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FINAL REPORT ON THE SCREENING OF PROSPECTIVE SITES FOR THE GEOLOGICAL STORAGE OF CO_2 IN THE SOUTHERN BALTIC SEA

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1.0 INTRODUCTION

SLR was commissioned by VTT, Technical Research Centre of Finland to identify and characterise the potential CO_2 storage sites in the southern Baltic Sea. There has been a number of CO_2 storage studies carried out in the Baltic region (Elrstrom, 2011, Erlstrom, 2008, VTT, 2010, Sliaupa S., 2009, Shogenova, 2009), some of which have been funded by the European Commission EUGeocapacity and CO2NET East projects. None of these reports has prioritised CO_2 storage sites in the Baltic Sea Basin from a strategic prospective. In Section 4 geological, resource and societal criteria are applied to rank CO_2 storage sites in order of priority for further investigation in Section 6 where storage capacity estimates are provided.

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 (**Appendix A**). This assessment by SLR is searching for a geological formation that is ultimately capable of storing 50 million tonnes of dense phase CO_2 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_2) 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_2 stability. The Precambrian crystalline basement of the Baltic Sea Basin lacks porosity and permeability for CO_2 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_2 that are sealed by shale and claystone aquitards (see Figure 1below). Mesozoic rocks that unconformably overlie the Paleozoic are not deeply buried enough for CO_2 storage and are confined to the south and southwest of the Baltic Sea area.

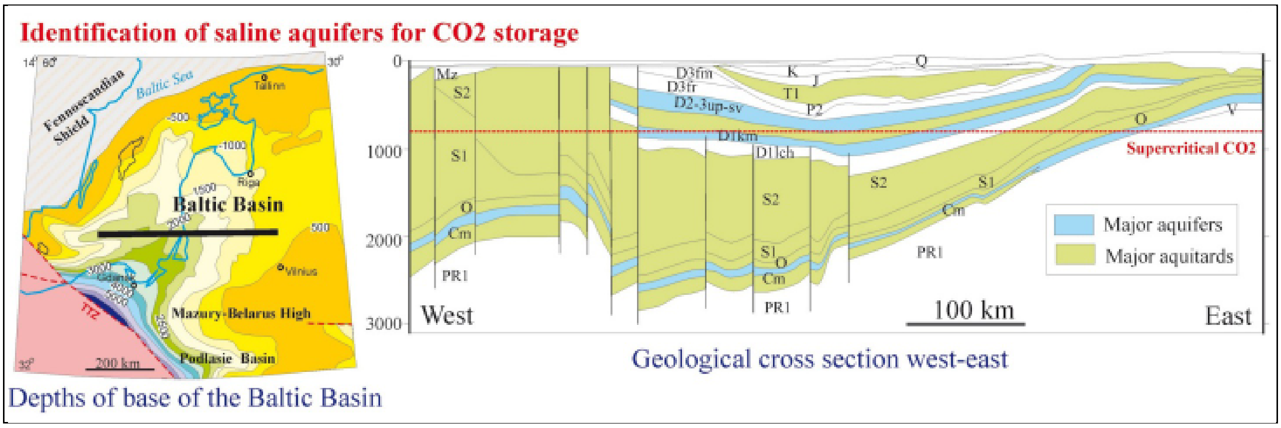


Figure 1 Map showing depth in metres of the Caledonian Baltic Sea Basin with a geological cross section indicating the aquifers that could store CO2 in supercritical state below 800m[1]

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

[1] 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 Sliaupa S., 2009).

underlain by Proterozoic crystalline basement (Figure 1). The area of the basin is about 200,000km^2 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. The sub-basins are separated by the Leba High and Liepaya-Saldus Ridge where structural traps are abundant (**Appendix A**). 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 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_2.

The main targets for CO_2 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_2 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_2 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_2 can be trapped in monoclinal structures (Erlstrom, 2008).

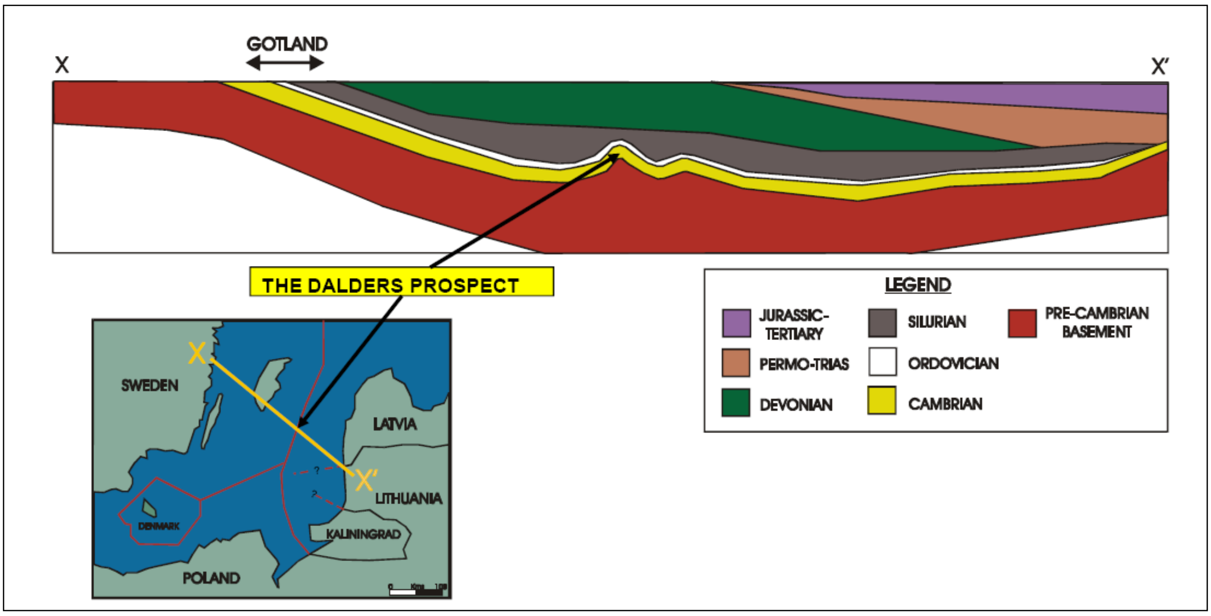


Figure 2 Location of the Dalders Prospect and the Dalders Monocline (from OPAB)

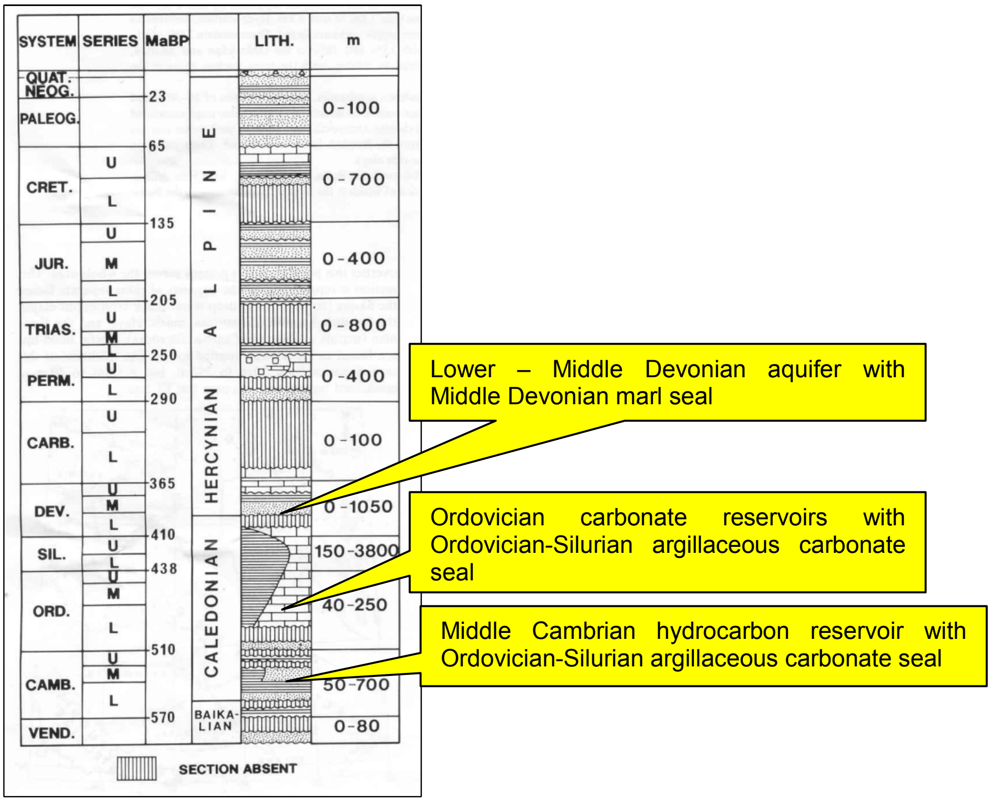


Figure 3 Geological section of the sedimentary basins in the Baltic Sea area[2]

[2] 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 4th 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^2. The synclinal structure is approximately 700km long and 500km wide. The axis of the syneclise plunges to the southwest. Towards the north, east and southeast the syneclise is bounded by the Baltic Shield, the Latvian Saddle and Byelorussian Anteclise, 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 (**Appendix A**) 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^2.
- **Gdansk-Kura Depression(GKD)** located in the south-eastern Baltic Sea, covers parts of Poland Russian and Lithuania and has an approximate surface are of 8000km^2.
- **Liepaja Saldus Ridge (LSR)** located in the southern part of the Baltic Sea and extends southeast to northwest across the Baltic Sea into Latvia. The Liepaja Saldus Ridge has a surface area of 2500 km^2.
- **Latvian, Estonian, Lithuanian Border Zone (LEL)** is located in the mid Baltic Sea and extends south east north west covering parts of Estonia, Latvia and Gotland Island. The border zone has an approximate surface area of 2500 km^2.

3.2 General Geology

The Baltic Sea Basin contains a full sedimentary sequences 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 Caladonian Complex
- The Variscan Complex
- The Alpine Complez

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-basin that contain the indentified CO_2 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_2 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_2 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)

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

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 Rodina 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.

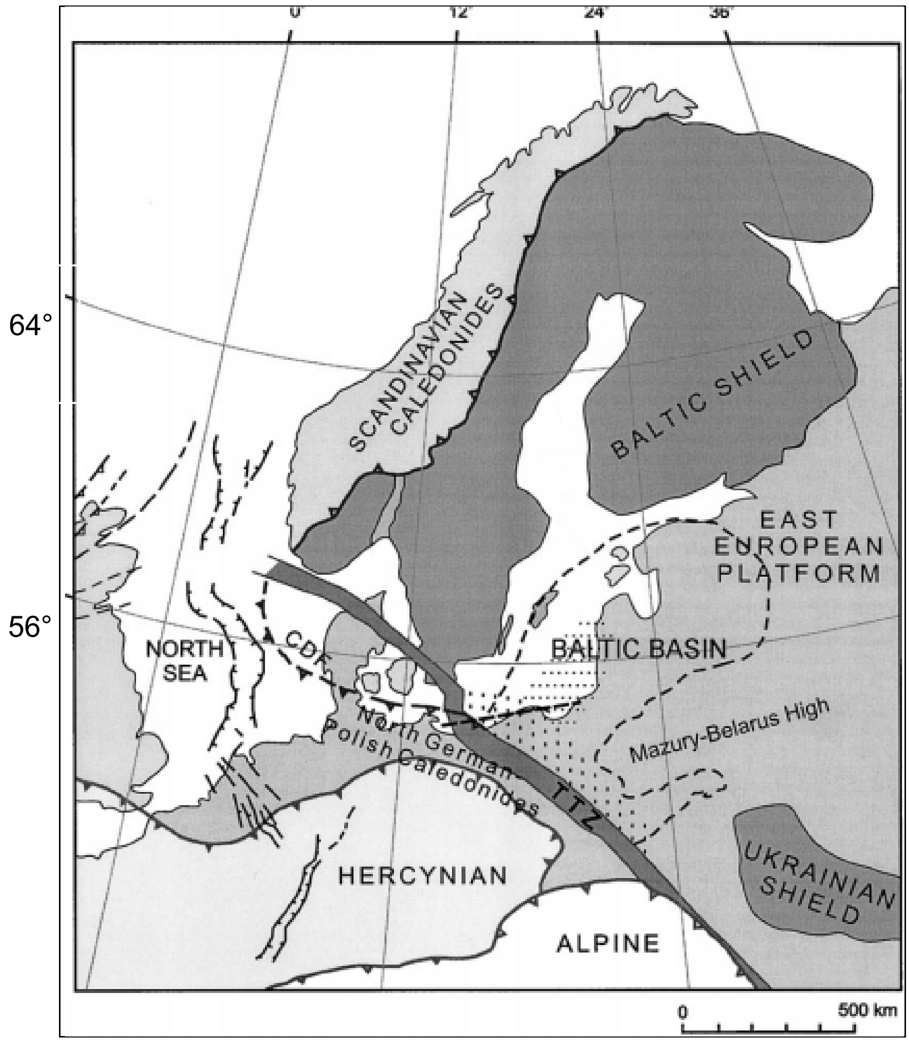


Figure 4: Major Tectonic structures and orogenic belts surrounding the Baltic Basin[3]

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 Broder Zone is a gently sloping monocline at the west north west 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_2 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 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

[3]Poprawa et al, 1999

particularly distinct. The ridge contains several untested potential CO_2 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 Incukalns 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 Bailkalian, Caledonian, Hercynian and Alpine, can be distinguished and are separated by angular unconformities.

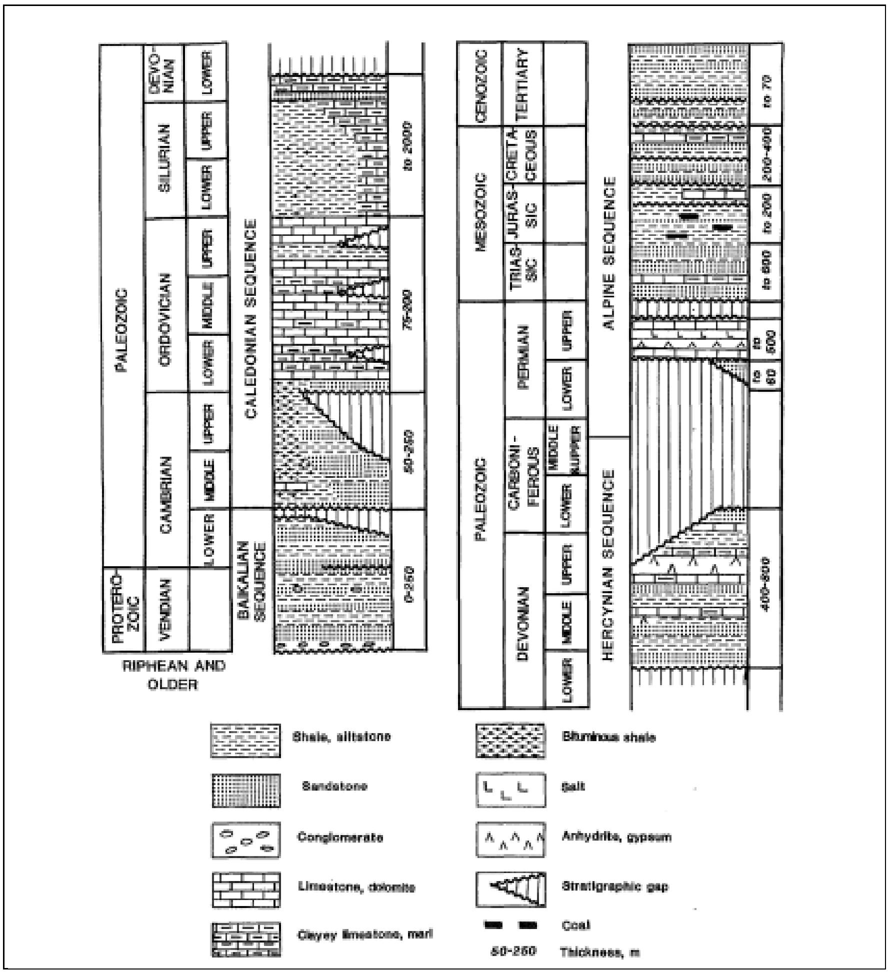


Figure 5: Stratigraphic Column of the Baltic Sea Basin showing the main depositional sequences[4].

[4] Ulmishek G, 1990

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 Sevconorwegian 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).

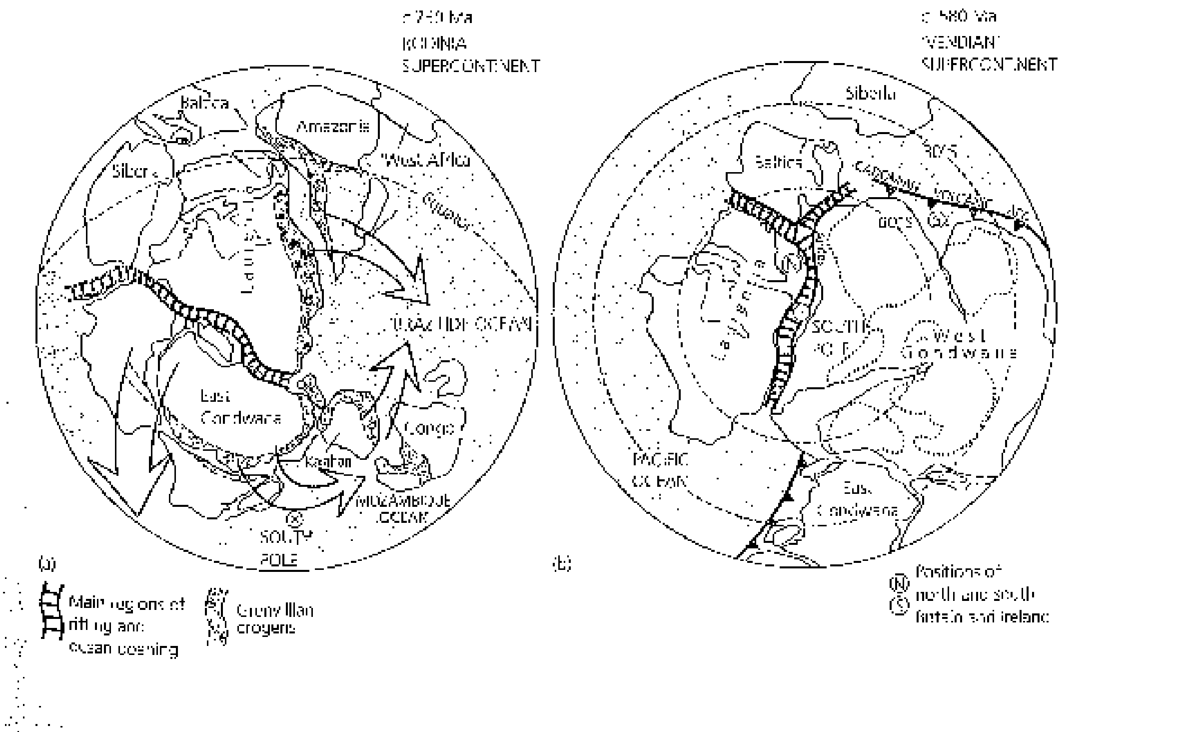


Figure 6 Global Paleocontinent reconstruction from the Neoproterozoic.

3.5.1 Proterozoic

The Proterozoic resulted in the deposition of a considerable thickness of the Jotnian red quatrzites, 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_2 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, see **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.

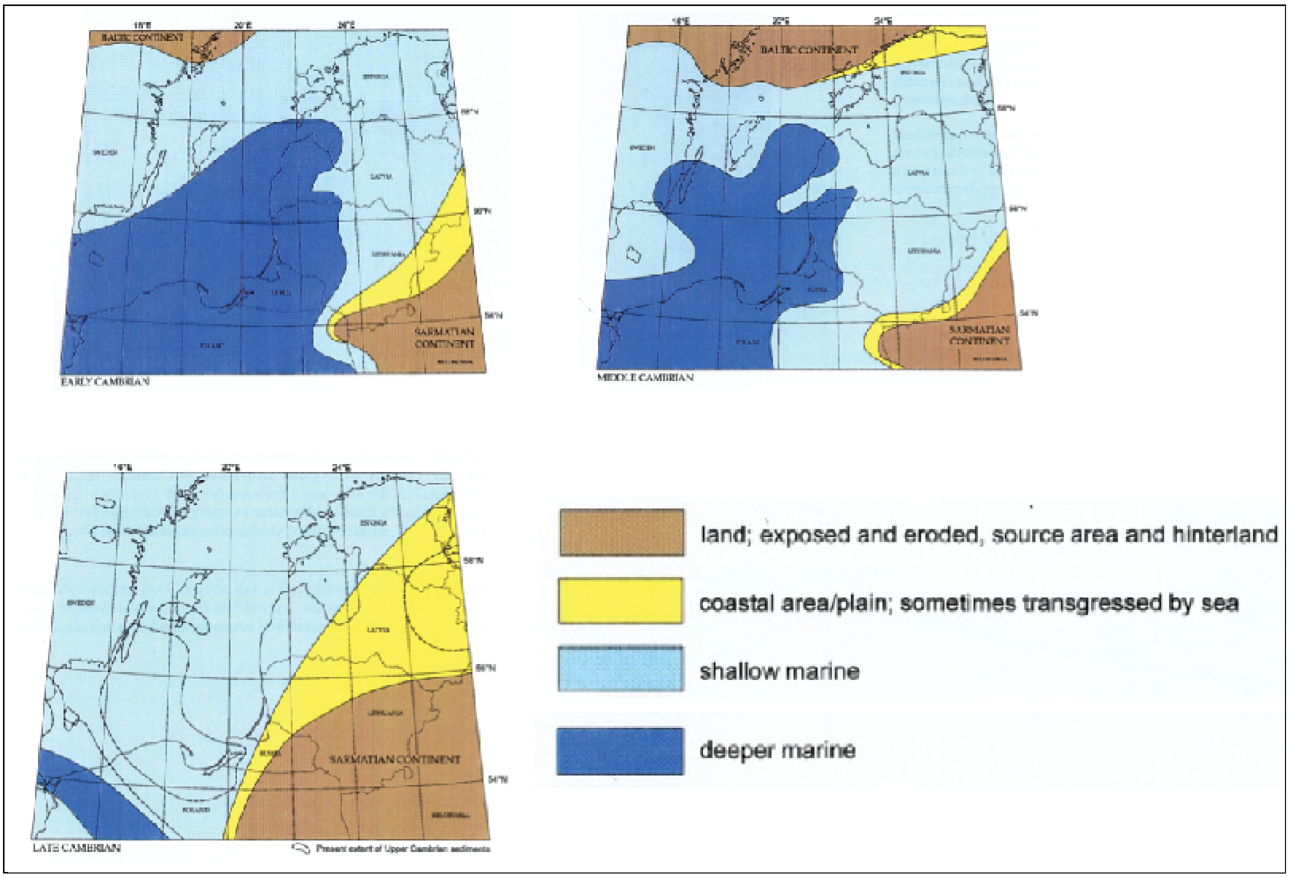


Figure 7 Reconstruction of the Cambrian paleoenvironment, separated into Early, Middle and Late Cambrian[5]

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 this 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_2 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_2 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_2 storage. The upper Permian is made up of carbonate and evaporitic deposits.

[5] Tarvis, T. 2007

3.5.10 Mesozoic & Cenozoic

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

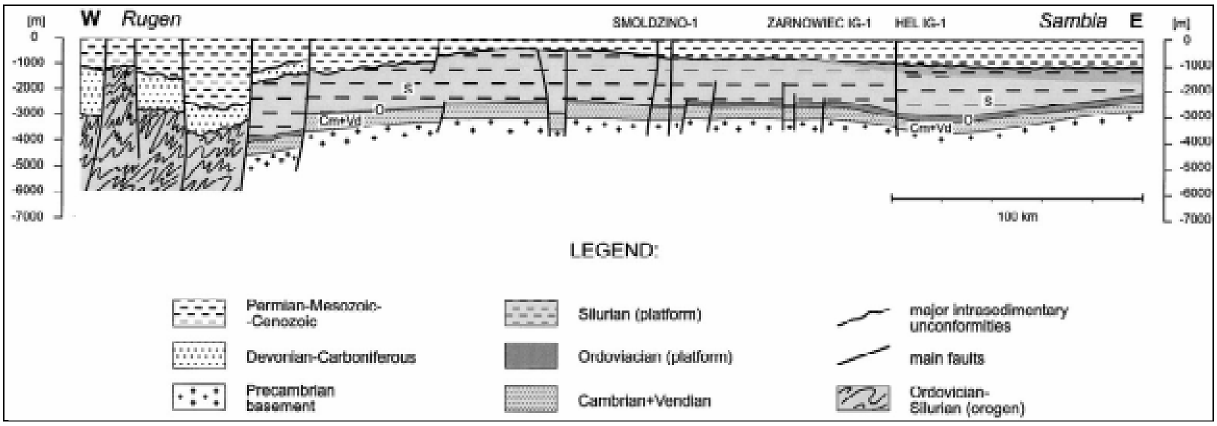


Figure 8 Sambia-Rugen cross section through the central western part of the Baltic Basin and the Caledonides.

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_2 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 Darcies. 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.

The Ordovician has little potential as a CO_2 storage reservoir due to the variability of carbonate porosity and permeability as well as size of individual reef structures.

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.

3.6.3 Traps

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_2 Storage

The conclusion of the geological overview is that the only workable reservoir seal pair for CO_2 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.

The basin screening in Section 4 concentrates on the assessment of these sub-basins for CO_2 storage.

4.0 BASIN SCREENING

Bachu developed a quantitative evaluation of a sedimentary basin's suitability for CO_2 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_2 geological sequestration (Bachu 2003)

	Criterion	Classes 1	2	3	4	5
1	Tectonic setting	Convergent oceanic	Convergent intramontane	Divergent continental shelf	Divergent foredeep	Divergent cratonic
2	Size	Small	Medium	Large	Giant	
3	Depth	Shallow (<1,500 m)	Intermediate (1,500–3,500 m)	Deep (>3,500 m)		
4	Geology	Extensively faulted and fractured	Moderately faulted and fractured	Limited faulting and fracturing, extensive shales		
5	Hydrogeology	Shallow, short flow systems, or compaction flow	Intermediate flow systems	Regional, long-range flow systems; topography or erosional flow		
6	Geothermal	Warm basin	Moderate	Cold basin		
7	Hydrocarbon potential	None	Small	Medium	Large	Giant
8	Maturity	Unexplored	Exploration	Developing	Mature	Over mature
9	Coal and CBM	None	Deep (>800 m)	Shallow (200–800 m)		
10	Salts	None	Domes	Beds		
11	On/Off Shore	Deep offshore	Shallow offshore	Onshore		
12	Climate	Arctic	Sub-Arctic	Desert	Tropical	Temperate
13	Accessibility	Inaccessible	Difficult	Acceptable	Easy	
14	Infrastructure	None	Minor	Moderate	Extensive	
15	CO_2 Sources	None	Few	Moderate	Major	

Sedimentary basins were selected for their suitability for storage of CO_2 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_2 storage

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

Table 4 Proposed secondary qualifiers for assessing the potential of sedimentary basins for CO_2 storage

	Potential Criterion	Poor Potential	Good Potential	Weight
1	CO_2 sources	At >500 km distance	At <500 km distance	0.08
2	Physical accessibility	Difficult	Good	0.03
3	Infrastructure	None or poor	Developed	0.05
4	Hydrogeology Flow systems	Shallow, short	Deep and/or long	0.08
5	Geothermal regime[1]	Warm	Cold	0.10
6	Hydrocarbon potential and industry maturity	None, poor	Large, mature	0.08
7	Coal	Too shallow or too deep	Between 400 and 1000 m depth	0.04
8	Coal value[2]	Economic	Uneconomic	0.04
9	Climate	Arctic and sub-arctic	Temperate	0.08
			TOTAL	**0.58**

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_2 storage because it is a stable divergent cratonic basin with limited faulting and extensive sealing shale. It has regional long range flow systems. The cold climate and geothermal gradient increase CO_2 storage capacity and decrease CO_2 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_2 sequestration and storage is inefficient (low CO_2 density) and unsafe because of very high CO_2 buoyancy. 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_2 storage in saline aquifers but further reservoir engineering studies are required to establish the integrity of CO_2 trapping in monoclines where no structural closure exists. This applies in particular 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_2 from point sources surrounding the Baltic Sea. Both pipeline and shipping transport are considered. In Tables 4, 6, 8 and 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_2 storage sites below 800m onshore and offshore in shallow water. There are major CO_2 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_2 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 (**Appendix A**) 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_2 storage

	Criterion	*Threshold*	*Slupsk Monocline*	*Weight*
1	Depth	>800 m	Deep (1000+ m)	0.07
2	Size at surface	>2500 km^2	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_2 storage

	Potential Criterion	*Poor Potential*	*Good Potential*	*Weight*
1	CO_2 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 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 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_2.
- A significant part of the Dalders monocline is accessible in Swedish territory.
- When the Latvia/Lithuania border is ratified all of the Dalders structure could be accessible for oil field development with CO_2 Enhanced Oil Recovery (EOR).

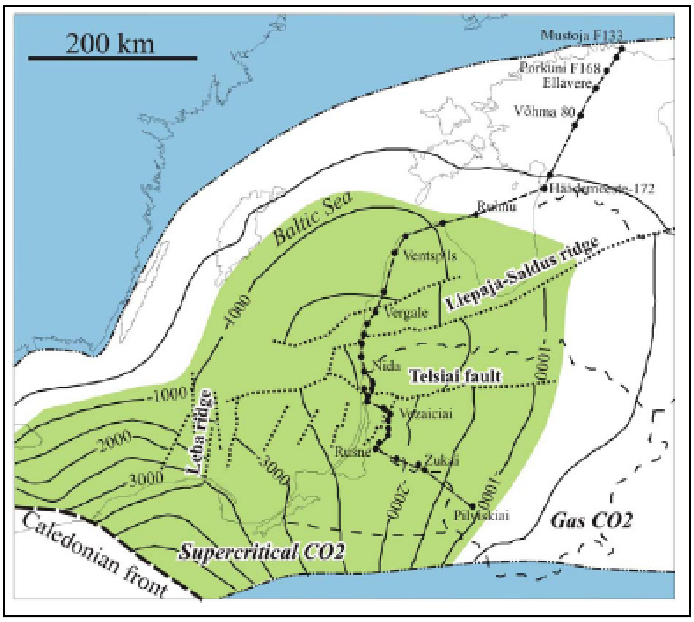


Figure 9 Depth of top of the Cambrian aquifer.[6]

The score of 0.76 for the Slupsk Border Zone makes it a potential candidate for CO_2 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(Petroswede 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_2 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 is a monoclonal structure that surrounds the margins of the Baltic Basin (**Appendix A**). 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_2 storage (**Figure 9**). There is onshore pipeline infrastructure in Latvia and an underground gas storage facility at Inčukalns which proves the CO_2 storage capacity of the Cambrian sandstone reservoirs and the physical accessibility. The area is also less than 400kms from CO_2 point sources in Finland.

[6] The line of the geological cross-section shown in Fig. 6 is indicated. The green area indicates the pressure temperature field for supercritical CO_2 (after Sliaupa S., 2009).

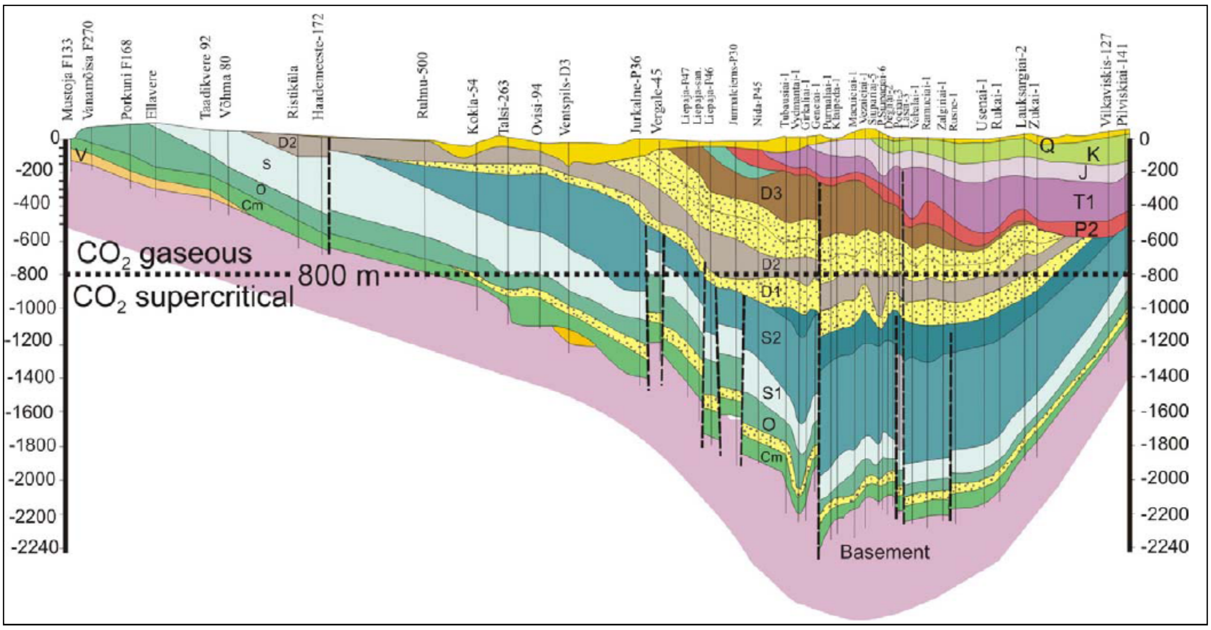


Figure 10 Geological cross section across Estonia, Latvia, and Lithuania[7]

Table 7 Criteria for consideration of Latvian Estonian and Lithuanian Monocline for CO_2 storage

	Criterion	*Threshold*	*Latvian Estonian Lithuanian Monocline*	*Weight*
1	Depth	>1000 m	Deep (1000+ m)	0.07
2	Size at surface	>2500 km^2	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

[7] **Modified after Sliaupa et al. 2008**

Table 8 Secondary qualifiers for assessing the potential of Latvian Estonian and Lithuanian Monocline for CO_2 storage

	Potential Criterion	Poor Potential	Good Potential	Weight
1	CO_2 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 Table 6 and Table 7 for Latvian Estonian and Lithuanian Monocline = 0.71

COMMENTS:

- Ten sources in Lithuania emit more than 0.1Mt of CO2 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_2 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.
- 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 CO2 storage.

The LEL, with a score of 0.71, is a possible candidate for CO_2 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 CO2 were identified in Lithuania. Ordovician algal reefs occur at shallow depths in small structures in Gotland and onshore Latvia. Thirty large structures are identified in Latvia, onshore and offshore (Sliaupa S., 2009).

4.3 Liepaja-Saldus Ridge

The Liepaja-Saldus Ridge (**Appendix A**) 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_2 storage

	Criterion	Threshold	Liepaja-Saldus High	Weight
1	Depth	>800 m	Deep (1000+ m)	0.07
2	Size at surface	>2500 km^2	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_2 storage

	Potential Criterion	Poor Potential	Good Potential	Weight
1	CO_2 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_2 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 (**Appendix A**). 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_2 storage

	Suitability Criterion	Gdansk-Kura Depression	Weight
1	Depth	Deep (1000+ m)	0.07
2	Size at surface	Moderate size structures (in Poland ~8,000 km^2)	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_2 storage

	Potential Criterion	Poor Potential	Good Potential	Weight
1	CO_2 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 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_2 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. The Liepaja Depression is not a candidate for CO2 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), Latvian Estonian Lithuanian Border Zone (0.71).

Table 13 Ranking of Baltic Sea sub-basins in terms of suitability for CO_2 geological sequestration

Rank	Basin	Characteristics	Score
1	Slupsk Border Zone	Proven reservoir/seal pair, moderate size structures, offshore, large saline aquifer, limited faulting, good accessibility, <500kms to strategic CO_2 sources	0.76
2	Gdansk-Kura Depression	Existing oil and gas production infrastructure, moderate sized structures, offshore, fair accessibility, >500kms to some strategic CO_2 sources	0.75
3	Liepaja Saldus Ridge	Proven reservoir/seal pair, moderate size structures, offshore, fair accessibility, <500kms to strategic CO_2 sources	0.75
4	Latvian Estonian Lithuanian Border Zone	Proven reservoir/seal pairs, small structures, potential saline aquifer, only small area sufficiently deep for CO_2 storage, accessible, 250kms to strategic CO_2 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_2 storage structure that is accessible to Swedish CO_2 point sources. The Gdansk-Kura Depression is geologically suitable for CO_2 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_2 from the Lotos refinery in Gdansk. The Liepaja Saldus Ridge is closer to CO_2 sources in Finland and has potential CO_2 storage in saline aquifers offshore Latvia. The LEL Border Zone has the lowest rank because only a small area is sufficiently deep for CO_2 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. Blidinziai	GKD	B34	LSR	Kasnobor W	GKD
Lapgiriai	LEL			Dejmina	GKD
Lauksargiai	GKD			Kasnobor	GKD
Plunge	GKD			Slavinsk	GKD
Girkaliai	GKD			Kasnobor N	GKD
Ablinga	GKD			Malinovsk	GKD
Vezaiciai	GKD			Usakovsk	GKD
Siupariai	GKD			Gajevsk	GKD
P. Siupariai	GKD			Laduskino	GKD
Degliai	GKD			Veselovsk	GKD
Silale	GKD			Slavsk	GKD
Pociai	GKD			D5-1	GKD
Vilkyciai	GKD				
Sakuciai	GKD				
Kybartai	LEL				
Kudirka	LEL				

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

where:

ρ_{CO_2}= CO_2 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_2 storage potential of the Lithuanian, Polish and 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_2 density was obtained from the data included in the LOTOS, 2010 presentation.

CO_2 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_2 density value of 0.650t/m^3 was used due to the lack of specific formation data.

6.2.2 Detailed Hydrocarbon Fields:

Calculations of CO_2 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:

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

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

where:

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

$\boldsymbol{R_f}$ = Recovery Factor

$\boldsymbol{F_{ig}}$ = Fraction of Injected Gas

$\boldsymbol{OGIP}$ = Original Gas in Place (at surface conditions)

$\boldsymbol{B_g}$ = Gas Formation Volume Factor <<1

$\boldsymbol{OOIP}$= Original Oil in Place (at surface conditions)

$\boldsymbol{B_o}$ = Oil Formation Volume Factor >1

$\boldsymbol{V_{iw}}$ = Volume of Injected water

$\boldsymbol{V_{pw}}$ = 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 15Table 14** 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
B3	Total	LSR	**Genciai**	Total	GKD
B4	B4-1	LSR	**Nausodis**	Total	GKD
B6	B6-1	LSR	**Kretinga**	Total	GKD
B8	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:

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

where:

ρ_{CO_2}= CO_2 density at reservoir conditions (best estimate based on available data & using the CO_2 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)

$\emptyset$ = 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^2 was calculated. The Dalders Monocline as outlined in the structural elements of the Baltic Syneclise (Tarvis, 2007) and mapped below 900m (LO&G, Enclosure 2, 2002) was calculated as 19,634km^2. 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_2 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_2 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_2 density of 0.603 t/m^3 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% was 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 (see **Appendix A**). 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. The Dalders structure located in the central part of the Baltic Sea Area has an estimated theoretical storage potential of 128Mt. The Dalders structure is shown also on **Appendix A**.

Table 17 Theoretical Storage Capacity Summary

	Estimated CO_2 Storage Capacity (10^6 tonnes)
POLAND	
Regional Cambrian Below 900m	16,222
of which Dalders Monocline	1,942
Individual Baltic Sea Field Total	943
of which Dalders Structure	128

Results from the individual hydrocarbon fields, saline aquifer structure and bulk assessments are further discussed 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 18 Hydrocarbon Field Theoretical Storage Capacity

LITHUANIA	Estimated CO_2 Storage Capacity (10^6 tonnes)
S. Blidinziai	0.32
Lapgiriai	0.32
Lauksargiai	0.16
Plunge	0.28
Girkaliai	3.75
Ablinga	0.66
Vezaiciai	2.78
Siupariai	2.50
P. Siupariai	5.51
Degliai	1.89
Silale	1.23
Pociai	0.50
Vilkyciai	5.05
Sakuciai	1.90
Kybartai	0.48
Kudirka	1.53
TOTAL	**28.87**

POLAND	Estimated CO_2 Storage Capacity (10^6 tonnes)
B34	3.28
TOTAL	**3.28**

KALININGRAD	Estimated CO_2 Storage Capacity (10^6 tonnes)
Kasnobor W	26.16
Dejmina	5.17
Kasnobor	36.15
Slavinsk	4.97
Kasnobor N	6.72
Malinovsk	19.23
Usakovsk	36.29
Gajevsk	1.14
Laduskino	26.22
Veselovsk	1.87
Slavsk	3.17
TOTAL	**167.10**

Detailed UR data (LO&G, 2002) relating to the Kaliningrad fields was not available. Therefore FVF values based on the Lithuanian field values and a CO_2 density value of 0.6500 t/m^3 were used. The total theoretical storage capacity value of 167.1 Mt of CO_2 for the Kaliningrad fields is more than likely an overestimate.

Individual Lithuanian hydrocarbon fields are estimated to have a total theoretical storage capacity of just under 29 Mt using a reasonable amount of data that was available for the UR estimates (LO&G, 2002), the FVF and CO_2 density values (Streimikiene, 2010).

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

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 Hyrocarbon Fields Method also show relatively small storage potential associated with individual hydrocarbon fields across the Baltic Sea region.

Table 19 Hydrocarbon Field Detailed Theoretical Storage Capacity

	Trap/ Structure Name	Hydrocarbon Field CO_2 Storage Capacity (10^6 tonnes)
POLAND		
B3	Total	4.75
B4	B4-1	0.40
B6	B6-1	0.31
B8	B8-1	3.63
	TOTAL	**9.09**
LITHUANIA		
Genciai	Total	1.48
Nausodis	Total	0.18
Kretinga	Total	0.19
	TOTAL	**1.86**

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.

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 18,145.11 Mt. The largest proportion of this is the generic regional estimated CO_2 storage potential for the Cambrian below 900m which is 16,221Mt of the 18,145.11 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^2 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 20 Regional Saline Aquifer Theoretical Storage Capacity

Saline Aquifer Bulk - Storage Potential	Estimated CO_2 Storage Capacity (10^6 tonnes)
Cambrian below 900m	**16,221.56**
Dalders Monocline	**1,923.55**

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:

The combined total of the seven bulk trap assessments in the Latvian offshore and the Dalders structure represent a theoretical storage capacity of 761.37 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 21**).

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

Table 21 Saline Aquifer Field Theoretical Storage Capacity

Structure Name	Saline Aquifer Field CO_2 Storage Capacity (10^6 tonnes)
Dalders Structure	127.91
E5	36.31
E6	35.26
E7	18.01
E12-E2-13-D10	144.09
E17	104.70
P4	29.03
E23	266.05
TOTAL	**761.37**

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 significant potential are present in the Latvian offshore region with the E23, E17 and combined E12 structures of particular interest.

Since the completion of the Progress Report in May 2012, additional data from offshore Latvia has been acquired and delivered improved closure structure geometry. With the exception of E6 and E7, none of the structures have been drilled and NG ratios and average porosity values are estimated 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.

7.0 STATIC MODEL:

Based on the well and Cambrian depth structure map data available for the Baltic Sea that were compiled as part of this initial assessment, four areas of interest have been identified in the Baltic Sea as potential 'Sweet Spots' for CO_2 storage. This section describes the methodology for development of the static model for the selected areas shown in **Table 22**.

Table 22 Static Model Structure Sizes

	Area in km^2	Area in m^2
Dalders Structure	161	160,784,104
Dalders Monocline	19,634	-
E-6 Structure	26	26,368,579
E-7 Structure	26	26,298,247

For the four areas of interest, the depth of the Top Cambrian has been selected as the top of the Middle Cambrian Faludden sandstone (SST) because due to an unconformity the Upper Cambrian is absent in most of the Baltic Sea region. Where it is present (e.g. B-10 and B-3 wells) it never exceeds 10m. The bottom of the reservoir was the Bottom Faludden SST Layer and, with the exception of the Dalders monocline, the thickness of the Faludden SST reservoir is assumed as being constant throughout the structure based on the thickness recorded in the available wells for each area. Details of the available data are summarised in **Table 23** below.

Table 23 Depth of the Top Cambrian, Bottom Cambrian and Base Faludden SST from well data in the four areas of interest (m.b.R.T.).

	Top Cambrian	Bottom Cambrian	Thickness Cambrian	Top Faludden SST	Base Faludden SST	Thickness Faludden SST
Dalders structure						
B-9	994.6	1239.6	245	998.5	1046.6	48.1
Dalders Monocline						
B-10	407.1	496.1	89	413	435.6	22.6
B-11	773.2	1006.5	233.3	773.2	805	31.8
B-3	736	1003	267	742	772	30
B-5				718	745	27
B-7				829.5	870.5	41
B-9	994.6	1239.6	245	998.5	1046.6	48.1
B0-12	569.3	790.3	221	569.3	608.1	38.8
B0-13	689	928	239	689	722	33
BO-20				628.3	654.1	25.8
BO-21	688.7	925	236.3	688.7	718.5	29.8
E6-1	875	1045	170	875	928	53
E7-1	1389	1601	212	1389	1446	57
P6	1254	1542.5	288.5	1254	1337	83
E-6 Structure						
E6-1	875	1045	170	875	928	53
E-7 Structure						
E7-1	1389	1601	212	1389	1146	57

The methodology used for the compilation of the individual static models as well as the assumptions made for the individual structures is described in the individual sections below.

7.1 Dalders Monocline

Principal data set used:

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

Assumption relating to the Top Cambrian:

Giving the limited amount of wells (only two within the Dalders Monocline), a progressive variation of the thickness (see below) was assumed with the overall thickness of the Faludden Sandstone increasing towards the north east.

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.

Determination of the Base Faludden Sandstone Layer:

The thickness of the Faludden SST was determined using the same interpolation methodology as for the Top Cambrian. The thickness was assumed to increase from the south west (about 30m) to the north east (about 110m) based on the reservoir thickness observed in the P6 and B-9 wells. The reservoir thickness recorded adjacent to the Monocline in the offshore Polish fields (LOTOS, 2010) were used to verify the thickness assumption for the Dalders Monocline.

Boundary of the Dalders Monocline:

The boundary of the Dalders Monocline is determined by the regional fault structures bounding the Monocline on its south eastern margin and the 900m depth limit for the Top Cambrian in the shallowest part of the Monocline taking into consideration the progressive thickening of the Cambrian towards the north east.

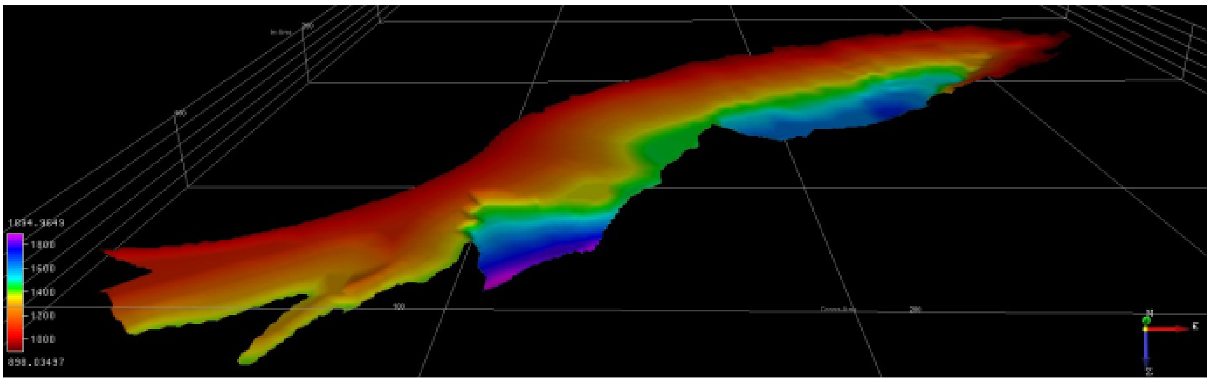


Figure 11 Top Cambrian Layers of the Dalders Monocline.

7.2 Dalders Structure

Principal data set used:

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

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. Figure 12 below shows the surface of the Top Cambrian in the Dalders Structure.

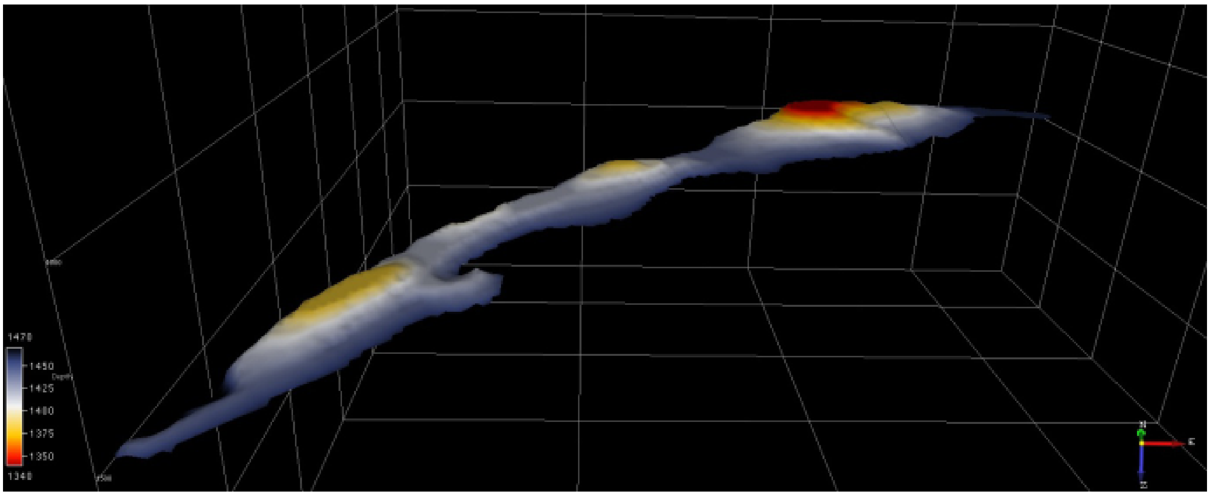


Figure 12 Top Cambrian Layers of the Dalders structure.

Determination of the Base Faludden Sandstone Layer:

The thickness of the Faludden SST has been determined using the closest wells in the area (B-9 and E7-1). From these values a value 55m was used as a constant thickness for the Dalders Structure model.

Boundary of the Dalders Structure:

The boundary of the Dalders structure was determined using the mapped fault structures to the north and the 1460m Middle Cambrian contour.

7.3 E6 Structure

Principal data set used:

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

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 13 below shows the surface of the Top Cambrian in the E6 structure.

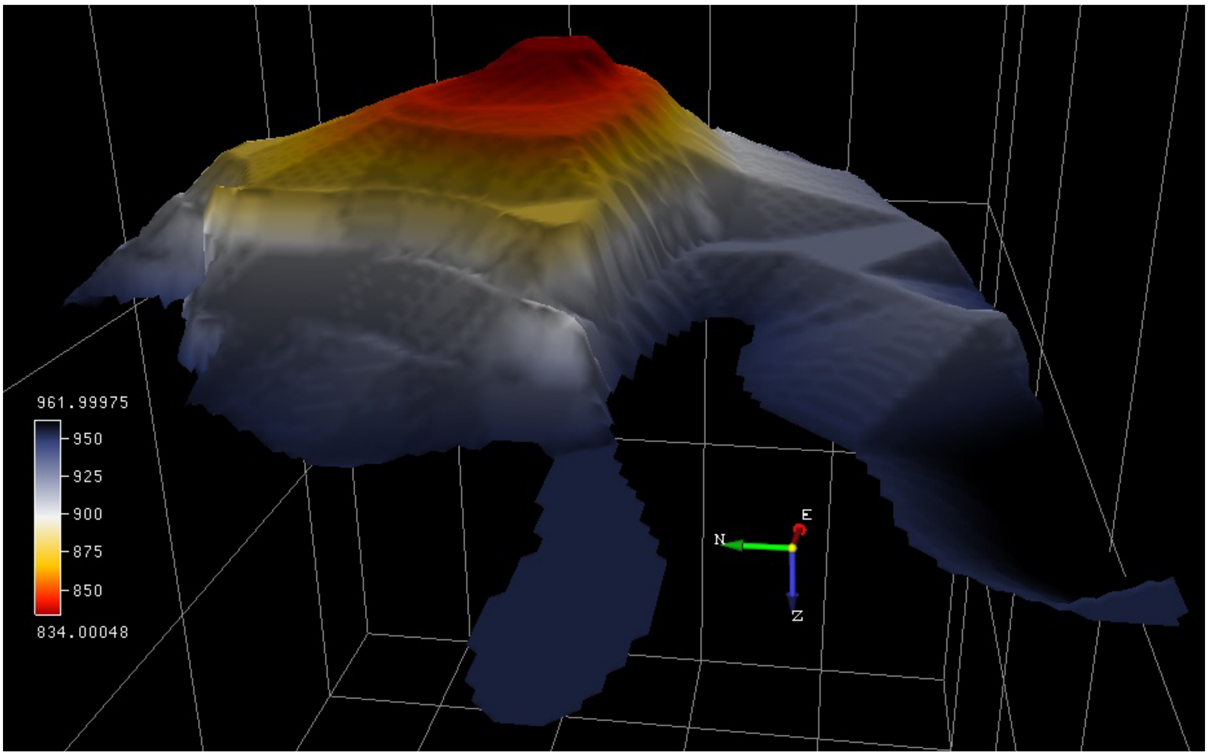


Figure 13 Top Cambrian Layers of the E6 Structure.

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 all E6 structure.

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

Principal data set used:

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

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 14 below shows the surface of the Top Cambrian in the E7 structure.

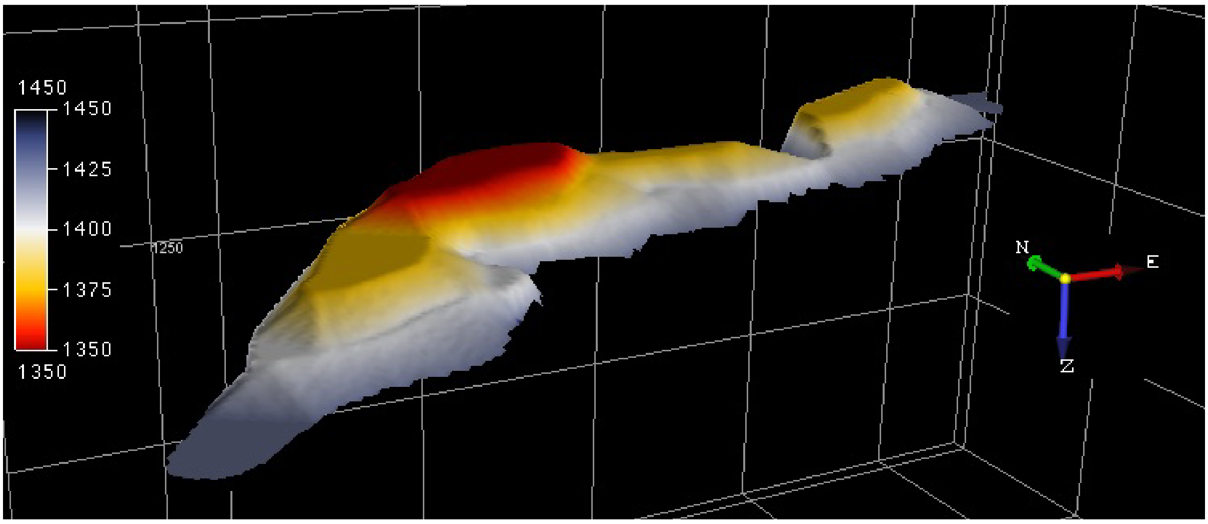


Figure 14 Top Cambrian Layers of the E7 structure.

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.

Boundary of the E6 Structure:

The boundary of the DaldeE6rs structure was determined using the mapped fault structures and the 950m contour.

8.0 CONCLUSIONS:

- A total theoretical storage capacity potential for individual Baltic Sea fields including both the hydrocarbons and the saline aquifer fields has been calculated as 942 Mt. The potential assessed as part of this initial review phase suggests individual hydrocarbon fields may be too small to be considered for matched storage capacity.

- Regional theoretical storage of Cambrian sandstone saline aquifers below 900m in the Baltic Sea region is estimated at 16 Gt with storage potential for the Dalders monocline estimated at 2 Gt of this figure. The area covered by the Dalders Monocline represents significant potential storage in Baltic Sea strategically located in the centre of the study area.

- Eight individual Latvian offshore fields including the Dalders structure were modelled individually based on detailed Cambrian depth structure maps, fault structure outlines and well data. The overall theoretical storage capacity was estimated to be 761 Mt, representing a significant increase from the Progress Report of May 2012, with the inclusion of additional data from the Latvian offshore.

- Structures identified in offshore Latvia were assessed based on summary well and formation data. A total theoretical storage potential of 10Mt from five structures was calculated, however this requires further detailed assessment using additional exploration well data results and seismic depth structure maps.

- Based on additional detailed field data for the Latvian offshore, four structures including the Dalders Monocline, Dalders Structure, the E6 and the E7 structures were identified as sweet spots and individual static reservoir models were developed.

- Data from offshore Polish fields was limited and a detailed theoretical storage potential assessment is not possible without access to further data.

- Access to oil and gas field data from offshore Poland is needed to increase the confidence of the theoretical storage capacity calculations and facilitate the completion of a dynamic reservoir model.

- To fully evaluate the Dalders Monocline and facilitate the development of a dynamic model, additional information such as reservoir models, formation porosity and permeability data, field data and Cambrian depth structures maps from onshore structures is required.

9.0 RECOMMENDATIONS

- A reservoir study of the CO_2 trapping potential of the Dalders Monocline should be carried out.

- The storage capacity potential of offshore Latvia needs to be further investigated by obtaining additional well data that will contribute to the assessment for CO_2 sequestration offshore on the Liepaja Saldus Ridge.

- Obtain additional available data to expand the existing dataset, improve the characterisation of structures identified as having potential for CO_2 storage, increase the certainty of the existing storage capacity calculations and facilitate the development of a static reservoir model to assess effective potential storage capacity.

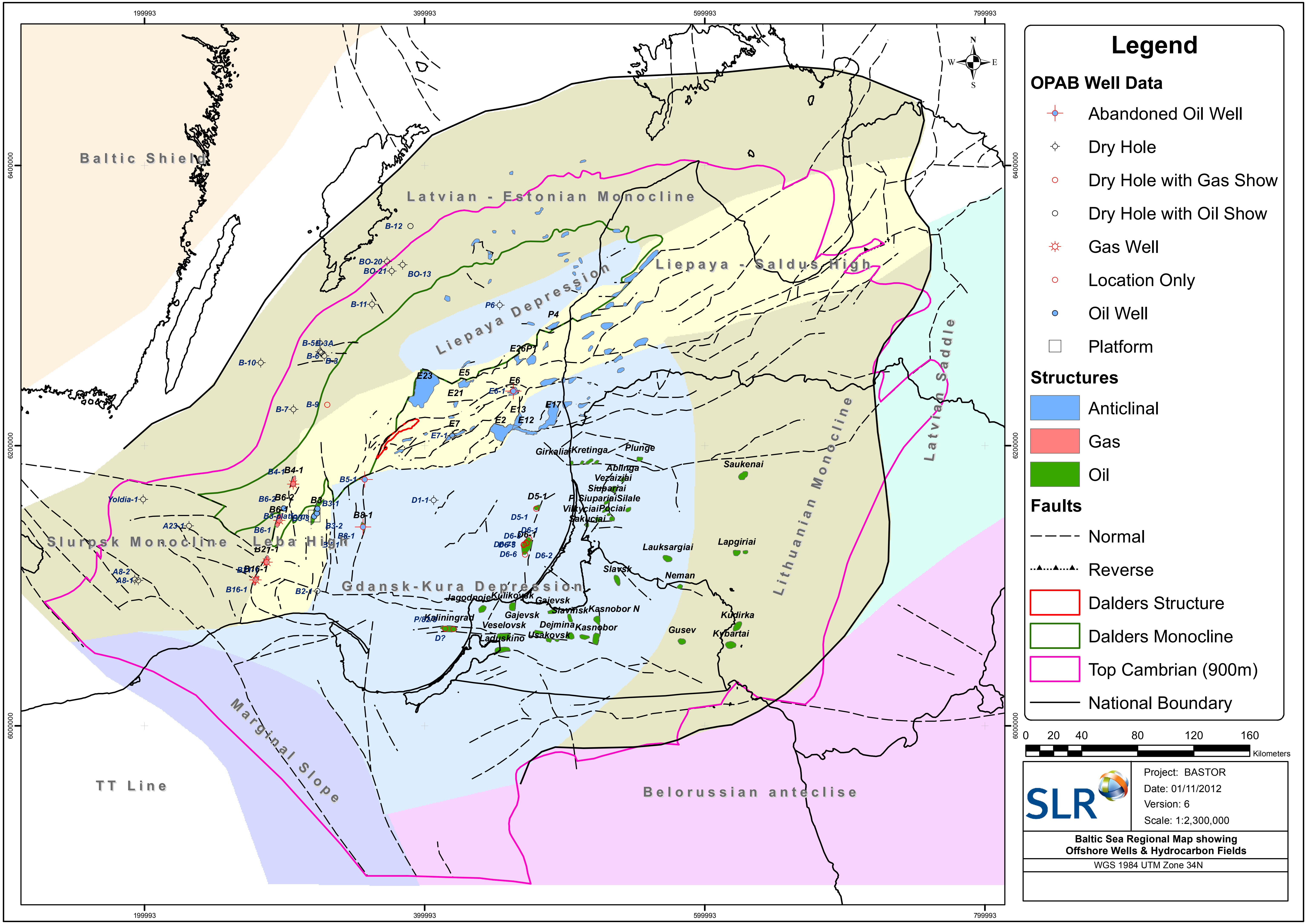
- Discussions with the former PetroBaltic partners should be initiated to develop an integrated approach to enhanced oil recovery and longer term CO_2 sequestration using depleting oil and gas fields offshore Poland and Kaliningrad.

- Baltic State cooperation is imperative to ensure the success of any Baltic Sea CO_2 storage initiative. Additional efforts to increase this cooperation between Baltic States should be undertaken to ensure that an effective strategy for CO_2 storage in the Baltic Sea region is adopted.

- Cambrian depth structure maps based on more recent and reprocessed seismic line data covering the Dalders Structure are needed to further improve the geometry of the closures and identify any additional fault structures that may be limiting the connectivity in the reservoir.

- Reservoir formation data from core samples and wire line logs from any newly drilled wells in the area is required to improve the understanding of the estimated Net to Gross ratios, porosity, permeability, formation pressure and temperature values associated with the reservoir across the Baltic Sea region.

Appendix A Baltic Sea Regional Map showing offshore wells and hydrocarbon fields



Legend
OPAB Well Data
Abandoned Oil Well
Dry Hole
Dry Hole with Gas Show
Dry Hole with Oil Show
Gas Well
Location Only
Oil Well
Platform
Structures
Anticlinal
Gas
Oil
Faults
Normal
Reverse
Dalders Structure
Dalders Monocline
Top Cambrian (900m)
National Boundary
0 20 40 80 120 160
Kilometers
Project: BASTOR
Date: 01/11/2012
Version: 6
Scale: 1:2,300,000
SLR
Baltic Sea Regional Map showing Offshore Wells & Hydrocarbon Fields
WGS 1984 UTM Zone 34N
Baltic Shield
Latvian - Estonian Monocline
Liepaya Depression
Liepaya - Saldus High
Latvian Saddle
Lithuanian Monocline
Slurpsk Monocline
Leba High
Gdansk-Kura Depression
Marginal Slope
TT Line
Belorussian anteclise
199993
399993
599993
799993
6400000
6200000
6000000
Kretinga
Plunge
Girkaliai
Ablinga
Vezaiciai
Siuparai
Saukenai
Lauksargiai
Lapgiriai
Slavsk
Neman
Kudirka
Kybartai
Gusev
Jagodnoje
Kulikovsk
Gajevsk
Slavinsk
Kasnobor N
Kasnobor
Dejmina
Veselovsk
Usakovsk
Ladushkino
Kaliningrad
E23
E5
E21
E6
E6-1
E13
E17
E2
E12
E7
E7-1
E26
P1
P4
P6
B-12
BO-20
BO-21
BO-13
B-11
B-10
B-7
B-9
B-3
B-6
B4-1
B5-1
B6-2
B6-1
B3
B8-1
B3-2
B21-1
B16-1
B2-1
A23-1
A8-2
A8-1
Yoldia-1
D1-1
D5-1
D6-1
D6-2
D6-6

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11.0 CLOSURE

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