not provide an accurate way of determining the boundary of this structure.

The Middle Cambrian depth map showing contours of the Middle Cambrian Sandstone in the Dalders Structure (Amoco, 1995) was combined with the digital Top Cambrian E7 structure map and the fault structure outlines to define the boundary of the Dalders Structure. The NG ratios of 76% and an average formation porosity of 13% based on information from Donoho, 1996 and Amoco Enclosure 24 was used. An average reservoir formation thickness of 55m, as published in the Structural Analysis section by Donoho *et al* (1996), was used for the Dalders structure.

The 'cartoon approach' of the GeoCapacity (2009) methodology was used to estimate the storage efficiency factor for these structures. The reservoir can be considered high quality based on the porosity and permeability values recorded for the Faludden sandstone in the E6-1, E7-1 and P6 wells. This is supported by permeability values in the B3 field (Lotus 2011). However, there are a small number of mapped structural features that limit the apparent connectivity in the reservoir between the individual trap structures. There are variations in permeability of between 10mD to 100mD observed in the cores from the E6-1, E7-1 and P6-1 well within the bulk aquifer volume. Based on these observations a storage efficiency value of 20% was chosen.

#### **6.4 Theoretical Storage Capacity Calculation Results:**

The summary tables below show the storage capacity calculation results for the Baltic Sea region based on the methodology described above. The best prospects are the Dalders Monocline and the Cambrian across the Baltic Sea region below 900m depth Table 17. The Cambrian has an estimated theoretical storage potential 16,222Mt of which 1,924Mt is in the Dalders Monocline and 128Mt in the Dalders Structure, located in the central part of the Baltic Sea Area (Table 17). The total individual field storage capacity is estimated to be 943Mt of which the individual hydrocarbon fields are estimated to have theoretical storage potential of 210Mt.

**Table 17 Theoretical Storage Capacity Summary**

	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
<b>Regional Cambrian Below 900m</b>	16,222
<b>of which Dalders Monocline</b>	1,924
<b>Individual Baltic Sea Field Total</b>	743
<b>Dalders Structure</b>	128

. The estimates for onshore theoretical storage capacity are summarised below:

**Table 18 Proportion of onshore CO<sub>2</sub> storage capacity**

	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)	Estimated CO <sub>2</sub> Storage Capacity onshore (10 <sup>6</sup> tonnes)	Percentage of the overall CO <sub>2</sub> storage capacity
		-	-
<b>Regional Cambrian Below 900m</b>	16,222	9151	56
<b>of which Dalders Monocline</b>	1,924	157	8
<b>of which Dalders Structure</b>	128	0	0
<b>Individual Baltic Sea Field Total</b>	743	88	12
<b>of which in Poland</b>	6	0	0
<b>of which in Latvia</b>	633	0	0
<b>of which in Lithuania</b>	31	31	100
<b>of which in Kaliningrad</b>	73	57	78

Results from the individual hydrocarbon fields, saline aquifer structure and bulk assessments are discussed in more detail below.

### 6.4.1 Generic Hydrocarbon Fields:

The results from the theoretical capacity calculations using the Generic Hydrocarbon Fields method show relatively small storage potential associated with individual hydrocarbon fields across the Baltic Sea region.

**Table 19 Hydrocarbon Field Theoretical Storage Capacity**  
(\* indicates the onshore fields)

LITHUANIA	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)	POLAND	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)	KALININGRAD	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
S. Blidinziai*	0.32	B34	3.28	Slavinsk*	4.97
Lapgiriai*	0.32	<b>TOTAL</b>	<b>3.28</b>	Gajevsk*	1.14
Lauksargiai*	0.16			Laduskino*	26.22
Plunge*	0.28			Veselovsk*	1.87
Girkaliai*	3.75			Slavsk*	3.17
Ablinga*	0.66			Gusevskij*	0.32
Vezaiciai*	2.78			Solnečnaja*	0.31
Siupariai*	2.50			Zverevskaja*	0.05
P. Siupariai*	5.51			Rjazanskaja	0.13
Degliai*	1.89			Borokskaja*	0.07
Silale*	1.23			Dubravnaja*	0.08
Pociai*	0.50			D158	0.94
Vilkyciai*	5.05			D30	1.47
Sakuciai*	1.90			D160	0.70
Kybartai*	0.48			C32	2.71
Kudirka*	1.53			d21	1.03
<b>TOTAL</b>	<b>28.87</b>			d22	1.97
				Kravtsovskoye (D-6)	7.17
				<b>TOTAL</b>	<b>54.33</b>

Country	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
Lithuania	28.87
Poland	3.28
Kaliningrad	54.33
<b>TOTAL</b>	<b>86.47</b>

UR data were collected from LO&G (2002), Zytner et al (2008), Otmac (2011) and Sliapiene and Sliapia (2001) for the Kaliningrad fields. FVF values based on the Lithuanian field values and a CO<sub>2</sub> density value of 0.6500 t/m<sup>3</sup> were used for the fields from the LO&G report and 0.7300 t/m<sup>3</sup> for the other fields. The total theoretical storage capacity value is 54.33 Mt of CO<sub>2</sub> for the Kaliningrad fields.

Individual Lithuanian hydrocarbon fields are estimated to have a total theoretical storage capacity of just under 29 Mt using the data that was available from the UR estimates (LO&G, 2002), the FVF and CO<sub>2</sub> density values (Streimikiene, 2010).

A theoretical storage capacity for the B34 field was calculated to be 3.3Mt.

Overall, 27 of the 35 fields considered for the Generic Hydrocarbon Fields class are onshore and correspond to 77.71% of the 86.47 Mt theoretical storage capacity.

Storage capacity calculations were not completed for hydrocarbon fields where no data was available. These include:

- Poland: B16, B21
- Lithuania: Saukenai

- Kaliningrad: Kulikovsk, Jagodnoje, Kaliningrad, Gusev, Neman

#### 6.4.2 Detailed Hydrocarbon Fields:

The results from the theoretical capacity calculations using the Detailed Hydrocarbon Fields Method also show relatively small storage potential associated with individual hydrocarbon fields across the Baltic Sea region.

**Table 20 Hydrocarbon Field Detailed Theoretical Storage Capacity**  
(\* indicates the onshore fields)

Trap/ Structure Name		Hydrocarbon Field CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
<b>POLAND</b>		
<b>B3</b>	Total	1.20
<b>B4</b>	B4-1	0.29
<b>B6</b>	B6-1	0.24
<b>B8</b>	B8-1	0.89
<b>TOTAL</b>		<b>2.62</b>
<b>LITHUANIA</b>		
<b>Genciai*</b>	Total	1.48
<b>Nausodis*</b>	Total	0.18
<b>Kretinga*</b>	Total	0.19
<b>TOTAL</b>		<b>1.86</b>

The B3 and B8 oil fields have the greatest theoretical storage potential with 4.75Mt and 3.63Mt respectively based on the limited available information for the Polish offshore sector of the Baltic Sea. Detailed field data from the Genciai, Nausodis & Kretinga fields show a combined theoretical storage capacity of 1.86Mt.

All the fields in Lithuania are onshore, this implies 3 structures from the 7 described in table 20 are onshore and 41.52% of the storage capacity is onshore for the detailed hydrocarbon fields class.

#### 6.4.3 Saline Aquifer Regional Bulk Storage Potential:

The regional saline aquifer bulk storage assessments show the highest theoretical storage potential with a combined total of 18,145 Mt. The largest proportion of this is the generic regional estimated CO<sub>2</sub> storage potential for the Cambrian below 900m which is 16,221Mt of the 18,145 Mt total. The additional 1,923Mt theoretical storage capacity has been calculated for the area of the Dalders Monocline. While both of these numbers are encouraging, more data on reservoir thickness, porosity and FVFs across the regional Cambrian reservoir target and better definition from seismic of the 19,634km<sup>2</sup> extent of the Dalders Monocline is required as the current estimates are based only on the values observed in the P6-1 and B-9 wells.

**Table 21 Regional Saline Aquifer Theoretical Storage Capacity**

Saline Aquifer Bulk - Storage Potential	Estimated CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
<b>Cambrian below 900m</b>	<b>16,221.56</b>
<b>Dalders Monocline</b>	<b>1,923.55</b>

The confidence in these calculated storage capacity calculations was improved significantly by the inclusion of the LEGMC Cambrian structure map and fault line data resulting in accurate boundaries for the individual structure being selected.

#### 6.4.4 Saline Aquifer Field Storage Potential:

A field storage potential calculation for four Middle Cambrian sandstones structures in the Dalders structure shows a total theoretical storage capacity of 127.91Mt.

The combined total of the seven bulk trap assessments in the Latvian offshore, the Kaliningrad fields and the Dalders structure represent a theoretical storage capacity of 780.35 Mt with the highest values recorded in the E23, the combined E12-E13-E2-D10 structure and Dalders structure with 266.05 Mt, 144.09 Mt and 127.91 Mt respectively (Table 22).

**Table 22 Saline Aquifer Field Theoretical Storage Capacity**

Structure Name	Saline Aquifer Field CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)	Structure Name	Saline Aquifer Field CO <sub>2</sub> Storage Capacity (10 <sup>6</sup> tonnes)
<b>Dalders Structure</b>	127.91	Cheremuhovo	0.2769
		Hrustalninskaya	0.3474
<b>LATVIA</b>		Lesnaya	1.1017
<b>E5</b>	36.31	Volodarovskaya	0.2493
<b>E6</b>	35.26	Ključevaja	1.1749
<b>E7</b>	18.01	Gusevskaya	1.5629
<b>E12-E2-13-D10</b>	144.09	Aleshkinskoe	0.251
<b>E17</b>	104.70	Deyminskoe	1.1097
<b>P4</b>	29.03	Western Krasnoborskoe (+ south)	2.5817
<b>E23</b>	266.05	Krasnoborskoe	2.5045
		Malinovskoe (North & South)	3.0772
<b>KALININGRAD</b>		Northern Krasnoborskoe	0.0545
<b>Bobruisk</b>	0.7208	Semenovskoe	0.1409
<b>Bolshakovskaya-2</b>	0.1901	Ushakovskoe (+ west)	3.6508
		<b>TOTAL</b>	<b>780.35</b>

The assessment for the seven individual Latvian offshore closures is based on formation data obtained from summarised information from the E6-1, E7-1 and P6 boreholes including formation pressure data recorded during the testing operations. The outline of the structures has been mapped based on 1:25,000 and 1:50,000 digital LEGMC data Top Cambrian depth structure maps and fault data. The assessment demonstrates that structures with CO<sub>2</sub> storage capacity > 100Mt are present in the Latvian offshore region with the E23, E17 and combined E12 structures of particular interest. Estimates of the NG ratios and average porosity values are based on data from the E6-1 and E7-1 wells. Further data from future exploration drilling and testing of the offshore Latvian structures should be used to confirm the porosity, NG ratios as well as formation temperature and pressure data and further increase the confidence in the theoretical storage capacity calculations.

In Kaliningrad, 16 saline aquifer structures are described based on detailed data supplied by VNIGRI. The volumes and the NG ratios of the remaining eight structures are based on Otmas (2011), CO<sub>2</sub> density and the average reservoir thickness is based on well data provided by VNIGRI.

## 7.0 STATIC MODEL:

Based on the well and Cambrian depth structure map data available for the Baltic Sea area, four areas of interest have been identified for further study as CO<sub>2</sub> storage sites. This section describes the methodology used to develop the static model for the selected structures shown in Table 23.

**Table 23 Static Model Structure Sizes**

	Area in km <sup>2</sup>	Area in m <sup>2</sup>
<b>Dalders Structure</b>	161	160,784,104
<b>Dalders Monocline</b>	72,169	72,169,300,000
<b>E-6 Structure</b>	26	26,368,579
<b>E-7 Structure</b>	26	26,298,247

For the four areas of interest, the depth of the Top of the Middle Cambrian sandstone reservoir has been selected as the reference layer for the static models as it extends throughout the whole Baltic Sea region. The Middle Cambrian is composed of several sandstone (SST) intervals of which the top one is the main reservoir, known as the Faludden SST (Sweden), Paradoxides Paradoxissimus (Poland) and Deimena SST (Latvia and Lithuania). The three additional surfaces are the bottom of the Middle Cambrian, the top of the Alum Shale (Upper Cambrian) and the top of the Ordovician. The Alum Shale and Ordovician act as cap rocks overlying the Faludden SST reservoir. Details of the available data are summarised in Table 24 below.

**Table 24 Depth of the Top Ordovician, Top Alum Shale, Top Middle Cambrian, Bottom Cambrian, Thickness Ordovician, Thickness Alums Shale and Thickness Faludden SST from well data (m.b.R.T.).**

	Top Ordovician	Top Alum Shale	Top Middle Cambrian	Thickness Ordovician	Thickness Alum Shale	Thickness Faludden SST
<b>Dalders Monocline</b>						
<b>B-3</b>	679	736	742	57	6	30
<b>B-3A</b>	-	767	771	-	4	32
<b>B-5</b>	633	713	750	80	37	27
<b>B-7</b>	751.1	823.5	829.6	72.4	6.1	41
<b>B-9</b>	928.2	994.6	998.4	66.4	3.8	48.1
<b>B-10</b>	433	439	522	-	6	22.6
<b>B-11</b>	688.8	-	773.2	84.4	0	49.8
<b>B-12</b>	463.9	-	569.3	105.4	0	-
<b>BO-13</b>	597.4	-	689	91.6	0	33
<b>BO-21</b>	564.5	-	688.7	124.2	0	29.8
<b>P6</b>	1181	-	1254	73	0	83
<b>B6-1</b>	1334	1410	1431	76	21	69.5
<b>E-6 Structure</b>						
<b>E6-1</b>	729	871.5	875	142.5	3.5	53
<b>E-7 Structure</b>						
<b>E7-1</b>	1256	1378.9	1389	122.9	10.1	57

Other Locations						
D1-1	2256		2338	82	0	-
Yoldia-1	703	753	783	50	31	59

The methodology used to compile the individual static models and the assumptions made are described below.

## 7.1 Dalders Monocline

### 7.1.1 Principal data set used:

Digitised A0 Top & Base Cambrian Depth Map (1:1,000,000) *Source: LO\_G report*

### 7.1.2 Assumption relating to the Top Cambrian:

The depth of the top Cambrian is based on 17 wells throughout the Dalders Monocline. The wells are located south and east of Gotland in Swedish territorial water (12 wells), close to the southernmost boundary of the Dalders Monocline in Polish territorial waters (4 wells) and in offshore Latvia (1 well). The top Cambrian map is based on the base of the Cambrian map from the LO\_G report and the thickness of the Cambrian from Ūsaiytė (2000).

### 7.1.3 Interpolation of the Top Cambrian Layer:

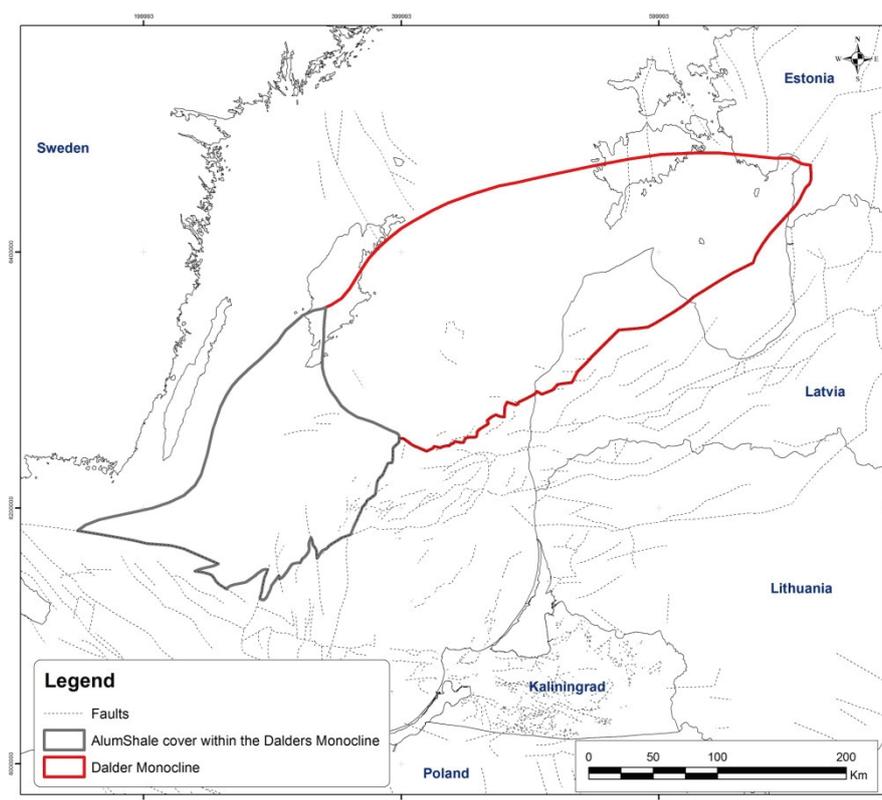
Digitised isolines from the original map were used for the interpolation using the Determination of Earth Surface Structures (DEST) algorithm (Favalli *et al.*, 2004) on a square grid of 1,000m\*1,000m. Figure 12 below shows the surface of the Top Cambrian in the Dalders Monocline.

### 7.1.4 Determination of the Base Faludden Sandstone Layer:

The thickness of the Faludden SST was determined using the available wells in and around the Dalders monocline in offshore Sweden, offshore and onshore Poland as well as offshore and onshore Latvia (see Table 24). The thickness values in these wells show that the thickest reservoir unit is located offshore Latvia (83m in the P6 well), decreasing toward the northwest with values reaching 25m offshore Gotland. The other values observed in the Monocline suggest the thickness varies between 30m and 70m. An additional constraint to the thickness is the Faludden SST map from Erlström *et. al* (2011) that indicates the limit of the Faludden SST. The base of the Faludden SST has been determined based on the thickness values in the wells, the limits of the Faludden SST (0m values along the northwest boundary) and the top of the Middle Cambrian.

### 7.1.5 Determination of the Top Alum Shale:

The thickness of the Alum shale was determined using well data from the Baltic Sea region. The Alum shale does not cover the whole Dalders Monocline and only overlies the reservoir in the southernmost half of the monocline. The limit of the Alum Shale within the Dalders Monocline follows a southeast northwest line that starts from south Gotland (Figure 11). The thickness of the Alum shale decreases from 20m in the Polish offshore to only a few meters in the Latvian and Swedish offshore.



**Figure 11 Boundaries of the Dalders Monocline (red polygon) and area covered by the Alum Shale within the Dalders Monocline (grey Polygon – OPAB, 2011).**

#### **7.1.6 Determination of the Top Ordovician:**

The thickness of the Ordovician follows a general northeast-southwest trend with low values recorded in the Sweden sector and increasing in offshore Poland and onshore Latvia. The thickness remains relatively low along a northwest-southeast trend between the southern part of offshore Sweden and offshore Kaliningrad. Ūsaitytė (2000), maps the thickness of the Ordovician with low values of less than 80m in the central part of the Dalders monocline, reaching 200m in the southern part of onshore Latvia. These values are supported by Ordovician formation thickness values recorded in offshore wells.

#### **7.1.7 Boundary of the Dalders Monocline:**

The northern boundary of the Dalders monocline is controlled by the limit of the Faludden Sandstone in Sweden (Erlström et al, 2011) and the Middle Cambrian in Poland (Modliński and Podhalańska, 2010) and Estonia (Raukas and Teedumäe, 1997). The southern boundary is controlled by the major faults to the north of the Liepaja Saldus Ridge.

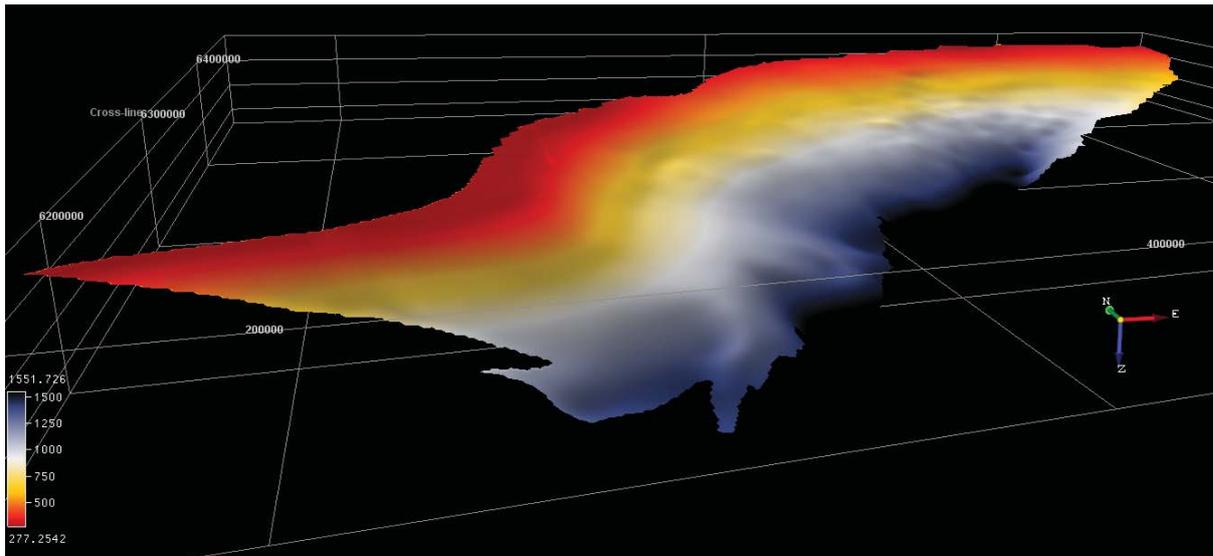


Figure 12 Top Cambrian Layers of the Dalders Monocline.

### 7.1.8 Porosity and Permeability in the Dalders Monocline:

The porosity of the Middle Cambrian in the Monocline was interpolated using effective porosity values measured in core samples from offshore wells. A general trend as low as 3% offshore Poland, increasing up to 20% in Latvia is observed. A low anomalous value of 12% is noticeable in the well P6 located in the central part of the Dalders Monocline, which could be due to the local depositional environment.

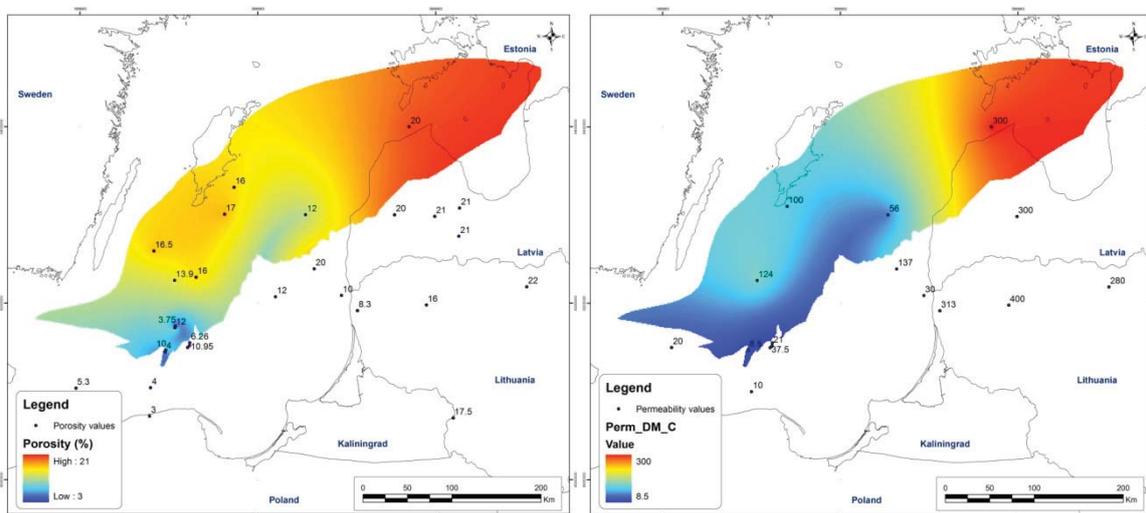


Figure 13 Porosity (to the left) and Permeability (to the right) of the Dalders Monocline.

The permeability of the Middle Cambrian in the Dalders Monocline has been defined using permeability values from measurements in wells and core samples. The trend is similar to that observed for the porosity with low values in the southwest and higher values in the northeast. The lowest value is 10mD in the B16 well (offshore Poland) and a maximum of 400mD in the Syderiai structure (onshore Lithuania).

## 7.2 Dalders Structure

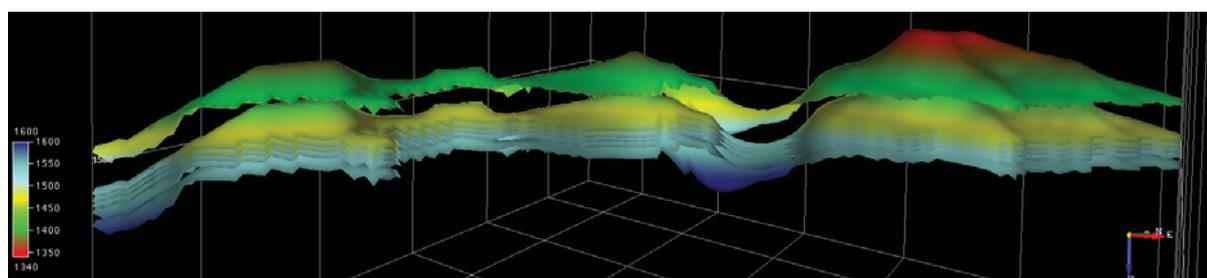
The static model for the Dalders structure was developed based on the lithofacies distributions of the Middle Cambrian sandstone unit observed in the B3 field in the Polish offshore sector. This was considered to be the best analogue to use for reservoir heterogeneity in the Dalders Structure and was used to map individual lithological sub-layers within the Middle Cambrian reservoir section. Well data from the B3 structure (B3-1, B3-2 and B3-3) were used to create five sub-layers.

### 7.2.1 *Principal data set used:*

Digitised Dalders Middle Cambrian Depth Map (Enclosure 21)      Source (AMOCO, 1995)

### 7.2.2 *Interpolation of the Top Cambrian Layer:*

Digitised isolines from the original map were used for the interpolation using the DEST algorithm on a square grid of 200m\*200m. The top Surface in Figure 14 below shows the Top of the Middle Cambrian in the Dalders Structure.



**Figure 14** Middle Cambrian Layers of the Dalders structure.

### 7.2.3 *Determination of the Base of the Middle Cambrian Layer:*

The total thickness of the Middle Cambrian is 100m, this is based on the values from the B-9 (147m) and E7-1 (97m) wells, which are the closest wells to the Dalders Structure. The sub-layers have been defined using the logs from the wells in the B3 structure (located in the northern part of the offshore Poland).

The total Middle Cambrian thickness in the B3 well is 50m. For this reason the thickness of the individual sub-layer was doubled to obtain consistent results with the anticipated Middle Cambrian values in the Dalders Structure.

The individual sub-layer thicknesses and the related lithologies are presented in Table 25 and show a main sandstone reservoir at the top (i.e. the Faludden SST reservoir) with a thickness of 56m, which is in agreement with the Faludden SST thickness values in the B-9 (48.1) and E7-1 (57) wells. Given the extension of the Dalders Structure, the thickness has been considered as constant over the whole area. Figure 14 show the layers of the Dalders Structure.

**Table 25 Sub-layers and their lithology for the Dalders Structure.**

Layer	Thickness (m)	Lithology
Middle Cambrian 1	56	Sandstone with shale influence
Middle Cambrian 2	10	Sandstone
Middle Cambrian 3	7	Sandstone with silt/shale
Middle Cambrian 4	9	Sandstone
Middle Cambrian 5	18	Sandstone with high shale content

**7.2.4 Boundary of the Dalders Structure:**

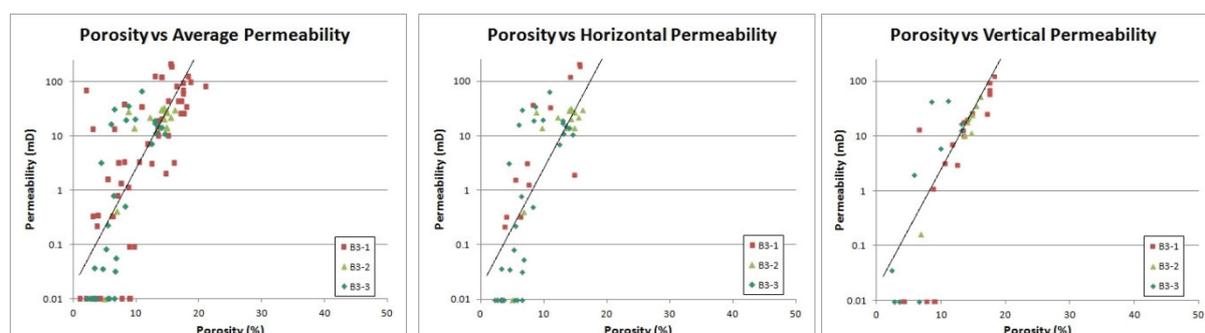
The boundary of the Dalders Structure was determined using the mapped fault structures to the north and the 1,460m Middle Cambrian contour.

**7.2.5 Permeability and Porosity of the Dalders Structure:**

The porosity and permeability values representing the heterogeneity of the reservoir are compiled from detailed measurements of the porosity and the permeability from core (i.e. effective porosity and permeability) in the B3 field wells (see Figure 15). Both porosity and permeability have been assigned for the B3-1\*, B3-2\* and B3-3\* synthetic wells created in the Dalders Structure. This information is based on the well recorded from the B3 field.

B3-1\* was used to define the southern apex of the Dalders Structure, B3-2\* the central part of the structure with B3-3\* defining the northern apex.

Table 26 demonstrates the porosity and the permeability values for each well that have been used for the interpolation of the sub-layer properties for the whole structure.



**Figure 15 Porosity vs Permeability from the three wells in the B3 structure.**

**Table 26 Porosity and permeability of the defined sub-layers in the Dalders Structure.**

Porosity (%)	B3-1	B3-2	B3-3	Permeability (mD)	B3-1	B3-2	B3-3
Middle Cambrian 1	10	8	5	Middle Cambrian 1	30	12	12
Middle Cambrian 2	18	12	4	Middle Cambrian 2	70	20	0.01
Middle Cambrian 3	10	15	8	Middle Cambrian 3	30	25	6
Middle Cambrian 4	16	15	14	Middle Cambrian 4	50	20	13
Middle Cambrian 5	8	5	6	Middle Cambrian 5	40	1	1

## 7.3 E6 Structure

### 7.3.1 *Principal data set used:*

Digital E6 Top Cambrian Depth structure contours and fault structure shapefiles (LEGMC, Latvia).

### 7.3.2 *Interpolation of the Top Cambrian Layer:*

Top Cambrian Depth structure contours were used for the interpolation using the Determination of Earth Surface Structures (DEST) algorithm on a square grid of 50m\*50m. Figure 16 below shows the surface of the Top Cambrian in the E6 structure.

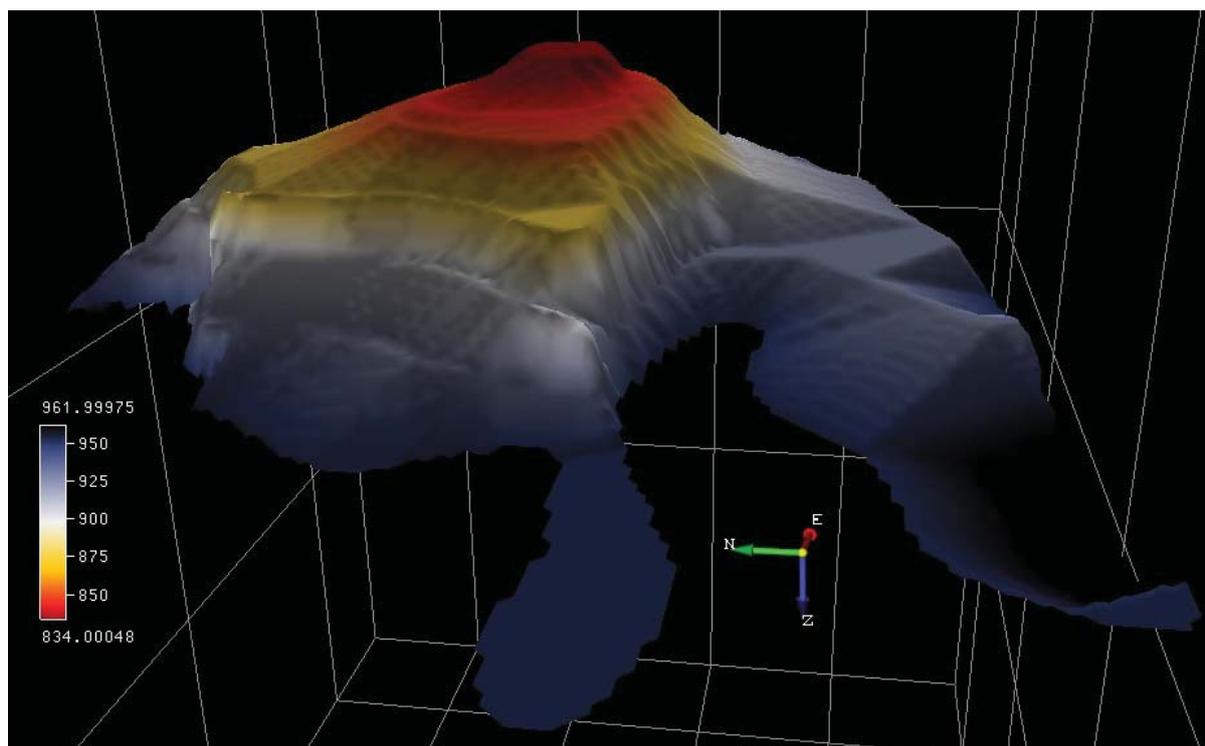


Figure 16 Top Cambrian Layers of the E6 Structure.

### 7.3.3 *Determination of the Base Faludden Sandstone Layer:*

The thickness of the Faludden SST based on the thickness recorded in the E6-1 well and a constant value of 57m for the E6 structure.

### 7.3.4 *Boundary of the E6 Structure:*

The boundary of the E6 structure was determined using the mapped fault structures and the 1425m contour.

## 7.4 E7 Structure

### 7.4.1 *Principal data set used:*

Digital E7 Top Cambrian Depth structure contours and fault structure shapefiles (LEGMC, Latvia).

### 7.4.2 *Interpolation of the Top Cambrian Layer:*

Top Cambrian Depth structure contours were used for the interpolation using the DEST algorithm on a square grid of 50m\*50m. Figure 17 below shows the surface of the Top Cambrian in the E7 structure.

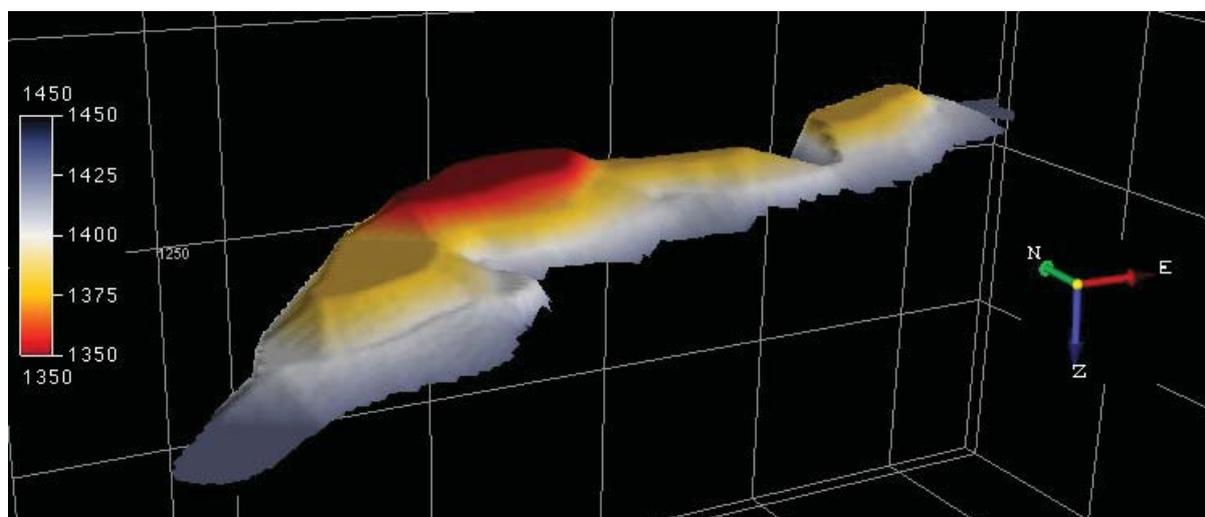


Figure 17 Top Cambrian Layers of the E7 structure.

### 7.4.3 *Determination of the Base Faludden Sandstone Layer:*

The thickness of the Faludden SST based on the thickness recorded in the E7-1 well and a constant value of 53m for the all E7 structure.

### 7.4.4 *Boundary of the E6 Structure:*

The boundary of the E6 structure was determined using the mapped fault structures and the 950m contour.

### 7.4.5 *Conclusions of the Static Modelling*

The Dalders Monocline and the Dalders Structure were selected for dynamic modelling. Both structures are large enough for industrial scale CO<sub>2</sub> storage. The Dalders Structure is also potentially a target for hydrocarbon exploration. The dynamic modelling is discussed in Section 9 below.

## 8.0 SEALING INTEGRITY

### 8.1 Methodology

The seal integrity study investigates basic overburden properties above the Middle Cambrian reservoir including stratigraphy, lithology and thickness as well as the nature of any faulting and fracturing observed in the two candidate structures for CO<sub>2</sub> storage. Favourable overburden properties may include the presence of shallow aquifers that could, through monitoring, give early warning of upward CO<sub>2</sub> migration (Chadwick, 2008).

There is a significant thickness of overburden composed of low permeability argillaceous lithologies that exceed 800m overlying the two target storage sites. These cap rocks are sufficient to contain CO<sub>2</sub> within the underlying Middle Cambrian aquifer. Where the cap rocks lack faulting and have low structural dips (which means that most of the cap rock succession is in direct contact with the seabed), the overburden will form a satisfactory regional seal. Results from a research cruise undertaken by the University of Gdansk over the B3 field were investigated as a possible analogue for the Dalders Structure (Sokołowski, A., Tęgowski, J. 2012). However, differences between the geological structure and stratigraphy of both sites, highlights the possible limitations of such a correlation.

The seal integrity study also assesses the leakage risk from pathways other than faults such as high permeability sediment stringers in the immediate overburden by examining shallow gas occurrence as indicators of previous or ongoing gas leakage.

In addition to physical trapping and structural traps CO<sub>2</sub> can be trapped by dissolution in the aquifer or trapped as residual gas. A longer migration distance towards a potential leak point would imply a greater degree of CO<sub>2</sub> trapping by dissolution and residual gas trapping. Before CO<sub>2</sub> can make its way out of the aquifer to surface, the residual gas trapping and dissolution alone may secure all of the CO<sub>2</sub> to be stored (Qiang Xu, 2009).

With respect to cap rock integrity, one would not expect major pathways for CO<sub>2</sub> migration along fault plans unless the complete cap rock is penetrated by a single fault. This can be identified from the existing seismic data. Due to high confining stresses at depths greater than 1,000m it can be expected that faults are closed and that shear zones would be filled with sealing debris of the sheared wall rock. Fault analysis using 3D seismic mapping should be used to fully evaluate the sealing potential of faults including clay smear and fault gauge ratio determinations.

### 8.2 Sealing Capacity Study Area

The study area is defined as previously mapped Palaeozoic sedimentary basins in the Baltic Sea Area, as described in the document *Geology and hydrocarbon prospects of the Paleozoic in the Baltic region*, 1993 by Brangulis, Kanev, Margulis and Pomerantseva (**Error! Reference source not found.** 1).

The report assesses the sealing capacity of the overburden above potential reservoirs for geological storage of carbon dioxide (CO<sub>2</sub>) in sedimentary basins in the Baltic Sea area. The thick Middle Cambrian contains sandstone and limestone aquifers that could store CO<sub>2</sub> that are sealed by shale and claystone aquitards (**Figure 18**).

The area of the Baltic Sea Basin is about 200,000km<sup>2</sup>. There is a 100-150m thick Lower to Middle Cambrian sandstone that is a potential reservoir for CO<sub>2</sub> storage (**Figure 3**). The overlying Ordovician rocks comprise interbedded sand and shale members including the Alum Shale. This is followed by interbedded shale and limestone including shallow shelf carbonate rocks. Further limestone and shale was deposited in the Silurian. In the south west graptolitic shales are found.

The shales grade to the northeast into marls, limestone, clays and shoal carbonates facies with barrier reefs. The upper part of the Caledonian sedimentary sequence is composed of lagoonal, continental deposits. Within this sequence the Cambrian and Devonian sandstones and the Ordovician and Silurian carbonates have the reservoir potential to store CO<sub>2</sub>.

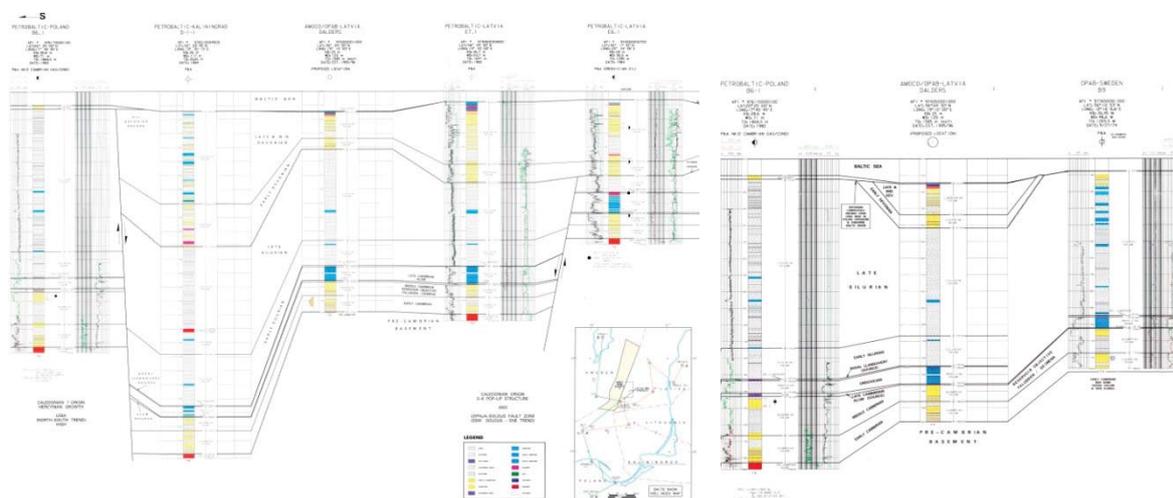
The offshore Dalders Structure (Figure 2 2), which straddles Swedish, Lithuanian and Latvian territory has been identified as a potential site for storage (Svenska Petroleum Exploration OPAB, 2010). Associated with the Dalders Structure is the Dalders Monocline that extends NW to Gotland in Sweden. While storage in confined aquifers and closed structures is the preferred CO<sub>2</sub> sequestration mechanism ( e.g. in the CCS-directive from the EC), it would significantly increase the potential of aquifers offshore Sweden if it can be shown theoretically and by demonstration and monitoring projects that CO<sub>2</sub> can be trapped in monoclinal structures (Erlstrom, 2008).

### 8.3 Sealing Integrity Results

#### 8.3.1 Introduction

The CO<sub>2</sub> storage location, the Dalders Monocline and the Dalders structure, contain Middle Cambrian reservoir formations covered by a thick sealing overburden of Upper Cambrian to Lower Ordovician shales, Ordovician marls, claystones and mudstone and most importantly a thick complex of Silurian shales. The effectiveness of the sealing properties of these formations and their relationships to faults structures were examined with respect to the potential of leakage and migration of CO<sub>2</sub>.

The cap rock suitability assessment used wireline logs, from both Swedish and Polish wells and previous seal integrity assessments completed as part of hydrocarbon prospectivity studies (Donoho and Hart, 1996).



**Figure 18 Baltic Basin Well Correlation (Donoho, 1996).**

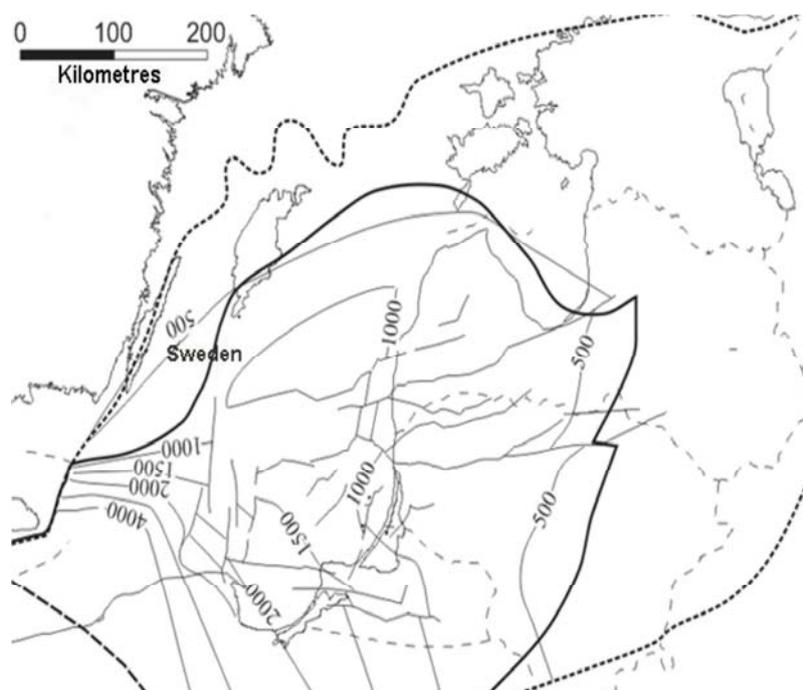
The petrophysical properties of the individual stratigraphic units derived from available wireline log data as well as petrophysical properties measured from cored samples are summarised in Table 27 below.

**Table 27 Porosity and permeability of sealing formations from the Central Baltic Sea regions**

Latvian Offshore Data	E7-1				P6-1			
	Depth (m.b.S.L)		Porosity	Permeability	Depth (m.b.S.L)		Porosity	Permeability
	Top	Base	(%)	(mD)	Top	Base	(%)	(mD)
<b>SILURIAN</b>	657	1253			480	1173	10.6	0.09
<b>ORDOVICIAN</b>	1256	1379	6.2	0.08	1180	1248	3.9	0.45
Swedish Offshore Data	B-3A				B-9			
	Depth (m.b.S.L)		Porosity	Permeability	Depth (m.b.S.L)		Porosity	Permeability
	Top	Base	(%)	(mD)	Top	Base	(%)	(mD)
<b>SILURIAN</b>	77	686			48.6	928		
<b>ORDOVICIAN</b>	686	767	< 1		928	995		
	BO-12				B-7			
	Depth (m.b.S.L)		Porosity	Permeability	Depth (m.b.S.L)		Porosity	Permeability
	Top	Base	(%)	(mD)	Top	Base	(%)	(mD)
<b>SILURIAN</b>	118	464			50.1	751		
<b>ORDOVICIAN</b>	464	569	< 3		751	824	< 3	

### 8.3.2 Cap Rocks

Two stratigraphic units act as seal to the Middle Cambrian reservoir in both the Dalders Structure and the Dalders Monocline. These include Ordovician shaly carbonates and Silurian successions that act as basin-scale aquitards. The overall thickness of the Ordovician and Silurian deposits increases towards the south and south-west reaching a maximum thickness of 2,000m along the Polish coast and reaching a maximum combined thickness of between 500m and 1,000m over the Dalders Monocline and Dalders structure (Figure 19).



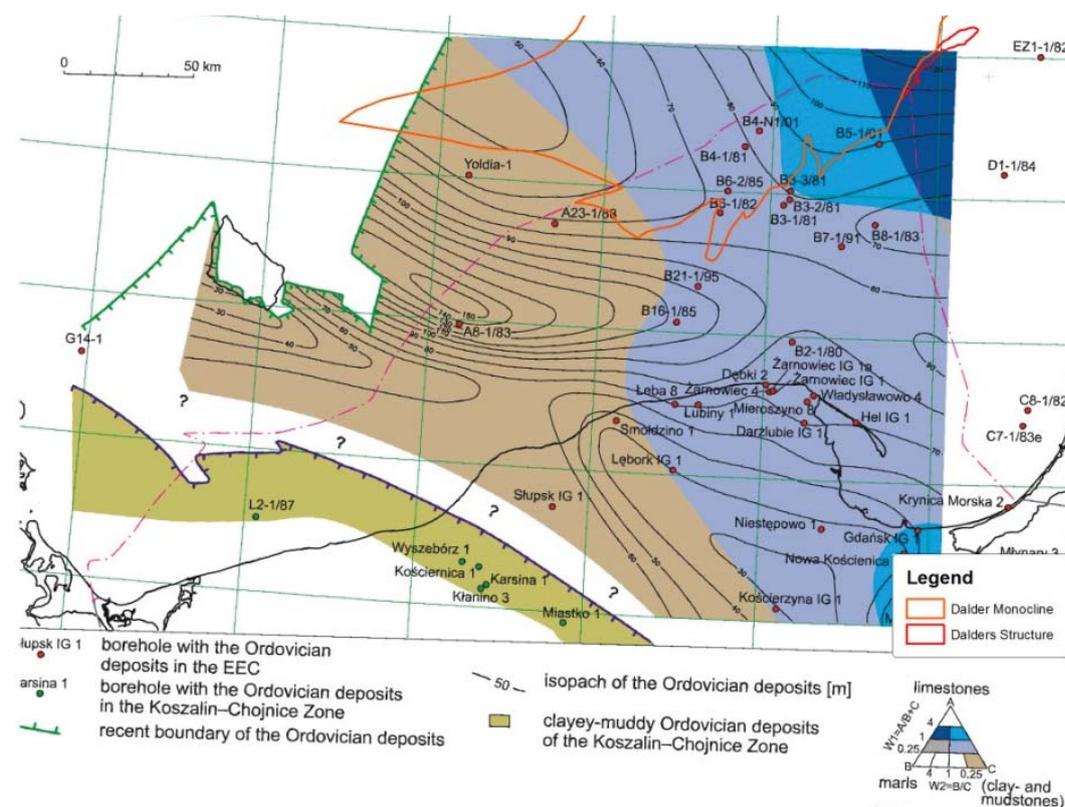
**Figure 19: Isopach map of the Ordovician-Silurian succession. Limit of supercritical CO<sub>2</sub> phase is marked by bold line (bold line). Hatchet line shows the limit of distribution of Ordovician–Silurian deposits (Šliaupiene and Šliaupa, 2012).**

### **8.3.3 Upper Cambrian and Ordovician lithologies**

Ordovician strata have been recognised in several boreholes, on and offshore in the Baltic depression. Several of these have been fully cored, allowing lithostratigraphical unit boundaries and locations to be precisely distinguished and petrophysical parameters determined. The Ordovician is dominated by claystones and mudstones, with limestone's and marls appearing in the middle Ordovician and the uppermost part composed of marls, shaly marls, mudstones and calcareous shale's.

The main lithologies observed in the southern Baltic Sea region range from limestones and marly limestones in the north western part of the southern Baltic Sea with interbedded calcareous claystones and mudstones in the central and south-western region (Figure 20 & Plate 4).

At the proposed CO<sub>2</sub> storage sites in the southern part of the Dalders Monocline south of Gotland and in the Dalders Structure, the Middle Cambrian reservoir is overlain by between 80m and 115m of Ordovician lithologies with good sealing cap rock properties.



**Figure 20 Lithofacies Map of the Ordovician deposits (Modliński and Podhalańska, 2010).**

The Upper Cambrian-Tremadocian claystones of the Piaśnica Formation (Modliński and Podhalańska, 2010), corresponding to the Alum Shale in the offshore Swedish sector of the Baltic Sea, represent the primary sealing formation directly overlying the CO<sub>2</sub> storage reservoir. Extensive work on the sealing potential of the Alum Shale and the overlying Ordovician deposits has been undertaken as part of a hydrocarbon prospectivity assessment (Donoho and Hart, 1996). Field data from the producing B3 field offshore Poland represent a good analogue of the potential sealing conditions expected in the Dalders structure.

Isopach depth structure maps for the Alum Shale derived from slow velocities identified from seismic line data, suggest the formation has an overall thickness of 6m across the extent of the Dalders structure. The slow formation velocities are attributed to the ductile nature of the shales that provide an effective seal over the top of the CO<sub>2</sub> storage structure (Donoho and Hart, 1996). Similar properties are observed in the analogous shales that seal the producing B-3 field in Poland (albeit the shale thickness is greater).

In the B3 and B4 fields offshore Poland the thickness of the Alum Shale is approximately 10m and decreases in thickness towards the north west in the Dalders Monocline where it pinches out south of Gotland Island. Isopach depth structure maps for the Alum Shale show a thickness of between 5m and 6m over the CO<sub>2</sub> storage reservoir in the Dalders Structure.

The Upper Cambrian and Lower Ordovician shales and the thick Ordovician marls and argillaceous carbonates form the cap rock for most of the reservoirs in the Baltic Basin. The Upper Cambrian is dominated by thin interbeds and lenses of, often bioclastic, limestone, with the uppermost Cambrian (shelf muds of the Piaśnica Formation) corresponding to Alum Shale's of Scandinavia. Similar lithologies are described from the offshore Latvian E7-1 and E6-1 wells, where these constitute up to 61m of the Upper Ordovician succession. Porosity and permeability values of a maximum of 7.1 % and 0.12 mD respectively were recorded in the Ordovician of both wells, which indicates impermeable sealing rock properties.

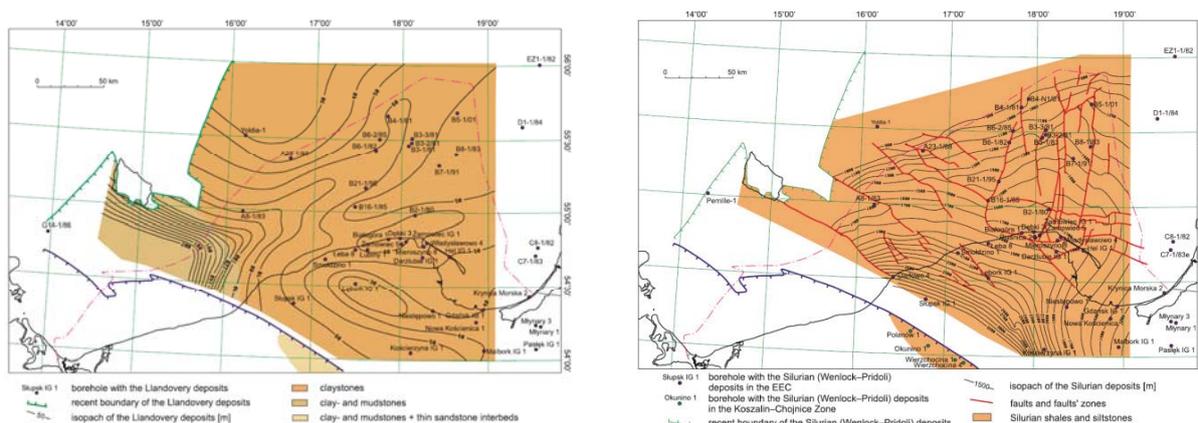
Similar lithologies are observed in the Polish offshore sector with the Lower Ordovician characterised by the Sluchowo Formation comprising black calcareous shales, green shales and interbedded basal conglomerate beds. The lowermost sequence is overlain by the marly limestones of the Kopalino formation and the Sasino and Praturby formation comprising shales and interbedded shales and sandstones that characterise the uppermost part of the Ordovician succession and mark the regressive character of the depositional environment (Modliński and Podhalańska, 2010). The total thickness of the Ordovician sequence in the Polish sector of the Baltic Sea varies between 30m (recorded in the Kościerzyna IG1 borehole and up to 150m in the A8-1/83 borehole (Figure 20). This is a significant thickness of impermeable sealing rocks above the target CO<sub>2</sub> storage reservoir.

Upper Cambrian claystone samples from wells Bartoszyce IG1, Barciany 1 Lesieniec and Pieszkowo 1 provide petrophysical properties highlighting the sealing properties of the Ordovician sequence. Permeability values of 0.01-0.001 mD were obtained (within the limit of accuracy of Oil and Gas Institute equipment - for the model one can take a realistic value of 0.005 mD, so it seems even the lowermost and poorest sealing formation is tight enough). The effective porosity of these samples is of 1-3 %. This corresponds to the good seals within the Mesozoic complexes. Additionally, just above the Upper Cambrian and Ordovician there is a thicker (at least 300-400 m) cap rock complex of Silurian that excludes the vertical migration of the injected CO<sub>2</sub> (Wojcicki and Paczesna, 2012).

#### **8.3.4 Silurian Shales**

The Silurian is characterised by the bending of the western margin of the Baltica plate, the docking of east Avalonia and the progressive advance of the North-German Polish orogen resulting in an extensive period of subsidence and resulting in the deposition of extensive graptolitic shales dominating the sedimentary succession in the western and central parts of the Baltic basin grading to marlstones in the transitional zone and to the carbonate platform in the shallow eastern margin of the Baltic basin (Šliaupienė and Šliaupa, 2012).

The Silurian has been drilled on and offshore, by a large number of boreholes in the Baltic Depression. A 2,245.2m Silurian succession was observed and almost completely cored, in Lębork IG 1 well, allowing precise location of all stage boundaries and their ranges to be determined. The dominant lithologies are thick claystones, mudstones with thin interbeds of fine-grained quartz sandstone (Modliński and Podhalańska, 2010).



**Figure 21 a) Lithofacies Map of Llandovery Deposits ; b) Lithofacies Map of Wenlock-Pridoli Deposits (Modliński and Podhalańska, 2010)**

The lowermost sequence of the Silurian deposits is characterised by the Llandovery aged, bituminous shales of the Paslek Formation (Figure 21a) that reach a maximum thickness of up to 100m in the Polish offshore sector. The Pelplin Formation, dominated by grey, black shales with occasional calcareous and marly limestone interbeds occurs at the base of the Wenlock sequence and reaches a thickness of 400m in the Polish offshore sector. The Pridoli Formation, Kociewie Formation and the Puck Shales formations comprising mainly shales and calcareous siltstones constitute the Upper Silurian Wenlock sequence having a thickness of up to 1,000m in the northern Polish offshore sector (B8-1/38) and increasing in thickness towards the south (Figure 21b).

In the northern part of the Baltic Sea region and the northern section of the Dalders Monocline the thickness of the Llandovery strata varies from a few dozen meters up to 160m in southern Estonian offshore and exceeding 300m adjacent to the Caledonian Deformation Front along the boundaries of the Dalders Monocline (Šliaupiene and Podhalańska, 2012).

### 8.3.5 Discussion

The Ordovician–Silurian shaly package is a reliable cap rock owing to its large thickness and predominance of impermeable lithologies. There is no evident risk from capillary leakage, because the producing hydrocarbon fields in the Cambrian sandstone reservoir overlain by Ordovician carbonates, claystones and mudstones demonstrate that Ordovician cap rock has prevented migration of hydrocarbons from the reservoir.

The possible migration of CO<sub>2</sub> through permeable zones as a result of the interactions between the cap rock and CO<sub>2</sub> is considered negligible due to the extensive thickness of the Ordovician–Silurian aquitard sequence. The risk of migration of CO<sub>2</sub> through carbonate in the sequence is considered as low because of the low porosities (up to 3–4%) and low permeability (<1 mD) values recorded in the Ordovician limestones (Table 27). The extensive thickness of the Silurian succession above the Ordovician would further inhibit any potential CO<sub>2</sub> migration and leakage. The main risk for leakage of CO<sub>2</sub> is via fault structures breaching the cap rock sequence.

The Faludden sandstone reservoir is overlain by a variable thickness of Alum Shale observed from well data as approximately 25m in the south western boundary and thinning towards the northern part of the Monocline north of the B11 well. The Alum Shale is a ductile shale with very effective sealing properties. The absence of the Alum Shale in the northern part of the Monocline connects the Middle Cambrian reservoir with the upper Cambrian sandstones leaving the Ordovician claystones and the overlying Silurian shales as the ultimate top seal.

## 8.4 Fault Structure Leakage Potential and CO<sub>2</sub> Migration

Both the Dalders Structure and the Dalders Monocline have two stratigraphic units acting as seal to the Middle Cambrian reservoir. The lowermost of these units is a thin sequence of Upper Cambrian to Lower Tremadocian Alum Shales that rests directly above the reservoir in both the Dalders structure and the Monocline. The Alum shale sequence is overlain by a series of Ordovician mudstones, siltstones and clays.

The extent of both stratigraphic units and their relationship with mapped large scale and smaller scale structures varies between the Monocline and the Dalders Structure.

Several tectonic events are identified as affecting the sedimentary pile of the Baltic Sea region with the earliest events occurring during the deposition of Vendian and Cambrian sediments in an extensional regime (Šliaupa & Hoth, 2010). There is little evidence of large scale regional faulting occurring during the Cambrian, Ordovician and early Silurian. Minor faulting occurred as a result of the growth of the Ordovician reefs (Kanev *et al.*, 2000). Basin scale tectonic activity developed in the late Silurian and early Devonian times in a north west south east compressional setting and resulted in the development of large scale, E-W and NE-SW striking reverse fault structures. These are concentrated and best observed along the Lepaya - Saldus High and characterise the main bounding structures of the Dalders Monocline and Dalders Structure. The main characteristics observed are steeply dipping fault planes (70°-80°) in a common WNW direction (Šliaupiene and Šliaupa, 2012).

To the south of the Lepaya - Saldus High and in the Leba High, fault structures are coincident with the principal Caledonian fault trends and result in large scale N-S trending fault structures associated with the Polish offshore sector gas fields. In the northern part of the Baltic region smaller scale fault structures with a predominant NW-SE strike are also observed (Plate 4).

Reactivation of most of the regional fault structures described in the Baltic Sea region occurred during the late Carboniferous and Permian stages with the most intense deformation in the SW part of the Baltic Sea adjacent to the Teisseyre–Tornquist Zone (TTZ). This reactivation phase resulted in the development of large scale E-W trending fault structures observed in Gdansk Bay and offshore Kaliningrad.

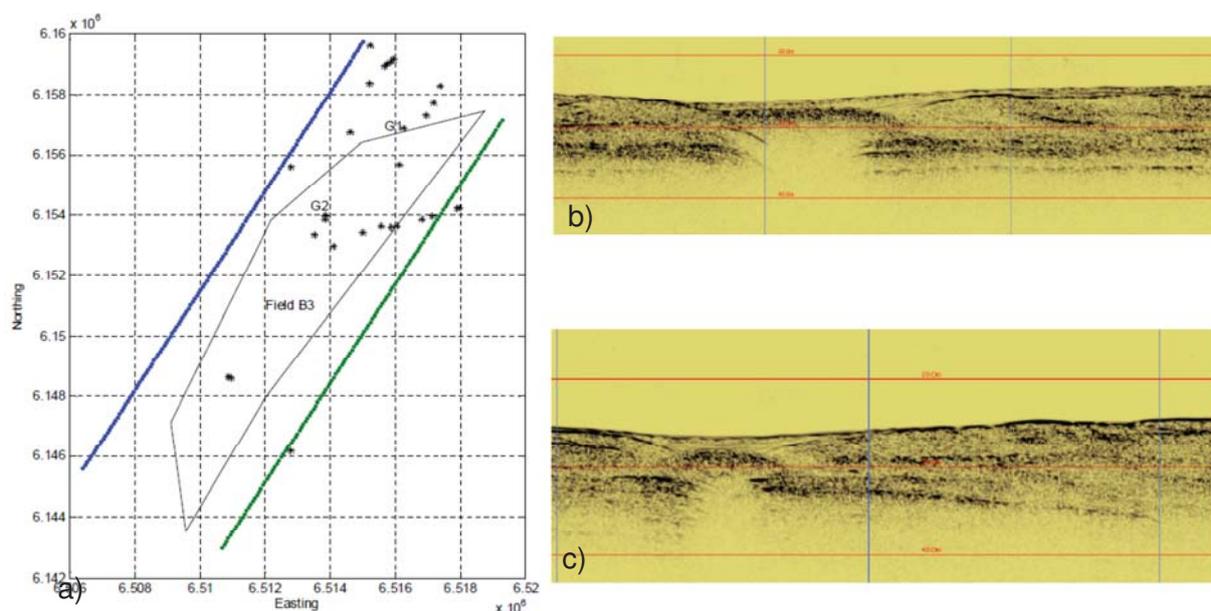
The Caledonian aged fault structures (NE-SW and E-W trending) show simple geometries developed in a compression basin setting in the case of the NE-SW structures and more complex, transpressional flower structures in the case of the E-W faults. Therefore the compressional NE-SW structures are tight and do not represent a risk from the point of view of CO<sub>2</sub> leakage whilst the transpressional E-W structures bear a higher risk (Šliaupiene and Šliaupa, 2012).

Two large scale, deep seated, NE-SW trending regional fault structures characterise the northern boundary of the Dalders Structure and the eastern boundary of the northern section of the Dalders Monocline. Displacement along these structures is estimated to have terminated around late Devonian times coincident with end of the Caledonian Orogeny with little or no evidence of later reactivation that could result in the breaching of the Dalders structure trap (Donoho and Hart, 1996). The absence of fault reactivation is further supported by the observed accumulations of hydrocarbons along fault bound anticline traps such as the B6 field offshore Poland, suggesting the potential leakage of CO<sub>2</sub> up fault structures is likely to be low.

The southern part of the monocline however is characterised by N-S trending structures that extend from offshore Poland to the offshore Swedish section of the Baltic Basin (Plate 4).

The University of Gdansk conducted a research cruise in 2012 to assess both the location of natural gas emissions from shallow and deep geological layers and to investigate the structure of benthic communities and basic geochemical parameters of the sediment in the

B3 area. Several gas diffusion chimneys and bottom sea craters were identified (Figure 22a, Figure 22b and Figure 22c) extending as shallow as 30m below the seabed. These features may indicate possible leakage of gas from the Middle Cambrian reservoir of the B3 field. The orientation of the features suggests a probable correlation with east west trending structures (Sokołowski and Tęgowski, 2012). The features may also be due to the presence of shallow biogenic gas unrelated to gas leakage from the deeper Middle Cambrian reservoir.



**Figure 22 a) Southern Baltic oil field B3 (border depicted by black solid line). Star points show positions of gas diffusion chimneys and bottom sea craters.**

**b) The sea crater and top part of gas diffusion chimney. The position of this structure is visible in Fig.22a as G1.**

**c) The sea crater and top part of gas diffusion chimney. The position of this structure is visible in Fig.22a as G2. (Sokołowski and Tęgowski, 2012)**

A closer analysis of the fault structures mapped in the B3 field and the location of the recorded diffusion chimneys by the Gdansk University research cruise, suggests that these are not on the main fault structure along the western boundary of the B3 field, but that these are associated with secondary fault structure which in some cases display a more E-W component. These structures potentially represent a greater risk for leakage and migration to the surface. Further evidence of potential leakage from E-W trending structures is suggested where these are described as flower structures or complex intersecting fault structures in other parts of the Baltic Basin. These have led to the migration of hydrocarbons from the Cambrian reservoir to the upper Ordovician limestone lithologies as for example in the E6-1 field (Šliaupienė and Šliaupa, 2012). This suggests that careful consideration needs to be given to any small scale faults associated with individual potential structures considered for CO<sub>2</sub> storage or test injection.

Lateral leakage of CO<sub>2</sub> potentially represents a greater risk across fault structures especially where the Middle Cambrian reservoir juxtaposes Ordovician limestones along the northern flanks of the Dalders structure or the Upper Cambrian sandstone lithologies in the northern part of the Dalders Monocline. However, where this juxtaposition has been observed in association with the predominating NE-SW structures across the Baltic Basin, the offsets recorded on the fault planes is greater than thickness of the Cambrian reservoir, leaving the reservoir juxtaposed against thick sequences of Ordovician claystones or Silurian shales (Šliaupienė and Šliaupa, 2012).

Clay smear and capillary pressure analyses from the B-9 (offshore Sweden) and E7-1 wells adjacent to the Dalders structure suggest that the risk of trans-fault leakage is low (Donoho and Hart, 1996). However these data are sparse and may not be representative across the complete Dalders Monocline region particularly in the southern section.

The nearly hydrostatic pressure regime identified in the reservoir and in the producing B3 field, suggests that whilst the reservoir is not overpressured, CO<sub>2</sub> injection rates and pressures will be critical at maintaining the seal integrity around fault structures and to prevent CO<sub>2</sub> leakage and migration.

## 8.5 Well Completion and Integrity

A number of hydrocarbon exploration wells were drilled in the Dalders Monocline during the 1970s and 1980s. Boreholes in the Swedish offshore sector have been plugged and abandoned whilst some well in the southern part of the Monocline in the Polish offshore sector are still in production. Table 28 below summarises available well completion information.

In the case of the plugged and abandoned boreholes the issue of corrosion has to be considered with respect to the potential for CO<sub>2</sub> leakage from the storage reservoir. Therefore, careful monitoring of these wells would be necessary to ensure secure CO<sub>2</sub> storage. In some cases it may be necessary to recomplete the well where it is clear that corrosion or a poor cement job has resulted in a potential leak point from the CO<sub>2</sub> storage reservoir.

**Table 28: Completion Details of Exploration Wells in the Dalders Monocline (Swedish offshore)**

	Well No.	B-3	B-3A	B-7	B-9	B-10	B-11	BO-12	BO-20
<b>Rotary Table Elevation (m)</b>		21.5	20.7	28.2	26.42	25.91	24.99	24.7	25
<b>Date</b>		1974	1973	1974	1974	1976	1976	1976	1976
<b>Casing String (K55 Buttress)</b>	<b>30"</b>	96	70	96.8	93	92.4	113.1	141.4	127
	<b>13 3/8"</b>	290	292	330.5	501	90.8	111.4	193.3	125.3
	<b>9 5/8"</b>					345.9	392.9	407.5	387.5
	<b>TD</b>	1002	966.7	1037.5	1266	535.8	1036.9	818.2	689
<b>Cement Plugs</b>	<b>Top (m)</b>	0	0	0	451	0	300	356	149
	<b>Bottom (m)</b>	56	54	86	551	133	335	420	302
	<b>Top (m)</b>	209	224	315	451	313	340	458	341
	<b>Bottom (m)</b>	320	304	345	551	393*	457	533	438
	<b>Top (m)</b>	662	681	-	-	420	579	567	600
	<b>Bottom (m)</b>	750	762	-	-	480	920	630	690
	<b>Top (m)</b>	-	-	-	-	-	-	700	-
	<b>Bottom (m)</b>	-	-	-	-	-	-	749	-

## 8.6 Conclusions of Seal Integrity Study

A geologically and geometrically suitable site for CO<sub>2</sub> sequestration has been identified in the Dalders Structure and Dalders Monocline. Based on the analysis of the stratigraphic and petrophysical properties of the sealing formation at both sites, the following conclusions have been reached:

- Three possible modes of seal failure have been identified for the Dalders Structure, these include top seal failure, migration up the bounding fault planes and leakage across fault plane, with the former two considered to be the lowest risk.
- The potential for top seal failure across the Baltic Basin has been considered in detail as part of this study. Whilst a relatively thin cover of Alum Shale directly overlies the

reservoir in both the Dalders Structure and the Dalders Monocline, a significant thickness of between 500m and 1,000m of combined Ordovician and Silurian deposits comprising mainly shales and claystones act as the ultimate seals. The potential for top seal failure is therefore considered low.

- Seal failure resulting in leakage across fault planes downthrown Ordovician carbonate lithologies is more likely, however the risk of this is still low when the thickness of the reservoir and large throws along the fault planes are considered.
- The potential for migration of CO<sub>2</sub> along fault planes has been considered in the context of the different structural events recorded in the Baltic Basin, the trends of the faults structures and their relationships with the reservoir and seals identified in the Dalders Structure and Monocline. The main boundaries of both structures are considered to be sealed leaving little or no risk of upward leakage or migration of CO<sub>2</sub> along fault planes.

Evidence from analogous fields in the offshore Polish sector demonstrates that smaller scale cross cutting fault structures with particular E-W and NW-SE orientations) are likely to be open. These are associated with the development of gas chimneys and the upward migration of hydrocarbons from the Cambrian reservoir to overlying Ordovician limestones. However there is no current evidence for smaller scale cross cutting faults on the Dalders Structure.

## 8.7 Recommendations

The principal recommendations for risk assessment of the Dalders Structure are as follows:

- A detailed structural study of the Dalders prospect should be conducted to clarify the probable migration pathways. A risk associated with anticlinal traps is the possibility of the build up of a large, vertical column of CO<sub>2</sub>, exerting buoyancy forces on the caprock. (Best practice for the Storage of CO<sub>2</sub> in Saline Aquifers, 2008.) Although a large thickness of caprock with limited faulting has been identified, its structural integrity would need assessing. Long term hydraulic and gas transport testing on the caprock samples initially from existing wells such as the Lebork IG1 onshore Poland should be undertaken in advance of new core samples being obtained from any potential test sites.
- Further seismic interpretation and where necessary, the acquisition of new data will be required in the vicinity of any proposed test injection site to be selected in the Dalders Monocline to map in detail any faults, structures and seismic attributes that remain poorly identified in the Swedish offshore sector. This should confirm the integrity of the sealing formations overlying the reservoir and identify any risk for CO<sub>2</sub> leakage and migration where these structures intersect the Ordovician and Silurian sequences.
- A detailed sensitivity analysis with respect to different injection scenarios, resulting reservoir pressures and their potential impact on the preservation of the seal integrity around fault structures where the cap rock is thinnest needs to be undertaken. The current dynamic reservoir modelling is addressing this to some degree. However the results of these sensitivity analyses will have to integrate with the results of the long term hydraulic and gas transport testing of caprock samples.
- Given the results of the biological and geochemical studies at the B3 site, conducted by the University of Gdansk research cruise, a multibeam seabed survey and sub-bottom profiling would need to be undertaken above any potential CO<sub>2</sub> storage or injection test location.
- Detailed analyses of cored Silurian and Ordovician-upper Cambrian sealing formation from newly drilled exploration wells in the proximity of the Dalders Structure and Monocline need to be reviewed and the results considered in the context of any future proposed test injection site selection and characterisation.

## 9.0 DYNAMIC MODELLING

### 9.1 Introduction

Based on the results of the static model described in Section 7, the Dalders Monocline and the Dalders Structure were selected for dynamic modelling (Plate 2). Both structures are large enough for industrial scale CO<sub>2</sub> sequestration. The Dalders Monocline is a large regional saline aquifer located in the offshore Swedish sector of the Baltic Sea. The Dalders Structure is a fault bounded anticlinal structure located in the central part of the Baltic Sea region that has been the subject of hydrocarbon exploration since the early 1990 but remains undrilled.

The data compiled for the static modelling for both structures comprised existing exploration well data, including core and petrophysical analysis as well as analogous reservoir production data. The dynamic modelling was applied to the static models for both candidate structures.

The University of Uppsala Earth Sciences Department undertook the dynamic modelling of both structures, with a view to assessing the potential of the Middle Cambrian sandstone reservoir and adjacent formations to store CO<sub>2</sub> and to provide a semi-quantitative analysis of the behaviours of the reservoir and CO<sub>2</sub> plume during the course of injection and post-injection periods.

The specific objectives of the modelling included:

- Define the reservoir pressure behaviour with respect to seal integrity for different injection scenarios based on the existing petrophysical reservoir properties and hydrogeological aquifer parameters;
- Calculate the CO<sub>2</sub> plume migration tip speed and distance and the potential for dissolution trapping;
- Identify suitable multi-well injection scenarios in the Dalders Monocline to meet the estimated industrial CO<sub>2</sub> storage requirements identified around the Baltic Sea.

### 9.2 Modelling Methodology

Three separate modelling approaches were used with a view to characterising different injection scenarios for the Dalders Monocline and Dalders Structure. The objectives and inputs of the three different methodologies are briefly described below. A methodology description for the individual techniques, as well as the results obtained for each are discussed in detail in **Appendix A**.

#### 9.2.1 Analytical Modelling:

A sensitivity analysis was undertaken based on the methodology by Mathias, 2010 a & b to determine the optimum CO<sub>2</sub> injection rates that would not result in cap rock breach or fault re-activation. The analysis was based on the static model reservoir characteristics for the Dalders Monocline. In the absence of detailed formation leak off test data, a threshold 50% excess above the formation pressure was assumed. This is equivalent to 150% overpressure during the injection phase.

Table 29 below presents the modelled reservoir properties used and the resulting base case injection scenario for the Dalders Monocline. The sensitivity analysis demonstrates that the injection rates required to maintain the reservoir pressure below 180 bar are strongly controlled by the permeability, reservoir thickness and the number of injection wells. These values were used as reference values for the modelling techniques discussed below.

**Table 29 Sensitive Analysis parameters and base case reservoir properties.**

Property	Minimum Value	Intermediate	Maximum	Base Case
Reservoir Pressure	120 bar			180
Porosity	0.12			
Permeability	20 mD	40 mD	80 mD	40mD
No. of Wells	3	5	7	5
Reservoir Thickness	40 m	50 m	60 m	50 m
Injection Time	50 years			
Injection Rate				0.5 Mt/yr

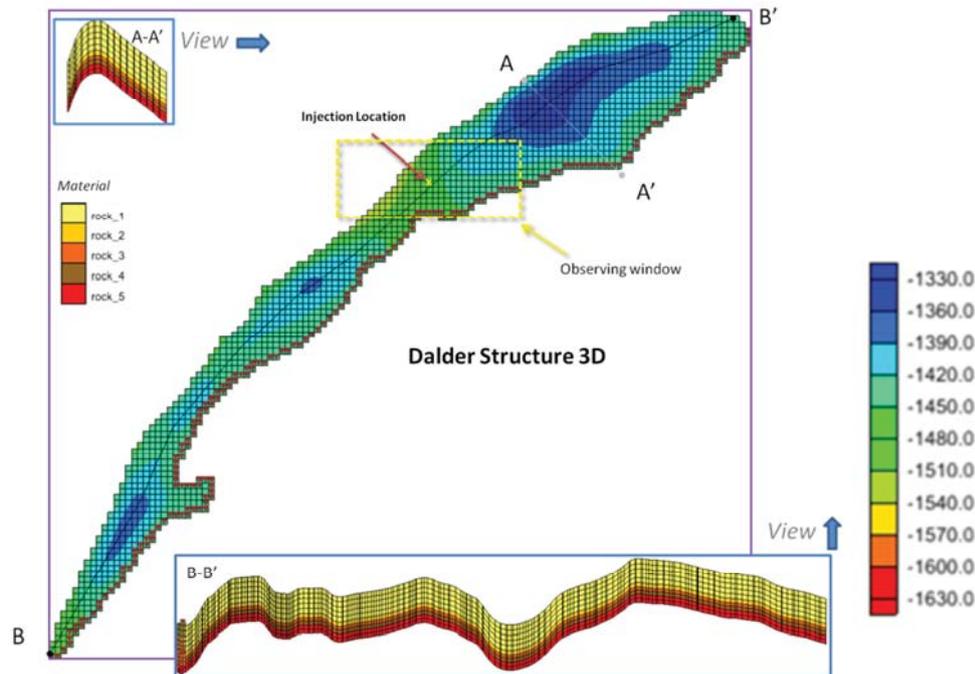
### 9.2.2 TOUGH2 Modelling:

The TOUGH2/ECO2N and TOUGH2MP simulators were used to simulate CO<sub>2</sub> migration in the reservoir (Pruess et.al, 1999; Pruess, 2005) in 3D and pseudo 3D. Several modelling scenarios were used based on the available datasets for reservoir porosity and permeability properties interpolated across the Monocline area, assuming a homogenous reservoir.

An initial model of CO<sub>2</sub> migration was conducted for the entire Monocline region (see boundaries A-B-C in – Plate 3). This model focussed on injection from one well (Inj\_0) whilst two subsequent models focussed on the injection in the southern part of the Dalders Monocline only (A-B'-C) where the Ordovician Alum Shale cap rock provides a seal directly above the top of the reservoir.

The third and last model, of greatest interest to the industrial viability of CO<sub>2</sub> injection in the Dalders Monocline, focussed on potential impacts of pressure build up and CO<sub>2</sub> migration in a multi well injection scenario (Inj\_1, Inj\_2, Inj\_3).

A similar single well model was also conducted for the Dalders Structure (Figure 23). The available information from drilled boreholes close to the structure allowed a heterogeneous reservoir model to be developed, based on analogous lithofacies and reservoir properties observed in the B3 field in the Polish offshore sector, the E7-1 well data offshore Latvia and the B-9 well data from offshore Sweden (Plate 1).



**Figure 23 Dalders Structure - Conceptual model extent, location of the injection well. Heterogeneous reservoir characteristics shown in the colours that indicate the depth as expressed in meters in mean sea level.**

Several different boundary conditions for the Dalders Monocline and the Dalders structure were considered. Based on the available structural data at the time of modelling, the most likely boundary conditions were chosen. These are listed in Table 30 below.

**Table 30 Boundary Conditions for TOUGH 2 Models.**

Dalders Monocline	Boundary Condition	Description
A to B	Open	Hydrostatic Pressure Boundary
A to B'	Open	Hydrostatic Pressure Boundary
A, C to B	Closed	Sealed Regional Scale Fault Structure
<b>Dalders Structure</b>		
B to A to B'	Closed	Sealed Regional Scale Fault Structure
B to A' to B'	Open	Hydrostatic Pressure Boundary

As part of the TOUGH 2 modelling several modelling parameters were used for the different scenarios presented above. Some of the reference values with respect to comparable injection rates for the different models are listed below.

- Irreducible water saturation,  $S_{l,r}$  [-] 0.300
- Residual gas saturation,  $S_{g,r}$  [-] 0.050
- Van-Gnuchten parameter,  $m$  [-] 0.457
- Reference for Leverett scaling on capillary pressure,  $P_{ref}$  [Pa]  $1.98 \times 10^4$
- Reference permeability - *regional Dalders Monocline*,  $k_{ref}$  [mD] 100
- Pore compressibility [Pa<sup>-1</sup>]  $4.5 \times 10^{-10}$

- Brine Salinity (% NaCl) 11.54
- Formation temperature (°C) 50

Several injection rates were considered for the Dalders Monocline and the Dalders Structure models. These are summarised in Table 31 below

Model Domain	Description	No. of Injection Wells	Injection Rates Modelled (MtCO <sub>2</sub> /year)			Injection Location	Injection Time (yrs)	Post Injection Monitoring (yrs)
<b>Dalders Monocline</b>	Regional Model for the entire Dalders Monocline Area	1	3.0			Inj_0	50	1000
<b>Southern Dalders Monocline Area</b>	Southern Dalders Monocline Area	1	1.0			Inj_0	50	1000
	Southern Dalders Monocline Area	1	0.5			Inj_1	50	1000
	Southern Dalders Monocline Area - Multiple Well, Simultaneous Injection	3	0.5	0.5	0.2	Inj_1,2&3	50	1000
<b>Dalders Structure</b>	Single Well Injection into the lowermost part of the reservoir	1	0.3				20	1000
	Single Well Injection into the lowermost part of the reservoir	1	0.5				20	1000

**Table 31 TOUGH2MP Model scenarios and Injection Rates**

The TOUGH2/ECO2N was used to simulate the migration of CO<sub>2</sub> in the Cambrian reservoir within the Dalders Monocline. The model was run using the static model parameters and based on the following assumptions:

- Plume width 1km
- Plume depth 1,200m
- Aquifer slope 0.5
- Variable thickness range from the static model 80m to 5m
- Porosity 0.1
- Brooks-Corey function parameter ( $\lambda$ ) 0.67
- Brine Saturation ( $S_{br}$ ) 0.3
- Residual Gas Saturations ( $S_{gr}$ ) 0.1, 0.2 & 0.3
- Permeability (mD) 30 & 100

### 9.2.3 Vertical Equilibrium Model:

The Vertical Equilibrium model was used to simulate CO<sub>2</sub> spreading and related pressure increase in the Dalders Monocline and Dalders Structure. The modelling technique assumes a vertical equilibrium pressure (Bear, 1972) in the reservoir and enables modelling of variable density and viscosity properties based on different reservoir pressure and temperature conditions. The VEM methodology is less computationally intensive and permits the integration of cap rock topography information. In the case of both the Dalders Monocline and Dalders Structure this was defined as the extent of the Ordovician Alum Shale above the Middle Cambrian reservoir.

Focussed on the inclusion of CO<sub>2</sub> density and viscosity parameters, this technique allows simulation of the thickness and movement of the CO<sub>2</sub> plume tip during the injection and post injection phases.

The modelling domain reservoir parameters were derived from the static model data as for the Tough 2 modelling and the boundary conditions are the same as those presented in Section 9.2.1. The injection and monitoring simulation parameters for the VEM model are outlined in Table 32 below.

**Table 32: VEM Model scenarios and Injection Rates**

Model Domain	Description	No. of Injection Wells	Injection Rates Modelled (MtCO <sub>2</sub> /year)			Injection Location	Injection Time (yrs)	Post Injection Monitoring (yrs)
Southern Dalders Monocline Area	Southern Dalders Monocline Area	1	0.5			Inj_2	50	500
	Southern Dalders Monocline Area - Multiple Well, Simultaneous Injection	3	1	1	1	Inj_1,2&3	50	500
	Southern Dalders Monocline Area - Multiple Well, Simultaneous Injection	3	0.5	0.5	0.5	Inj_1,2&3	50	500
Dalders Structure	Single Well Injection into the lowermost part of the reservoir	1	0.3				50	500

### 9.3 Dynamic Modelling Results

Several scenarios of dynamic modelling were developed for both the Dalders Monocline and the Dalders Structure. The requirements for CO<sub>2</sub> sequestration based on calculated emission from the industrial sector in the Baltic Sea region suggests that the injection of 50Mt of CO<sub>2</sub> per annum over 25 years is needed.

Initial analytical modelling demonstrates that in order to preserve cap integrity and avoid fault reactivation, injection rates should not exceed 0.5Mt per well per year.

This section summarises and discusses the modelled scenarios of CO<sub>2</sub> injection. More in depth analysis and the results of the individual scenarios modelled are available in the dynamic modelling report include in **Appendix A**.

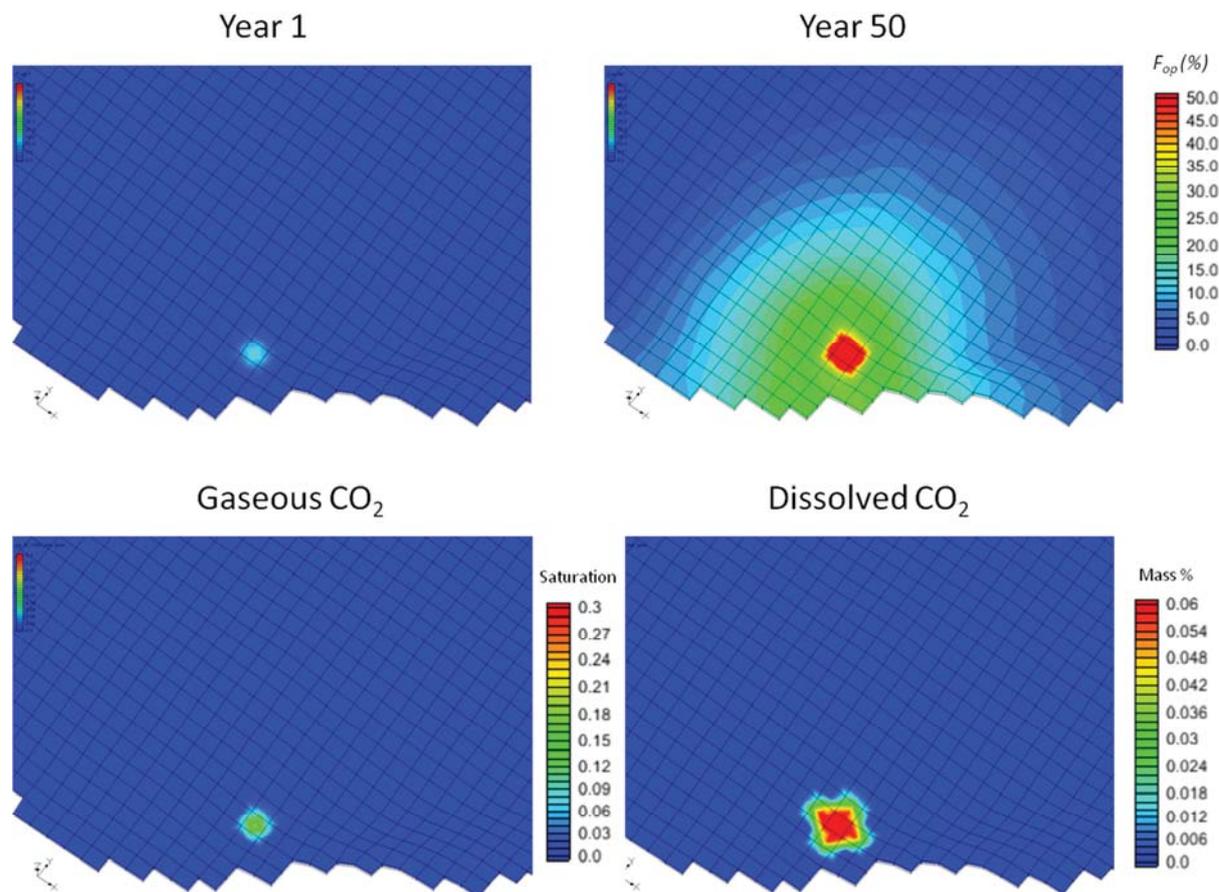
Results for both the Dalders Monocline and the Dalders structure discussed below are focussed on:

- Pressure regime and overpressure ratio calculated
- CO<sub>2</sub> saturation within the reservoir
- CO<sub>2</sub> dissolution
- CO<sub>2</sub> plume migration
- Mobile CO<sub>2</sub> Plume Thickness

#### 9.3.1 Dalders Monocline

Section 9.2.2 presented several dynamic modelling scenarios for the Dalders Monocline. These involved different injection rates as well as single and multi-well injections. The highest single well injection rate of 3Mt/yr was simulated for the entire Monocline domain

based on the injection well being located in an area of higher reservoir quality where higher porosity and permeability values in the order of 15% and 96mD respectively were estimated. The results of this model show that overpressure of 102% is reached at the injection point following the injection period (50 years) with the development of a CO<sub>2</sub> plume of insignificant size with respect to the Dalders Monocline size (Figure 24).



**Figure 24 Percentage overpressure ( $F_{op}$ ) showing pressure build up at years 1 (a) and 50 (b) at the end of injection. CO<sub>2</sub> plume (c) and distribution of dissolved CO<sub>2</sub> (d) at the end of year 1000.**

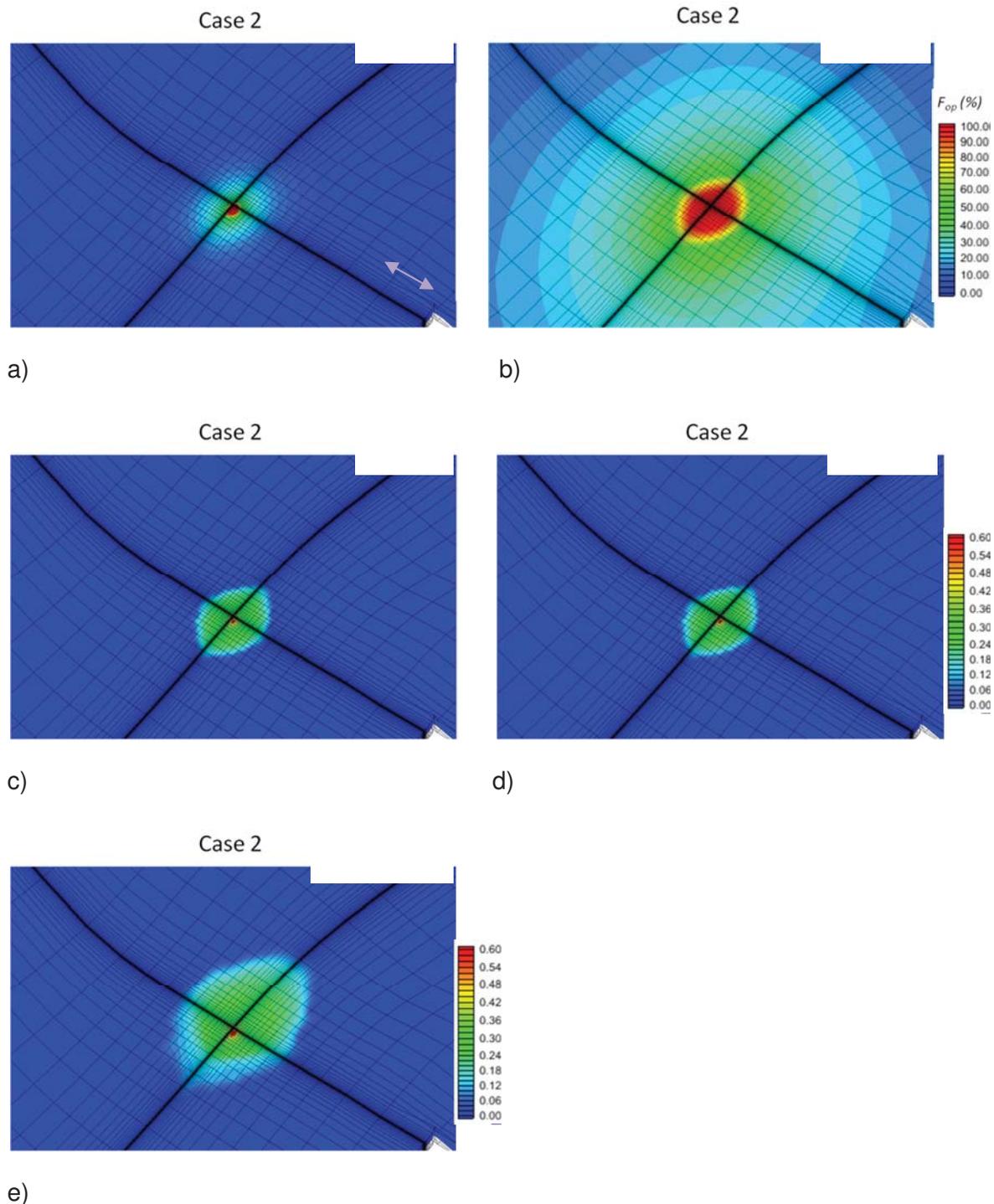
A limited amount of well data with reservoir petrophysical properties is available for the northern part of the Dalders Monocline where the modelled injection well for this scenario is located. For this reason the results of this model can only be considered indicative.

The southern part of the Dalders Monocline, located in the northern part of the Polish offshore sector and southern Swedish offshore sector, was selected because there is more well data including reservoir and cap rock properties, and fault characteristics based on seismic data from operating hydrocarbon fields. Two dynamic modelling scenarios were run for this area, the results of which are discussed in detail below:

- Single well injection at 1 Mt/ye injection rate
- Multiple well injection from 3 wells

*Single Well Injection - 1 Mt/yr:*

Injection simulation at a rate of 1Mt/yr of CO<sub>2</sub> for a period of 50 years in the southern part of the Monocline from a single well resulted in an overpressure of 150% at the injection point (Figure 25a & b).



**Figure 25: Overpressure after 1 year of CO<sub>2</sub> injection (a) and after 50 years of injection (b). CO<sub>2</sub> saturation after 1 year of CO<sub>2</sub> injection (c) and after 50 years of injection (d) and post injection saturation at year 1,000 (e).**

The CO<sub>2</sub> saturation values demonstrate the relatively small size of the CO<sub>2</sub> plume after 50 years of injection (approximately 5km) and the migration of the plume up-dip towards the north east away from the closed south eastern faulted boundary of the Monocline. The

plume size post injection was approximately 18km in length. A similar scenario using a reduced injection of 0.5 Mt/yr for the same well location demonstrated similar results with overpressure build-up of up to 40% at the end of the injection phase with similar up-dip plume migration observed at the end of the modelling phase.

### Multi Well Injection

A multi well simulation was carried out for the southern part of the Monocline area to assess the viability of using multiple injection points for CO<sub>2</sub> injection. Both a TOUGH 2 and VE model were run to simulate injection from wells Inj\_1, Inj\_2 and Inj\_3 (refer to Plate 3). The injection rates in the TOUGH 2 model were 0.5Mt/yr for wells 1 and 2 and 0.2Mt/yr for well 3 due to its close proximity to the southern closed, faulted boundary of the Monocline. The VE model simulations used 0.5Mt/yr from three wells in one simulation and 1Mt/yr for the second.

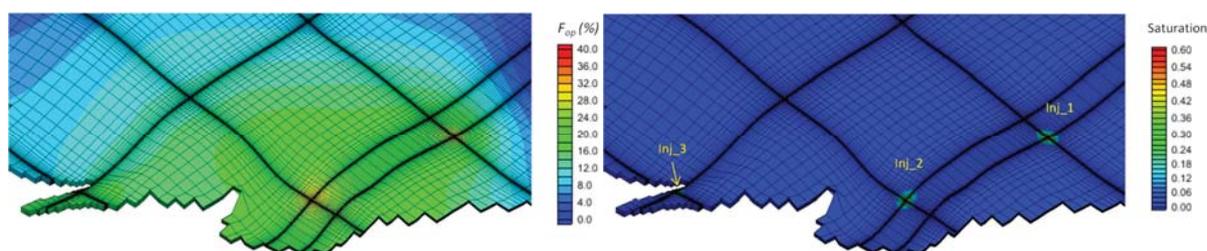


Figure 26 TOUGH2

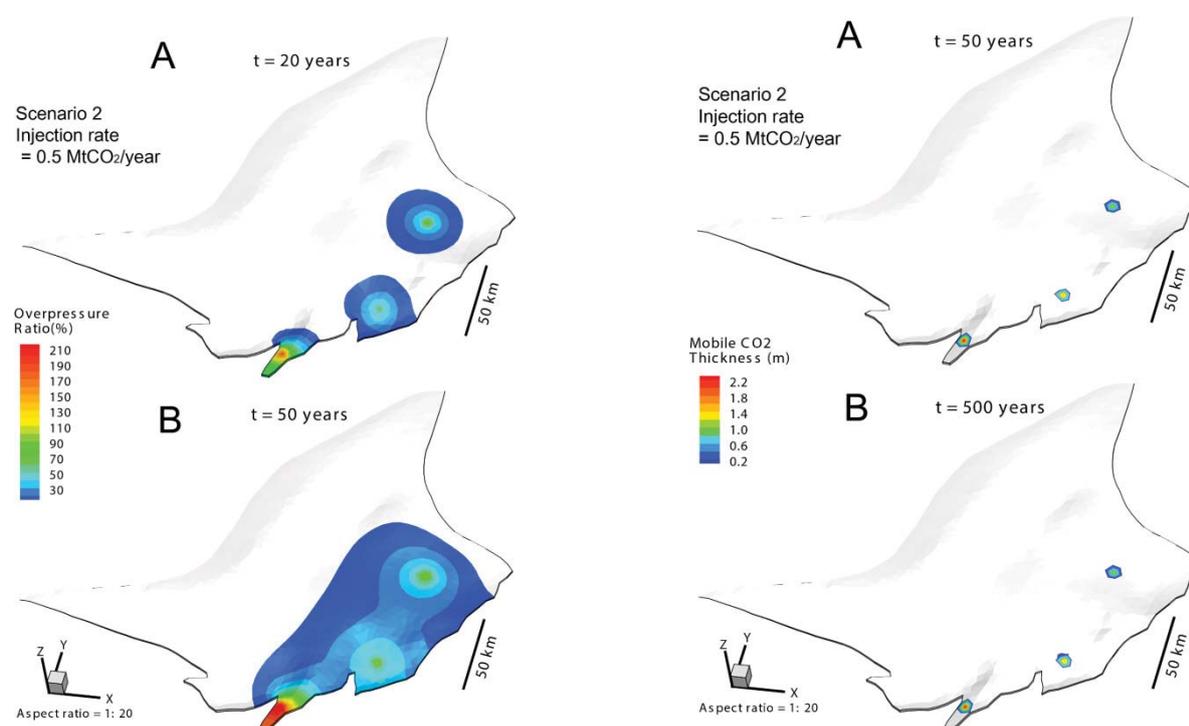
a) overpressure profile after 50 years of injection.

b) CO<sub>2</sub> saturation after 50 years of injection.

Both methods show that with an injection rate of 0.5Mt/yr modest overpressure develops in the reservoir. Some difference were observed with respect to the absolute values obtained with 40% overall for the TOUGH2 model (Figure 26a) and 70%, 90% and over 200% in the VE model for the Inj\_1, Inj\_2 and Inj\_3 wells respectively (Figure 26a). These results confirm that the highest overpressure is reached in the southern tip of the modelling domain where injection well Inj\_3 is located (Plate 3). This injection point is close to the closed, fault bound, southern margin of the Monocline, which explains these high values.

Differences in the results for the two models are as a result of the different modelled injection pressures used in the TOUGH2 simulations. Nonetheless, both models demonstrate that the 0.5 Mt/yr multi well injection scenario results in patchy overpressure responses from each well in the modelling domain during the injection period with a gradual rise in intra-well reservoir pressure reached at the end of the injection period. More significantly the 0.5Mt/yr injection rate does not reach the threshold of 50% overpressure in the reservoir for the TOUGH2 multiwell injection model.

The TOUGH2 and VE models both demonstrate (**Figure 27a** and **Figure 27b**) that the CO<sub>2</sub> plume, generated after 0.5Mt/yr year injection rate for 50 years, is approximately 10km in diameter at each well and there is very limited plume migration and thickness after 500 years.



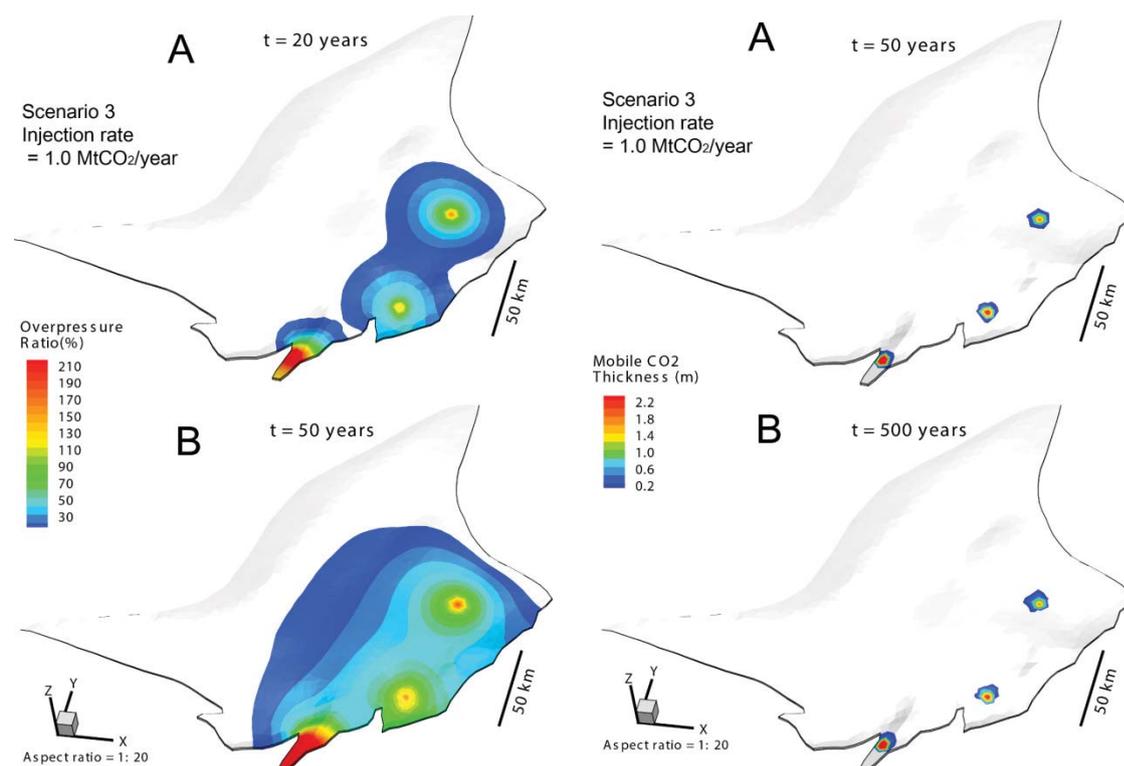
**Figure 27: VEM – a) Overpressure ratio with multiple-well injection at a rate of 0.5 Mt CO<sub>2</sub>/year per well for 50 years (end of injection at 20 years).**

**b) Mobile CO<sub>2</sub> plume migration with multiple well injection after 50 years and 500 years.**

A second multi well injection simulation using an injection rate of 1MT/yr in each well was carried out using the VE model. The results of this modelling are shown in Figure 28 below.

The overpressure ratio in the reservoir observed as a result of this simulation was recorded as being between 140% and 180%, with the overpressure distribution between the wells increasing more rapidly even after 20 years of injection. This results in a significantly larger overpressure area after 50 years of injection reaching the northern open boundary of the Monocline where values of up to approximately 30% overpressure were recorded.

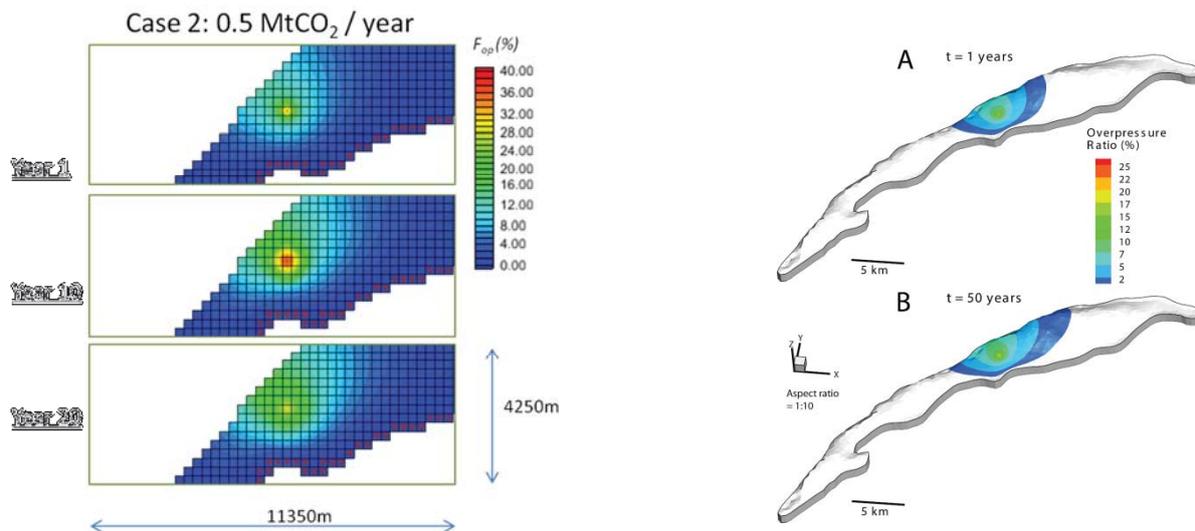
Figure 28b also shows an increased CO<sub>2</sub> plume thickness of 4m, as well as an increased radius of about 15km observed at each well with a main migration direction remaining towards the north. Despite this increase the size of the plume and its thickness remain insignificant with respect to the regional scale of the Monocline.



**Figure 28: VEM - a) Overpressure ratio with multiple-well injection at a rate of 1 Mt CO<sub>2</sub>/year per well for 50 years (end of injection at 20 years). b) Mobile CO<sub>2</sub> plume migration with multiple well injection after 50 years and 500 years.**

### 9.3.2 Dalders Structure

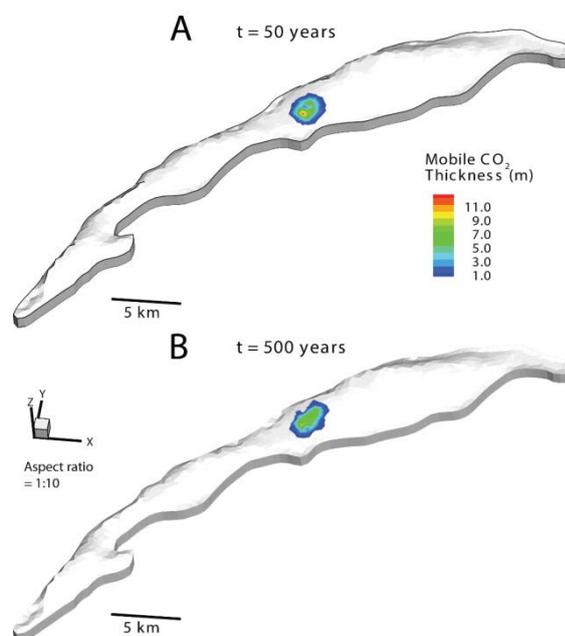
The pressure build-up as a result of TOUGH2 and VEM modelling of injection of CO<sub>2</sub> in the Dalders Structure is displayed in **Figure 29** using the overpressure factor (for definition, see Part B). The TOUGH2 model assumed an injection rate of 0.5Mt per year whilst the VE model assumed an injection rate of 0.3Mt/yr. Both models are in agreement, with low pressure increase of less than 50% overpressure in the case of the TOUHG2 model and 20% in the case of the VE model from the equilibrium formation pressure (**Figure 29**). The pressure response in the reservoir is relatively fast during the injection phase, with the highest pressure increase observed along the closed northern boundary of the structure.



**Figure 29 - a). Overpressure ratio by the CO<sub>2</sub> injection. a) overpressure build up for injection rate of 0.5MT/yr at years 1, 10 and 20. Overpressure with injection rate of 0.3 Mt/year for 50 years. (b) 1 year after injection, (c) 50 years after injection.**

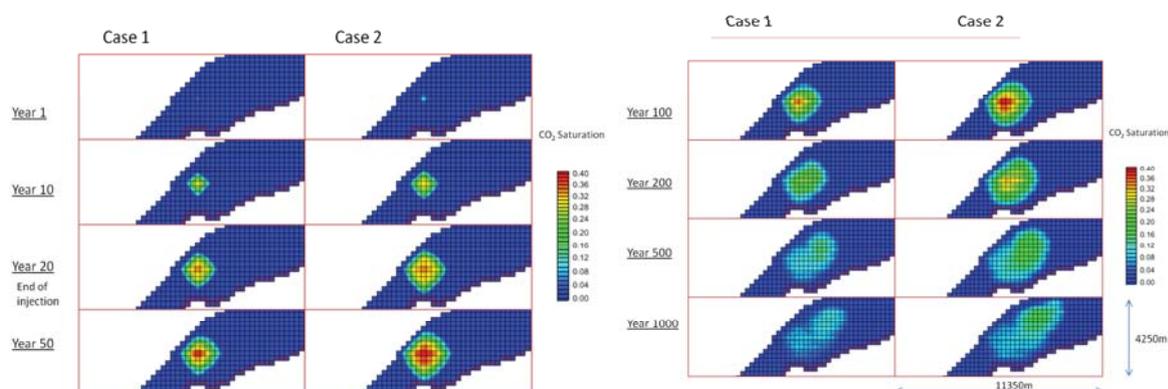
The CO<sub>2</sub> plume front in the Dalders Structure is modelled as reaching the southern boundary at the end of year 20 of injection. During the post injection phase (between 500 and 1,000 years), the plume continues to move up-dip towards the higher part of the structure towards the north east.

The size of mobile CO<sub>2</sub> plume after 50 years is estimated from the VE model, to be about 3km to 4 km with an overall thickness of between 7 m and 10 m thickness (Figure 30).



**Figure 30. Mobile CO<sub>2</sub> plume migration by the CO<sub>2</sub> injection with the rate of 0.3 Mt CO<sub>2</sub>/year for 50 years. (a) 50 years after injection, (b) 500 years after injection.**

Both the 0.3Mt/yr and the 0.5Mt/yr injection rate models show that CO<sub>2</sub> reaches the southern boundary of the Dalders Structure by the end of year 50 and escapes the spill point of the structure with 0.00005% and 0.11% of the total CO<sub>2</sub> injected escaping through the southern boundary. Post-injection simulation suggests that after 1000 year the total leakage accounts for 0.15% and 1.96% of the CO<sub>2</sub> injected. This is demonstrated in **Figure 31** below that shows the CO<sub>2</sub> saturation in the structure during the injection and post-injection phases.



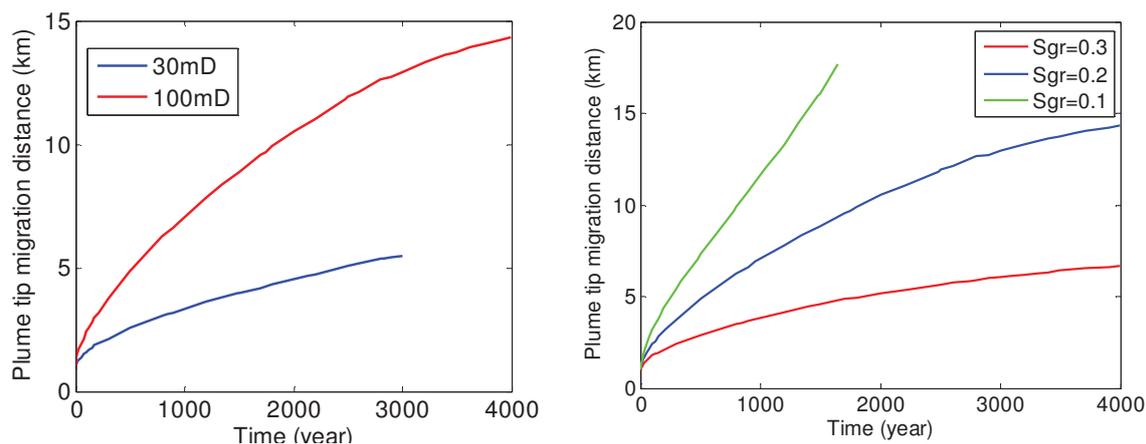
**Figure 31. CO<sub>2</sub> Saturation profile in the Dalders Structure at various times. Case 1 injection rate of 0.3Mt/yr. Case 2 injection rate of 0.5Mt/yr. Diagrams show the CO<sub>2</sub> reaching the southern boundary of the structure by year 50.**

#### 9.4 Plume Migration

A TOUGH2/EOC2N model was used in the later phases of the dynamic modelling with a view to better understanding CO<sub>2</sub> plume migration patterns and tip migration velocities in the Dalders Monocline.

The results of the modelling show that permeability and gas saturation values significantly influence the migration velocity of the CO<sub>2</sub> plume. A conservative permeability value of 100mD and gas saturation value of 0.2 were assumed for modelling the migration of CO<sub>2</sub> across the entire Dalders Monocline (**Figure 32**).

The modelling results considered a total injected volume of 30Mt of CO<sub>2</sub> from one well (mass of 1.7x10<sup>7</sup> kg) in a reservoir (represented by a 2D slice) with 100mD permeability and a residual gas saturation values of 0.2. If convective dissolution effects are not considered, the potential maximum migration distance of the plume is 50km for an average plume thickness of 15m in a period of 14,000 years. However, given this long time frame, convective dissolution processes can significantly reduce the plume migration distance. The mass that can potentially be dissolved in our modelled area (50 km long 2D slice) is about 9x10<sup>6</sup> kg, which is more than half of the initial CO<sub>2</sub> mass. This means that, in this case, convective dissolution has the potential to significantly drag the plume migration, and that the plume migration distance will be actually much smaller than 50 km.



**Figure 32: a) CO<sub>2</sub> plume tip migration distance as a function of time for permeabilities 30 and 100 mD. Residual gas saturation is 0.2 for both cases b) CO<sub>2</sub> plume tip distance as a function of time for different residual gas saturation values. Permeability k = 100 mD.**

## 9.5 Discussion

In the above paragraphs and in Appendix A the results from the preliminary dynamic modelling that was carried out for the southern part of the Dalders monocline and the Dalders structure is presented.

The dynamic modelling parameters used to estimate rates of injection of CO<sub>2</sub> in the Dalders Monocline are based on limited well data and reservoir properties, mostly confined to the southern part of the Monocline region within the Swedish offshore sector.

The preliminary simulations indicate for the southern part of the Dalders Monocline a maximum total injection rate of the order of 2.5 Mt/yr if five injection wells are used and assuming a maximum sustainable pressure increase of 50% from the hydrostatic condition. The 50% cutoff value was used as site-specific mechanical data is not available. Increasing the number of wells would allow a larger total injection rate (e.g. 7 wells would allow an injection rate of about 3 Mt/yr) as would reducing the total injection time from 50 years to e.g. 25 years. The maximum injection rate is sensitive to parameters such as formation thickness and permeability, and analysing the effect of their local variability fully does require more detailed modelling than was possible in this preliminary study. In these preliminary simulations impermeable sealing units (cap-rocks) were also assumed and it should be noted that the injection-induced pressure increase could be dissipated by brine displacement through cap-rock if the permeability of the cap-rock is not extremely low and the compressibility of the cap-rock is large. In addition, pore pressure could be further relieved through brine production wells, thus allowing higher injection rates. The role of using horizontal, rather than vertical injection wells should also be investigated. Further modelling studies should address these issues in more detail. Such analyses should optimally be accompanied with additional site-specific data and/or further parameter sensitivity studies where data acquisition is not possible.

The Cambrian reservoir in the southern section of the Monocline has relatively low porosity and permeability values (of the order of 8% to 11 % porosity and 9mD to 70mD permeability respectively) with an improvement of these values towards the north east (Plate 5) where permeability values of up 300mD for the Middle Cambrian sandstones have been documented in exploration wells. The example injection rate of 0.5Mt/yr from 5 wells is conservative and in areas of higher reservoir quality in the northern part it can be expected that higher CO<sub>2</sub> injection rates can be used without the risk of seal failure or fault

reactivation. However, based on the currently limited well data in the northern part of the Monocline, this can only be considered speculative until additional data is obtained.

The dynamic modelling results have assumed a threshold pressure of 50% above the hydrostatic pressure. This assumption was used as lack of formation leak off test data for the monocline area did not allow a more accurate estimate of this threshold. This could have implications for improved injection rates. The leak off test data would also provide thresholds for cap rock integrity and the risk for reactivation of existing fault structures.

The effects on overpressure modelled for higher injection rates suggest that these may be possible for single injection wells in better reservoir quality areas. However the use of CO<sub>2</sub> injection rates higher than 0.5Mt/yr in multiple well injections in the lower quality reservoir is not recommended. Should a grouped well injection methodology using several deviated wells from a central platform be adopted the overpressure and CO<sub>2</sub> plume sizes are likely to be different to the single injection point methodology adopted in this model.

The modelling scenarios considered in this study are, for the most part, based on an injection period of 50 years. This may exceed the infrastructure lifetime and possible timescale of operational CO<sub>2</sub> storage projects.

## 10.0 TEST INJECTION METHODOLOGY

### 10.1 Introduction

The results of the dynamic modelling phase have demonstrated that there is potential for injection of CO<sub>2</sub> in the Middle Cambrian sandstone reservoirs within the Swedish offshore sector in the Dalders Monocline and in the Dalders Structure situated in the central part of the Baltic Sea.

To further assess the business case for the injection of CO<sub>2</sub> in the Baltic Sea a more detailed assessment of the reservoir capacity for long term CO<sub>2</sub> storage is required. The compilation of regional reservoir data demonstrates that a proposed test injection methodology needs to be focussed on a number of key objectives to validate the feasibility of injection at the Dalders Monocline and Dalders Structure sites. These include:

- The characterisation of specific reservoir properties at the proposed test site
- Characterisation studies of the cap rock and potential sealing capacity, confirming the findings of the initial sealing integrity assessment
- Pump testing and hydraulic reservoir property estimations
- Residual trapping, CO<sub>2</sub> migration and pressure build up

### 10.2 Proposed Testing Methodology

The further development of the BASTOR project requires phased test injection methodology to be undertaken in order to prove the viability of injecting CO<sub>2</sub> in the Middle Cambrian sandstone. Existing projects such as the Mustang and Ottway projects have developed testing methodologies that fulfil these requirements. An indicative phased approach is presented below and describes the principal steps to be taken to drill and log a well at a selected target location, carry out formation property testing and carry out pump testing and injection of CO<sub>2</sub>. The proposed test injection methodology has been considered in the implementation of an adequate MMV methodology. This is further discussed in Section 11.0 below.

#### Step 1: Drilling

- Drilling of the borehole(s) (core retrieval at least some length for both the reservoir rock and the cap rock).
- Borehole logging (standard geophysical logging)

#### Step 2: Pre-injection tests

- Baseline geophysics (borehole and surface)
- Hydraulic characterization tests:
  - 1) Pumping test to get overall hydraulic conductivity
  - 2) FFEC test to get vertical variability of hydraulic conductivity
- Fluid sampling of in-situ fluids (and their chemical analysis in the laboratory)
- Tracer tests (especially intra-well tracer transport, if we have two wells)
- Thermal test (to obtain the thermal conductivity)

#### Step 3: Laboratory tests on rock samples

- Laboratory testing on the cores, including permeability, porosity, mineralogy, relative permeability- gas saturation functions, capillary pressure-gas saturation functions, rock mechanical properties, (behaviour of the rock when in contact with CO<sub>2</sub> and or brine saturated with CO<sub>2</sub>)
- To carry out these tests, we need to know the in-situ fluid composition (step 3)
-

**Step 4: CO<sub>2</sub> injection tests**

- Push-pull test (single well test) to get an understanding of in-situ residual trapping
- Two-well test, to get an understanding on formation heterogeneity, in-situ residual and dissolution trapping
- These tests require instrumentation of the boreholes, include pressure and temperature monitoring, and fluid sampling under high-pressure conditions and obviously surface installations for CO<sub>2</sub> injection

In-situ mechanical testing needs to be carefully coordinated with the other tests to obtain information about the prevailing stress fields.

## 11.0 MMV PROGRAMME

### 11.1 Introduction

The dynamic modelling of the Dalders Monocline and the Dalders Structure indicates the need to drill a CO<sub>2</sub> test injection well. This section describes the measurement, monitoring and verification (MMV) monitoring plan based on the results of the sensitivity analysis, the risks identified and the seal integrity assessment.

The EU Directive on the geological storage of Carbon Dioxide (2009/31/EC) outlines the requirements to assess the behaviour of injected CO<sub>2</sub>, to prevent any migration or leakage and assess if any identified leaks are potentially damaging to the environment and human health. Based on the data available and results of the dynamic modelling for the Dalders Structure, a monitoring plan has been developed using the International Energy Agency Monitoring Selection Tool for the injection and post injection phases. This model considers the risks identified in the sealing integrity report with respect to potential leakage pathways. However the lack of specific hydrochemical characteristics for the reservoir fluids as well as detailed temperature and pressure conditions for this area will require the monitoring plan discussed below to be reconsidered and redefined once additional well data becomes available.

### 11.2 Risk Assessment

The findings of the reservoir dynamic modelling and sealing integrity studies for the cap rock formations overlying the reservoir and the fault structures that characterise the Dalders Monocline are presented in sections 8 and 9 of this report. Based on these findings, the potential hazards with respects to leakage of CO<sub>2</sub> from a possible storage complex in the Dalders Monocline are summarised in Table 33 below.

**Table 33: CO<sub>2</sub> Storage Risk Identification**

Hazard	Characterisation	Risk	Mitigation
<b>Leakage Pathways</b>	Top seal failure - failure or breach of the cap rock	<b>Low</b> Significant thickness of Ordovician and Silurian Cap rock across the Monocline	Ensure adequate characterisation of sealing formations at the proposed injection site
	Migration up the bounding fault planes - where fault structures are not sealed and represent a risk of upward migration	<b>Low</b> Fault Structures binding the southern and eastern parts of the Monocline juxtapose the reservoir to mostly impermeable shales and siltstones	Detailed structural interpretation from seismic survey data to identify any small scale fault structures in the vicinity of the well bore. Restrict Injection Pressure to limit over pressure build up
	Across fault plane - where the reservoir is juxtaposed against permeable Ordovician Limestones	<b>Low</b> Regional Fault Structures binding the southern and eastern parts of the Monocline are characterised as sealed	Reservoir and cap rock characterisation from well data and seismic interpretation
	Existing wells - where the integrity of existing offshore wells casing and cements are compromised	<b>Low</b> Cement plug and casing details of existing wells have been verified	Consider possible casing corrosion in advance of injection to verify completion

			Adequate wireline logging of new wells
	Lateral migration up-dip within the reservoir towards the Swedish Coast and Gotland Island.	<b>Low</b> Cement plug and casing details of existing wells have been verified	Limit Injection pressure Limit injection rates Restrict injection sites to the eastern part of the Monocline
<b>Parameters Affecting Leakage</b>	Injection Rates - where these generate excessive overpressure in the reservoir	<b>Moderate</b>	Keep injection rates below 0.5 Mt/yr in areas of lower reservoir quality
	Reservoir porosity and permeability - areas of better reservoir quality have the potential to reduce reservoir overpressure at the time of injection but could result in greater migration of the CO <sub>2</sub> plume in the post injection phases. Areas where lower porosity and permeability has been observed have an increased risk of overpressure build up and potential for leakage through fault planes and cap rocks.	<b>Moderate</b>	Reservoir and cap rock characterisation from any proposed injection site
	Reservoir thickness - variations in reservoir thickness across the Monocline area will lead to potentially different migration pathways of the CO <sub>2</sub> plume, with reduced movement in areas where the reservoir is thickest.		Select injection sites where reservoir thickness is greatest Limit injection pressure in thin reservoir areas
	Cap rock properties - the Ordovician sequence (particularly in the southern part of the Monocline) is characterised by the presence of the Alum Shale that directly overlies the reservoir. Other lithological units including mudstones, siltstones and limestones are characteristic of the Ordovician. Whilst these do not directly overlie the reservoir there is a limited potential for upward migration where values of porosity and permeability are higher.		Cap rock characterisation and mechanical property testing where injection sites are selected
	Fault sealing rates - regional stress system studies suggest that the north east south west regional faults bounding the eastern part of the Monocline and the east west fault in the southern part are sealed. Other smaller scale structures oriented north south are considered potentially open	<b>Low</b> Initial Structural assessment suggests that east west and north south trending fault structures are less common in the Monocline area	Characterisation of fault structures that are associated or cross cutting the main bounding faults

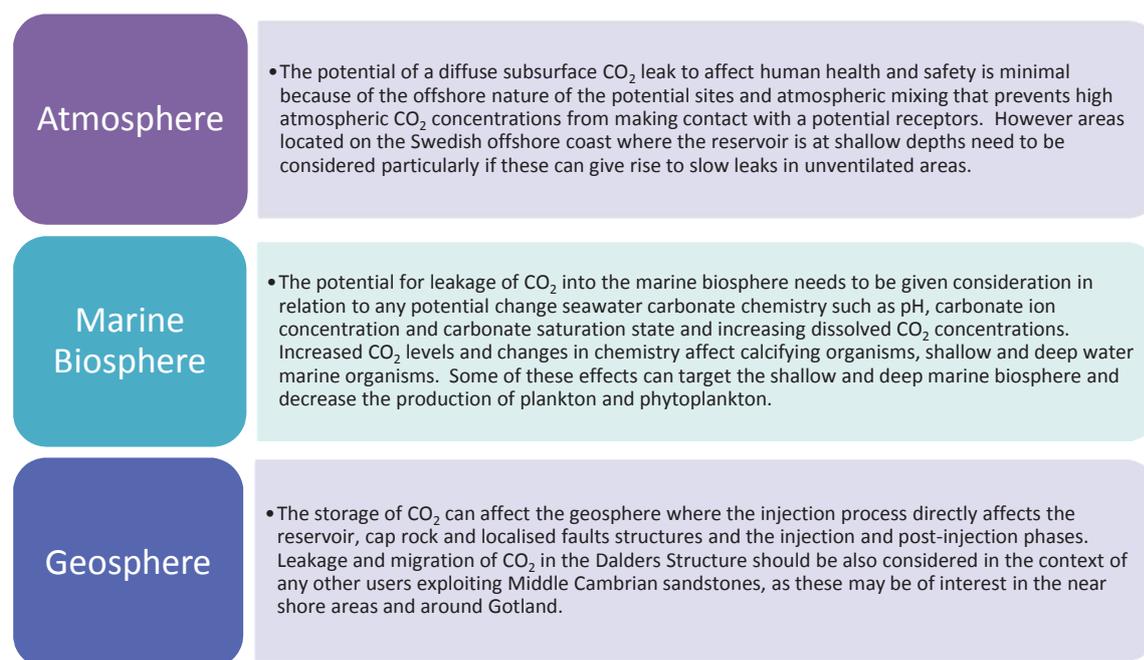
	and potential pathways for leakage		
	Injection Strategy - lower injection rates through several wells rather, than individual wells are likely to reduce the risk of excessive pressure build up, cap rock failure and fault re-activation.	Moderate	Strategy should favour injection from multiple wells at lower rates
<b>Secondary Effect of CO<sub>2</sub> Storage</b>	Displacement of brine within the aquifer resulting in brine pressure difference along the onshore extension of the Dalders Monocline	<b>Low</b>	
	CO <sub>2</sub> migration into the atmosphere where the middle Cambrian reservoir is at shallow depths	<b>Low</b>	Install onshore CO <sub>2</sub> surface detection measures

### 11.3 Exposure Assessment

To fulfil the objectives of the Measurement, Monitoring and Verification (MMV) plan, all phases of the project pre-injection, injection, post-injection and post-closure need to be considered in the context of the environmentally sensitive domains near to or connected to the storage complex. The successful implementation of the MMV plan can only be achieved against a set of base level data, which will allow accurate accounting of CO<sub>2</sub> stored in the storage complex.

The storage complex is divided up into a number of environmentally sensitive domains. The domains are the geosphere, marine biosphere and atmosphere and shown in Figure 33.

The offshore Dalders Monocline storage site does not include the fresh water domain. Wells are treated as a separate category because key risks are associated with well integrity. This is discussed separately in Section 11.7.



**Figure 33: Environmental Domains (adapted from Tucker et. al, 2013)**

## 11.4 Monitoring Selection Tool Parameters

The modelling tool parameters selected are based on the sensitivity analysis of the base case parameters outlined in the analytical model described in Section 9.2.1. The following parameters were chosen:

Reservoir Depth (km) 1.5 to 2.5

Reservoir Type Aquifer

Injection Rate 2.5 Mt/yr (based on 0.5Mt/yr injection from 5 wells)

Injection Period 50 years

Monitoring Aim Plume, Top-Seal, Migration, Leakage, Seismicity, Integrity

## 11.5 Injection Phase

A set of detailed monitoring techniques have been selected to address the risks identified as part of the injection phase of CO<sub>2</sub> Storage in the Dalders Monocline. These are outlined in **Figure 34** below.

Location	Offshore						
Depth	500 to 1500 m						
Type	Aquifer						
Quantity	125.000 Mt (2.500 Mt/yr for 50.0 yrs)						
Package	Non-protected+Syn-injection+All						

Tool	Rating %	Plume	Seal	Migration	Leakages	Seismicity	Integrity
3D surface seismic	67	4.0	4.0	4.0	1.0	0.0	3.0
Multicomponent surface seismic	62	3.0	4.0	3.0	0.0	2.0	3.0
Microseismic monitoring	46	2.0	2.0	1.0	0.0	4.0	2.0
Downhole pressure/temperature	46	1.0	4.0	1.0	0.0	2.0	3.0
Downhole fluid chemistry	42	1.0	2.0	2.0	3.0	0.0	2.0
Tracers	38	1.0	2.0	2.0	2.0	0.0	2.0
Bubble stream detection	38	0.0	0.0	1.0	4.0	0.0	4.0
2D surface seismic	38	2.0	2.0	2.0	1.0	0.0	2.0
Geophysical logs	38	1.0	2.0	2.0	0.0	0.0	4.0
Long-term downhole pH	29	1.0	2.0	2.0	2.0	0.0	0.0
Seabottom gas sampling	29	0.0	0.0	1.0	4.0	0.0	2.0
Surface gas flux	29	0.0	0.0	1.0	3.0	0.0	3.0
Cross-hole seismic	25	2.0	2.0	1.0	0.0	0.0	1.0
Vertical seismic profiling (VSP)	25	2.0	2.0	1.0	0.0	0.0	1.0
Sidescan sonar	21	0.0	0.0	0.0	3.0	0.0	2.0
Cross-hole EM	21	2.0	1.0	1.0	0.0	0.0	1.0
Multibeam echo sounding	21	0.0	0.0	0.0	3.0	0.0	2.0
Fluid geochemistry	17	0.0	0.0	1.0	2.0	0.0	1.0
Tiltmeters	17	0.0	1.0	0.0	1.0	2.0	0.0
Boomer/Sparker profiling	17	0.0	0.0	1.0	2.0	0.0	1.0
Bubble stream chemistry	17	0.0	0.0	0.0	3.0	0.0	1.0
Cross-hole ERT	17	2.0	1.0	1.0	0.0	0.0	0.0
Seawater chemistry	17	0.0	0.0	0.0	3.0	0.0	1.0
Single well EM	12	1.0	1.0	0.0	0.0	0.0	1.0
High resolution acoustic imaging	12	0.0	0.0	0.0	2.0	0.0	1.0
Surface gravimetry	12	1.0	0.0	2.0	0.0	0.0	0.0
Well gravimetry	12	1.0	1.0	1.0	0.0	0.0	0.0

Figure 34: IEA MMV Selection tool results for the injection phase.

Deployment of all of the monitoring techniques supplied by the IEA Monitoring Selection Tool is unlikely to be realistic, either logistically or financially. The most effective and appropriate monitoring techniques are highlighted in red. These are specifically designed to address site safety issues with regard to public opinion and are based on current demonstration and flagship projects that are referenced on the IEA Greenhouse Gas R&D Programme website.

## 11.6 Post-Injection Phase

A set of detailed monitoring measures have been selected to address the risks identified as part of the post-injection phase of CO<sub>2</sub> Storage in the Dalders Monocline. These are outlined in Figure 25 below.

Location	Offshore						
Depth	500 to 1500 m						
Type	Aquifer						
Quantity	125.000 Mt (2.500 Mt/yr for 50.0 yrs)						
Package	Non-protected+Post-injection+All						
Tool	Rating %	Plume	Seal	Migration	Leakages	Seismicity	Integrity
3D surface seismic	67	4.0	4.0	4.0	1.0	0.0	3.0
Multicomponent surface seismic	62	3.0	4.0	3.0	0.0	2.0	3.0
Microseismic monitoring	46	2.0	2.0	1.0	0.0	4.0	2.0
Downhole pressure/temperature	46	1.0	4.0	1.0	0.0	2.0	3.0
Downhole fluid chemistry	42	1.0	2.0	2.0	3.0	0.0	2.0
Tracers	38	1.0	2.0	2.0	2.0	0.0	2.0
Bubble stream detection	38	0.0	0.0	1.0	4.0	0.0	4.0
2D surface seismic	38	2.0	2.0	2.0	1.0	0.0	2.0
Geophysical logs	38	1.0	2.0	2.0	0.0	0.0	4.0
Long-term downhole pH	29	1.0	2.0	2.0	2.0	0.0	0.0
Seabottom gas sampling	29	0.0	0.0	1.0	4.0	0.0	2.0
Surface gas flux	29	0.0	0.0	1.0	3.0	0.0	3.0
Cross-hole seismic	25	2.0	2.0	1.0	0.0	0.0	1.0
Vertical seismic profiling (VSP)	25	2.0	2.0	1.0	0.0	0.0	1.0
Sidescan sonar	21	0.0	0.0	0.0	3.0	0.0	2.0
Cross-hole EM	21	2.0	1.0	1.0	0.0	0.0	1.0
Multibeam echo sounding	21	0.0	0.0	0.0	3.0	0.0	2.0
Fluid geochemistry	17	0.0	0.0	1.0	2.0	0.0	1.0
Tiltmeters	17	0.0	1.0	0.0	1.0	2.0	0.0
Boomer/Sparker profiling	17	0.0	0.0	1.0	2.0	0.0	1.0
Bubble stream chemistry	17	0.0	0.0	0.0	3.0	0.0	1.0
Cross-hole ERT	17	2.0	1.0	1.0	0.0	0.0	0.0
Seawater chemistry	17	0.0	0.0	0.0	3.0	0.0	1.0
Single well EM	12	1.0	1.0	0.0	0.0	0.0	1.0

Figure 35: IEA MMV Selection tool results for the post-injection phase.

The most effective and appropriate monitoring techniques are highlighted in red and are based on current demonstration and flagship projects that are referenced on the IEA Greenhouse Gas R&D Programme website.

## 11.7 Monitoring Technique Description:

The IEA MMV Selection tools makes recommendations for the deployment of specific monitoring techniques with the objective of assessing which of these are most applicable to the storage site and CO<sub>2</sub> volumes being considered over the duration of a proposed injection period. This section describes the potential risks and receiving environments different techniques that have been identified as strongly recommended (red categories in Figure 34 & Figure 35) and are regarded as key elements in meeting particular monitoring objectives of the MMV programme when considering CO<sub>2</sub> injection at a site in the Dalders Monocline. Exclusion of these essential techniques would reduce the potential for the aim to be achieved. Additional measures classified as 'definitely applicable' by the IEA tools (orange categories - Figure 34 & Figure 35) should be included to meet specific monitoring aims for the injection and storage in the Dalders Monocline.

Specific site conditions will have to be given careful consideration to ensure that they will not undermine the efficacy of each technique, or even preclude its deployment. Based on specific site conditions, the MMV plan proposed should be revised and updated.

The individual Techniques and their potential objectives are further discussed below in Table 34.

**Table 34: MMV Technology Review and Potential Deployment phases**

Technique	Objectives	Deployment Phases
<b>Multicomponent Surface Seismic</b>	<ul style="list-style-type: none"> <li>fluid behaviour monitoring</li> <li>imaging beneath gas accumulations</li> <li>discrimination of fluid pressure</li> <li>saturation changes. monitoring low permeability overburden sequences</li> </ul>	Injection and Post Injection
<b>Microseismic Monitoring</b>	<ul style="list-style-type: none"> <li>Collection of baseline seismicity</li> <li>detection, measurement and triangulation of low-level seismic events</li> <li>fracturing of the reservoir due to injection overpressure or migration of the injected CO<sub>2</sub></li> <li>Fault reactivation and cap rock failure</li> </ul>	Pre-injection, Injection & Post-Injection phases
<b>Bubble Stream Detection</b>	<ul style="list-style-type: none"> <li>Full 3D volumetric sweeps for bubble detection at an offshore storage site (this has already been successfully used in the Polish offshore sector)</li> </ul>	Injection & Post Injection
<b>Tracers</b>	<ul style="list-style-type: none"> <li>assess and confirm the migration of CO<sub>2</sub> (free and dissolved) within the reservoir</li> <li>detect migration in overlying and underlying formations;</li> <li>estimate volume and flow rates of CO<sub>2</sub> within the overlying and underlying formations</li> <li>detect possible interconnection between reservoir &amp; cap rock</li> </ul>	Injection
<b>Long Term Down hole pH</b>	<ul style="list-style-type: none"> <li>Monitor CO<sub>2</sub> dissolution into the formation water</li> <li>Characterise fluid-rock interactions, including mineral trapping.</li> <li>early indication of CO<sub>2</sub> migration in the overburden</li> </ul>	Injection & Post-injection
<b>Surface Gas Flux:</b>	<ul style="list-style-type: none"> <li>Measurement of the rate of CO<sub>2</sub> flowing from the ground surface to the atmosphere</li> <li>Quantifying any mass of CO<sub>2</sub> leaking from a storage site</li> <li>Compile baseline data from the margins of the Dalders Monocline (onshore Sweden) to identifying natural background variations as a proxy for onshore migration of CO<sub>2</sub> from the reservoir.</li> </ul>	Pre-injection Injection Post Injection phases
<b>Vertical Seismic Profiling (VSP)</b>	<ul style="list-style-type: none"> <li>Detailed formation characterisation in the near well bore area providing greater certainty of the reservoir and fault characteristics as well as their relationship with the cap rock;</li> </ul>	Pre-Injection Injection

	<ul style="list-style-type: none"> <li>multiple walkway surveys to characterise plume migration if a multi-well cluster is considered</li> </ul>	Post- Injection
<b>Cross Hole Seismic</b>	<ul style="list-style-type: none"> <li>measure CO<sub>2</sub> saturations</li> <li>measure pressure changes during CO<sub>2</sub> injection.</li> <li>CO<sub>2</sub> plume movement</li> <li>calibrate seismic data</li> <li>Early warning of CO<sub>2</sub> leakage</li> </ul>	Injection & Post Injection
<b>Cross Hole EM:</b>	<ul style="list-style-type: none"> <li>Electrical Conductivity mapping between boreholes</li> <li>Resistivity contrast mapping of saline aquifer fluids and more conductive CO<sub>2</sub> as an indication for plume migration</li> <li>changes in CO<sub>2</sub> saturation in the reservoir</li> </ul>	Injection and Post Injection
<b>Fluid geochemistry</b>	<ul style="list-style-type: none"> <li>fluid chemistry, including pH &amp; bicarbonate concentrations at the well head</li> <li>detection of CO<sub>2</sub> dissolved in reservoir fluid to assess any migration of CO<sub>2</sub> towards onshore Sweden</li> <li>general information on fluid-rock processes, leakage processes and changes to water quality</li> </ul>	Pre-Injection  Injection and Post Injection phases
<b>Bubble Stream Chemistry</b>	<ul style="list-style-type: none"> <li>Gas composition, flow rate and potential origin</li> </ul> <p><i>(consideration should be given to the use of a buoy based system such as that trialled in the Gulf of Trieste by the GeoNet2 project if long term monitoring is considered)</i></p>	Injection  (possible post injection phases)
<b>Tilt Meters</b>	<ul style="list-style-type: none"> <li>Baseline rock mechanical properties</li> <li>Rock mechanical integrity - reservoir and cap rock</li> <li>changes in strain within the reservoir, caprock or overburden</li> <li>Storage site deformation due to high overpressure</li> </ul>	Pre-Injection  & Injection Phases
<b>Cross Hole ERT</b>	<ul style="list-style-type: none"> <li>Resistivity contrasts between the CO<sub>2</sub> and reservoir</li> <li>monitoring of the approximate distribution of a CO<sub>2</sub> plume between wells.</li> </ul> <p><i>(subject to confirming borehole spacing and locations based on estimated CO<sub>2</sub> plume and reservoir thickness)</i></p>	Injection & Post-Injection
<b>Surface Gravimetry</b>	<ul style="list-style-type: none"> <li>Independent verification of changes in the subsurface mass at and post injection</li> <li>Complementary to seismic monitoring</li> <li>Estimates of CO<sub>2</sub> dissolution.</li> </ul>	Injection and Post Injection phases

### 11.8 Well Integrity Monitoring:

Additional monitoring measures aimed at addressing the prevention of leakage and CO<sub>2</sub> migration at or near the injection wells are proposed below.

- Pressure testing, at a minimum pressure to be confirmed based on leak off test data, of new wells being considered for injection.
- Caliper survey to measure any potential corrosion of the tubing.
- Corrosion coupons at the injection skid to confirm the dehydration specs are being adhered to and corrosion is not occurring in the pipeline and wellbore completion.
- Routine well maintenance of the wellhead valves and the measurement of the pressure on the different casing annuli.
- Cement Bond Logs, Ultrasonic Casing Logs and Electromagnetic Casing Logs (CBL, MWIT, USIT, EMIT) will verify the initial integrity of the cement bond and well completion along the entire length of each injector.
- Hold Up Depths (HUD) should be measured at every wire-line entry in a well before the CBL/MWIT/USIT/EMIT logs are run, to ensure no plugging exists across the perforation interval. This may have to be repeated at regular intervals as part of the lifetime of the project
- Distributed Temperature Sensing (DTS) along an optical fibre permanently deployed from the surface down to the first seal on the outside of the intermediate casing will provide a continuous means on verifying cement bond integrity and the absence of CO<sub>2</sub> outside the casing. In the unexpected event of a loss of cement bond integrity, any upward migration of CO<sub>2</sub> outside the casing will lower the temperature on the adjacent portion of the DTS fibre due to increased thermal insulation from the in-situ formation temperature provided by the out-of-place CO<sub>2</sub>.

## 12.0 CONCLUSIONS

The principal conclusion from this study is that there is large theoretical storage capacity in the Baltic Sea basin beneath a 900 metre thick impermeable caprock. Ranking of Baltic Sea sub-basins in terms of suitability for CO<sub>2</sub> geological sequestration identified the Slupsk Border Zone as the highest rank. Theoretical storage capacity calculations for the sub-basins indicated more than 100Mt of CO<sub>2</sub> storage capacity in the Dalders Structure within the Dalders Monocline. Preliminary dynamic simulations have been carried out focussing on the southern part of the Dalders monocline offshore Sweden. These suggest that, for example, maintaining the reservoir pressure at 50% above the hydrostatic pressure, would limit the injection rate to 0.5Mt per well per annum over a 50 year period if five injection wells are used. Increasing the number of wells, would increase the total annual rate (e.g. seven wells could correspond to a total rate of about 3 Mt per year) as would reducing the injection time to e.g. 25 years. The maximum injection rate is sensitive to parameters such as formation thickness and permeability, and analyzing the effect of their local variability fully does require more detailed modelling than was possible in this preliminary study. In these preliminary simulations impermeable sealing units (cap-rocks) were also assumed and it should be noted that the injection-induced pressure increase could be dissipated by brine displacement through cap-rock if cap-rock properties are suitable. In addition, pore pressure could be further relieved through brine production wells, thus allowing higher injection rates. The role of using horizontal, rather than vertical injection wells should also be investigated. Further modelling studies should address these issues in more detail. Such analyses should optimally be accompanied with additional site-specific data and/or further parameter sensitivity studies where data acquisition is not possible.

Keeping these reservations in mind, the above numerical values can be considered only indicative.

The results from the data analysis and the preliminary dynamic modelling do, however, indicate that the reservoir quality in the presently modelled area is not suitable to high injection rates and therefore not sufficient for CO<sub>2</sub> storage at the scale of projected emissions around the Baltic Sea. Other areas to the north east of the Monocline, such as offshore Latvia, where limited data is available, could include suitable areas for storage with better reservoir quality and where a higher rate of injection could be achieved.

The regional storage capacity assessment demonstrated that there are sweet spots in the Cambrian reservoir such as onshore Latvia, where there is commercial gas storage, and both onshore and offshore Kaliningrad, where there is ongoing hydrocarbon production.

## 13.0 RECOMMENDATIONS

The potential to store significant quantities of CO<sub>2</sub> in the Swedish part of the Dalders Monocline appears to be limited based on current data and assumptions of the reservoir and top seal properties used to model potential injection scenarios.

Existing seismic line data covering the Swedish offshore sector of the Dalders Monocline should be calibrated to available well data and re-interpreted to identify any primary and secondary fault structures and map reservoir porosity and permeability variations based on seismic attributes.

Further reservoir characterisation studies such as those discussed above should be combined with improved estimates of seal fracture pressures based on well leak off test data and core sample analyses.

This would improve the understanding of the connectivity in higher quality intervals of the reservoir and provide a more heterogeneous static model on which further CO<sub>2</sub> injection modelling scenarios could be undertaken.

Future exploration efforts should be focussed on areas where the best reservoir quality and storage potential are likely to be found. This should be done in parallel with more refined dynamic simulations to gain further understanding of the true storage capacity of various parts of the region.

Reservoir formation data from core samples and wire line logs should be obtained from any newly drilled wells in the area to improve the understanding of porosity, permeability and formation pressure values associated with the reservoir across the Baltic Sea region.

As offshore and onshore well data indicate that the north eastern portion of the Dalders Monocline appears to have better reservoir qualities than the current study area, new data covering this area, in particular offshore Latvia, could help to identify more suitable sites for CO<sub>2</sub> storage.

As the regional reservoir quality maps based on limited data indicate that onshore and offshore Kaliningrad would appear to have better reservoir qualities than the current study area, access to additional existing data from this area would help to identify more suitable sites for CO<sub>2</sub> storage

Thus Baltic State cooperation is imperative to ensure the success of any Baltic Sea CO<sub>2</sub> storage initiative. Additional efforts to increase this cooperation between Baltic States should be undertaken to ensure that an effective strategy for CO<sub>2</sub> storage in the Baltic Sea region is adopted.

## 14.0 BIBLIOGRAPHY

Amoco Latvia Oil Company. 1995. Dalders Prospect, Depth Structure Map, Top Mid-Cambrian Sandstone. Enclosure 21 - Dalders Summary Report. 1996.

Bachu, S. et al. (2007). Estimation of CO<sub>2</sub> storage Capacity in Geological Media - Phase 2. Work under auspices of the Carbon Sequestration leadership Forum

Bachu, S. (2003, March). Screening and ranking of sedimentary basins for sequestration of CO<sub>2</sub> in geological media in response to climate change. *Environmental Geology*, pp. 277-289.

Bear J (1972) *Dynamics of Fluids in Porous Media*. Dover Publications, Inc., New York.

Brangulis A.P., S. K. (1993). Geology and hydrocarbon prospects of the Paleozoic in the Baltic region. *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference (Ed J.R. Parker)* (pp. 651-656). London: The Geological Society of London.

Brangulis, A.P., Kanev, S.V., Margulis, L.S., Pomerantseva, R.A (2008).. Petroleum Geology of Northwest Europe: Proceedings of the 4<sup>th</sup> Conference. 1993 Petroleum Geology. Published by The Geological Society, London, pp 651- 656. Erlstrom, M. *Lagring av koldioxid i djupa akviferer*. Elforsk.

Chadwick, A. (2008). *Best Practice for the storage of CO<sub>2</sub> in Saline Aquifers*. Keyworth: British Geological Survey.

Donoho, D.W., Hart, W.H. 1996. Dalders Summary Report. Amoco.

Erlstrom, M. (2008). *Lagring av koldioxid i djupa akviferer*. Stockholm: Elforsk.

Erlstrom, M. F., Fredriksson, D. , Juhojuntti, N., Sivhed, U., Wickström, L. (2011). *Lagring av koldioxid i berggrunden*. Stockholm: Sveriges geologiska undersökning.

EU Geocapacity, (2009). WP4 Report - Capacity Standards and Site Selection Criteria. Assessing European Capacity for Geological Storage of Carbon Dioxide. SES6-518318

Favalli, M. and Pareschi, M.T., 2004. Digital elevation model construction from structured topographic data: The DEST algorithm. *Journal of Geophysical Research*, **109**, F04004.

Grigelis, A. 2011. Research of the bedrock geology of the Central Baltic Sea. *Baltica*. **24**. Issue 1. Pages1-12. Viknius.

Kanev, S., Kushik, E., Peregudov, Y. (2000). A large Ordovician carbonate buildup offshore Latvia. *Latvijas Geologijas Vestis Journal*, 8, 22–23.

Krushin, J. (1994). *A Semi-Quantitative Analysis of the Sealing Potential for the Middle Cambrian Sandstones, Dalders Prospect, Baltic Sea*. Amoco Production Company.

LO&G, 2002. Latvia Offshore, Hydrocarbon Potential of Blocks 1, 2 and 3 offered in Latvia's 1<sup>st</sup> E&P Licensing Round. Reiterated Opening April – October 2002.

LO&G, 2002. Enclosure 2, Baltic Basin, Top & Base Cambrian Depth Map 1:1M. Latvia Offshore, Hydrocarbon Potential of Blocks 1, 2 and 3 offered in Latvia's 1<sup>st</sup> E&P Licensing Round. Reiterated Opening April – October 2002.

LO&G, 2002. Enclosure 3, Latvia Licenses 1, 2 & 3 Evaluation Montage. Latvia Offshore, Hydrocarbon Potential of Blocks 1, 2 and 3 offered in Latvia's 1<sup>st</sup> E&P Licensing Round. Reiterated Opening April – October 2002.

LOTOS, 2010. The Possibility of CCS realisation in LOTOS Group by using oil fields on the Baltic Sea. Presentation to the CCS Workshop, Warsaw.

Mathias, S.A., González Martínez de Miguel, G.J., Thatcher, K.E., Zimmerman R.W. (2011a). Pressure buildup during CO<sub>2</sub> injection into a closed brine aquifer. *Transport in Porous Media*, 89, 383–97.

Mathias, S.A., González Martínez de Miguel, G.J., Hosseini, S.A. (2011b). Role of partial miscibility on pressure buildup due to constant rate injection of CO<sub>2</sub> into closed and open brine aquifers. *Water Resources Research*, 47, W12525.

Modliński, Z., Podhalańska, T. (2010). Outline of the lithology and depositional features of the lower Paleozoic strata in the Polish part of the Baltic region. *Geological Quarterly*, 54, 109-121.

Nilsson, P. A. (2011). *Bastor - Baltic Sea CO<sub>2</sub> Storage*. Stockholm.

OPAB (2011). Hagenfeldt, S., E. Dalders, Silurian to Ordovician Source Rocks. Internal Report

OPAB (1990). *Sweden Baltic Sea OPAB Farmout Prospectivity Appraisal*. Amoco Sweden Petroleum Company.

Otmas, A.A. (2011). Development and location of the oil structures in the Kaliningrad region. Thesis. St Petersburg.

Petroswede Svenska Petroleum Exploration (2010). *Annual Report 2009*. Petroswede AB.

Pruess, K., Oldenburg, C., Moridis, G. (1999). TOUGH2 User's Guide, Version 2.0. Report LBNL-43134. Lawrence Berkeley National Laboratory, Berkeley, California.

Pruess, K., Spycher, N. (2007). ECO2N - A fluid property module for the TOUGH2 code for studies of CO<sub>2</sub> storage in saline aquifers. *Energy Conversion and Management* 48, 1761-1767.

Purra, V., Flodén, T. Rapakivi-granit-anorthosite magmatism – a way of thinning and stabilisation of the Svecofennian crust, Baltic Sea Basin. *Tectonophysics*. 1999. **V 305**. Issue 1-3, Pages 75-92

Qiang Xu, J. (2009). *Reservoir Engineering Aspects in Site Characterization, Short-Term Modelling. and Long-Term Fate of CO<sub>2</sub> in Carbon Dioxide Geosequestration*. Bureau of Economic Geology: The American Association of Petroleum Geologists.

Raukas, A., Teedumäe, A. (eds) (1997). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn. 436 pp.

Schuppers, J., D., Holloway, S., May, F., Gerling, P., Bøe, R., Magnus, C. Riis, F., Osmundsen, P. T., Larsen, M., Andersen, P. R. and Hatzianis, G. (2003). Storage Capacity and quality of the hydrocarbon structures of the North Sea and the Aegian region. TNO-report NITG 02-020-B.

Shogenova, A. S. (2009). The Baltic Basin: structure, properties of reservoir rocks, and capacity for geological storage of CO<sub>2</sub>. *Estonian Journal of Earth Sciences*, pp. 259-267.

Šliaupa, S., Šliaupienė, R. 2010. Potential of geological storage of CO<sub>2</sub> in Lithuania. CGS Europe, Poster.

Šliaupa, S., Fokin, P., Lazuaskiene, J., Stephenson, R.A. The Vendian Early Palaeozoic sedimentary basins of the East European Craton. *Geological Society of London Memoirs*. 2006, **32**, Pages 449-462

Šliaupa, S. (2009). Potential of geological storage of CO<sub>2</sub> in Lithuania. *CO<sub>2</sub>NET EAST workshop 'CO<sub>2</sub> Capture and Storage - Response to Climate Change'*, (p. Poster). Bratislava.

Šliaupa S., Hoth P. 2010. Geological evolution and resources of the Baltic Sea Area from the Precambrian to the Quaternary. In: J. Harff, S. Björck, P. Hoth (eds.). *The Baltic Sea Basin*. Springer. Berlin. 13–51.

Šliaupiene, R., Šliaupa, S. (2010). CO<sub>2</sub> Storage potential of Lithuania. CGS Europe, Poster.

Šliaupiene, R., Šliaupa, S. (2011). Prospects for CO<sub>2</sub> geological storage in deep saline aquifers of Lithuania and adjacent territories. *Geologija*, 53, 121-133.

Šliaupiene, R., Šliaupa, S. (2012). Risk Factors of CO<sub>2</sub> Geological Storage in the Baltic Sedimentary Basins. *Geologija*, 54, 3, 100–123.

Siggerud, E. (2008). *Sedimentology Early to Late Cambrian within the Dalders Prospect, Central Baltic Sea*. In-House Report Svenska Petroleum Exploration AB.

Skirius, C. (1996). Baltic Sea Middle Cambrian Sandstone Analysis, Wells B3-1, B6 and E7-1. Amoco Report. EPTG.

Sokołowski, A., Tęgowski, J. (2012). Cruise Report within EU project ECO2 (B3 field, southern Baltic Sea, Poland). University of Gdańsk, Institute of Oceanography, Gdynia, Poland

Streimikiene, D. 2010. Use of comparative assessment framework for comparison of geological nuclear waste and CO<sub>2</sub> disposal technologies. World Energy Congress 2010.

Svenska Petroleum, AB. (1996). Proposal for the Facilities Design, Economics and Work Programme for the Development of the Kretinga and Nausodis Oil Fields. Volume A, Submission to the Licence Committee of Lithuania – Agreement Area Evaluation.

Svenska Petroleum, AB. (1996). The Geophysical, Geological and Development Appraisal of the Kretinga, Nausodis Fields and volumetric Reappraisal of the Genciai Field. Volume B, Submission to the Licence Committee of Lithuania – Agreement Area Evaluation.

Svenska Petroleum Exploration OPAB. (2010). GEOLOGICAL SUMMARY, BALTIC SEA, OPAB PRESENT KNOWLEDGEBASE. *Internal Presentation*.

Tarvis, T. (2007). Geology of the central Baltic Sea and its implication for hydrocarbon potential. Part 1 - Palaeozoic geology and structural evolution of the central Baltic Sea and its hydrocarbon potential. *Unpublished Masters Thesis*. University of Stockholm.

Tucker, O., Garnham, P., Wood, P., Berlang, W., Susnato, I. (2013). Development of an offshore monitoring plan for commercial CO<sub>2</sub> storage pilot. *Energy Procedia*. **37** (2013). pp. 4317 – 4335.

Ulmishek, G. (1990), The Geological Evolution and Petroleum Resources of the Baltic Basin: Chapter 31: Part II. Selected Analog, Interior Cratonic Basins: Analog Basin. AAPG Special Volumes, M51: Interior Cratonic Basins, Pages 603-632

Ūsaiytė, D. (2000) The geology of the southeastern Baltic Sea: a review. *Earth Science Reviews*, 50, 137-225

VTT. (2010). *Potential for carbon capture and storage (CCS) in the Nordic region*. VTT

Wójcicki, A., Paczesna, J. (2012). CO<sub>2</sub> storage potential in the Polish part of the Baltic Sea. Stockholm.

Woodcock, N. and Stracken, R. (2000). *Geological History of Britain and Ireland*. Blackwell Science Ltd.

Zytner Y.I., Fenin G.I., Chibisova V.S. and Rovinskaya E.L. (2009). Mineral resources of hydrocarbons and the licensing status Baltic oil province (Kaliningrad). *Petroleum geology. Theory and practice*, v4-4. [http://www.ngtp.ru/rub/6/44\\_2009.pdf](http://www.ngtp.ru/rub/6/44_2009.pdf) - in Russian.

## **15.0 CLOSURE**

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### Plate 2 – Structures

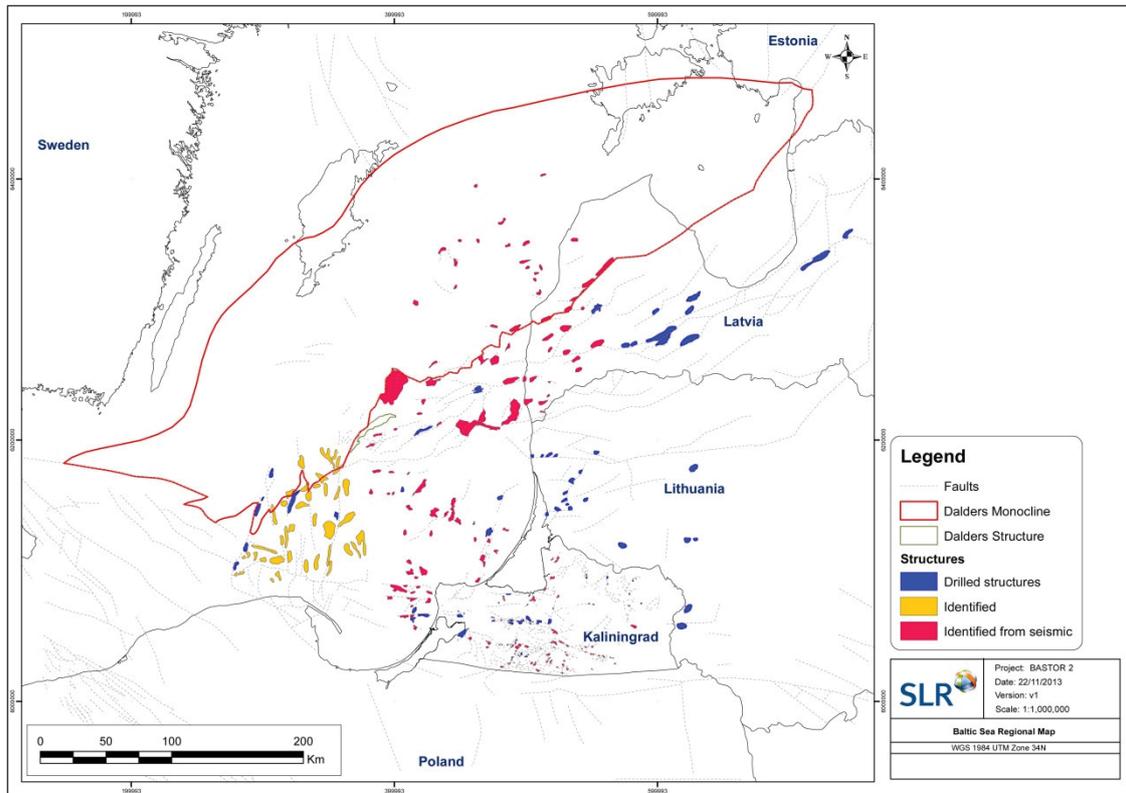
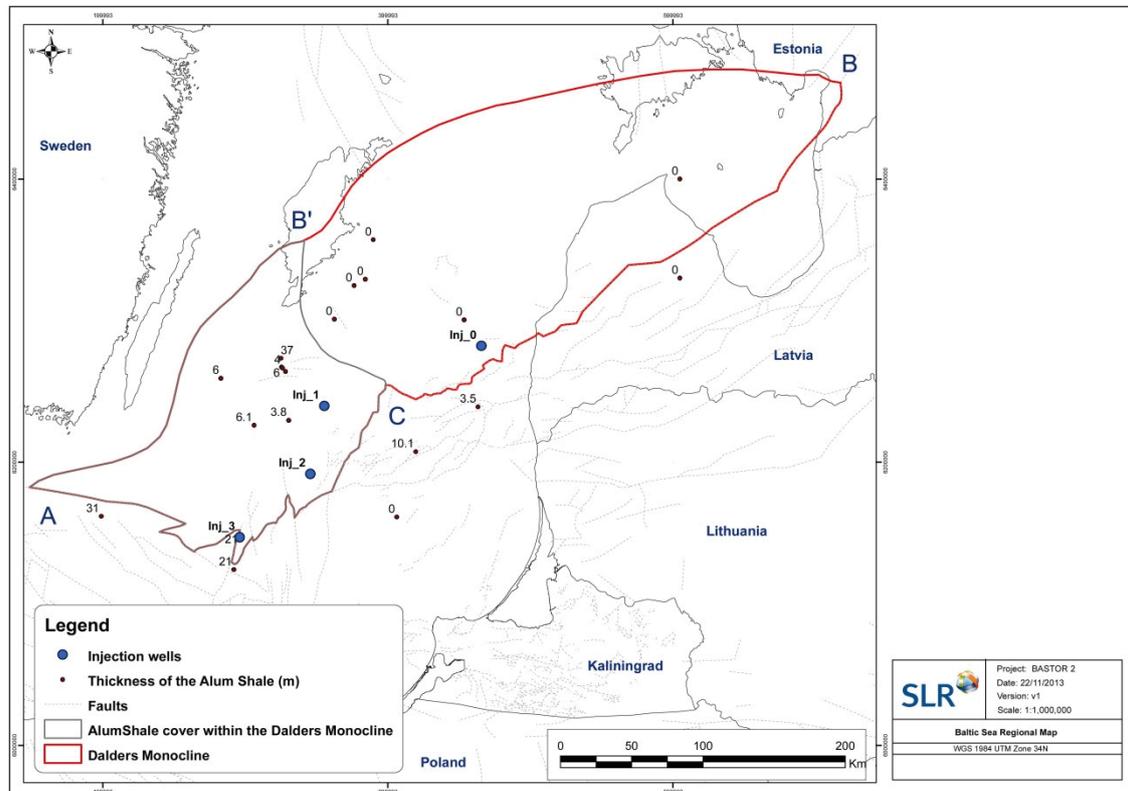
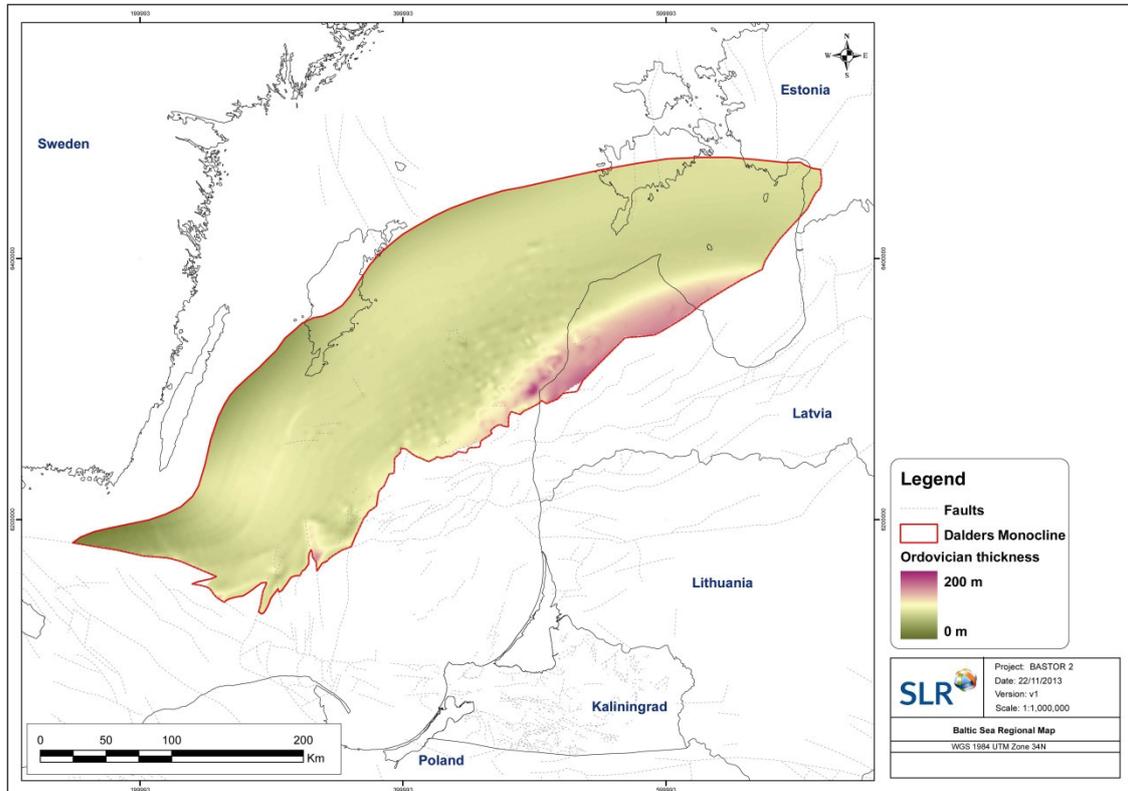


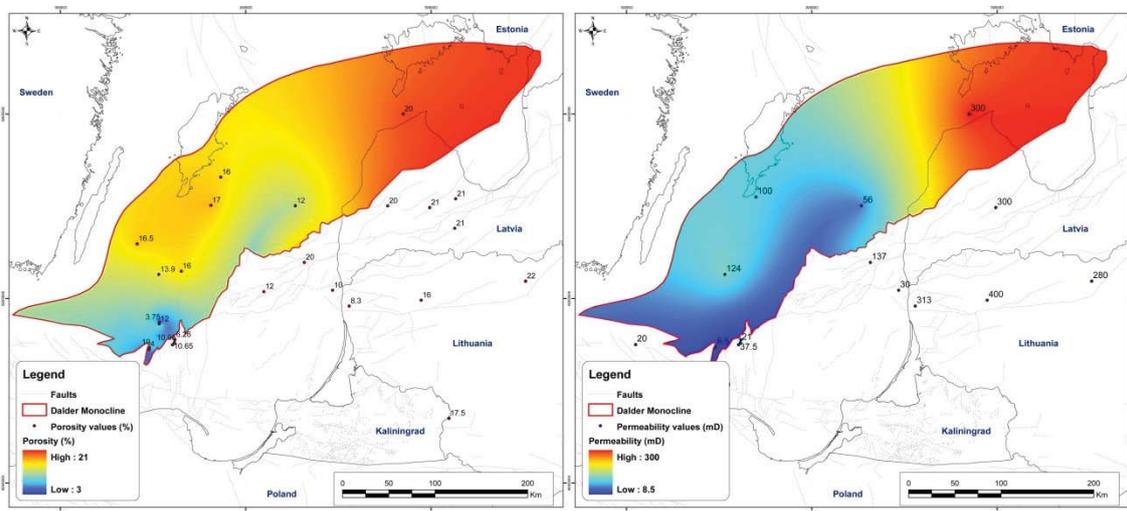
Plate 3 – Alum Shale and Injection Locations (OPAB, 2011)



### Plate 4 – Ordovician Thickness



### Plate 5 – Permeability and Porosity





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