A geophysical investigation of carbonate build-ups in the Baltic Basin using reflection seismic and well data

TEGAN LEVENDAL
During the Late Ordovician, the region around Gotland was part of a shallow epicratonic basin in the southern subtropics. Low latitudes, relatively warm sea temperatures and the presence of a shallow marine environment promoted algae to flourish and diverse carbonate build-ups such as carbonate mounds and reefs developed on the southern margin of Baltica. Locations where these build-ups can be found today include the Palaeozoic sequence beneath the island of Gotland, Sweden and surrounding areas offshore Gotland. Ordovician mud mounds on Gotland were exploited for their hydrocarbon potential during the 1970’s and 1980’s, with large amounts of seismic and well data being acquired by the oil company Oljeprospecketering AB (OPAB). In recent years this largely unpublished dataset has become available for research purposes. Furthermore, the islands of Gotland and Öland have been the target of helicopter-borne electromagnetic investigations conducted by the Geological Survey of Sweden (SGU) (SkyTEM and VLF). Moreover, new seismic reflection data acquired on a research vessel during 2017 complement the OPAB data over certain areas. In published scientific literature, carbonate mounds and reefs have mainly been identified based on outcrops, cuttings samples, cores and wireline logs. Therefore, the extensive seismic and well dataset used in this study provides an opportunity to showcase how large amounts of vintage data can be utilised to generate regional scale attribute maps which can describe geological systems.

In this thesis, the combination of historic seismic and well data, helicopter-borne resistivity data and newly acquired marine seismic data is utilised firstly, to investigate the geometry, distribution and reservoir characteristics of carbonate build-up structures in the Gotland area. Secondly, we generate detailed depth and thickness maps of the Ordovician formation in the subsurface of Gotland based on the seismic data. Thirdly, a detailed interpretation of a 3D seismic dataset acquired over a mound structure on Gotland and a scoping assessment of the potential to utilize these mud mounds for subsurface compressed air energy storage (CAES) is performed. Finally, an automating refraction velocity analysis in the marine seismic data is used to generate a basement velocity map over a large portion of the Swedish sector of the Baltic Sea.

Keywords: Reflection seismic, Ordovician, Silurian, Carbonate mud mounds, Reefs, Gotland, Sweden, CAES, Seismic interpretation, OPAB dataset, 3D seismic

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urn:nbn:se:uu:diva-393043 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-393043)
Dedicated to my mother.
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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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An additional journal article, published during my Ph.D. studies, that is not included in the thesis is:

Contributions

The papers included in this thesis are the result of close collaborations with several colleagues. My individual contributions in each paper are summarized below:

I  I performed the mapping and interpretation of all seismic profiles onshore Gotland. I identified all carbonate mounds on seismic profiles. My interpretations were later used in connection with a mathematical script, written by my assistant supervisor, to calculate the dimensions of the mounds. I wrote the first draft which was later improved by my co-authors. I worked closely with Oliver Lehnert (University of Erlangen-Nürnberg, Germany) and Mikael Erlström (Geological Survey of Sweden (SGU), Lund) to improve the introduction and geology sections, respectively.

II I performed all interpretations of the 3D seismic data. I prepared all the figures and wrote the first draft which was later improved by my co-authors. I worked closely with Oliver Lehnert to improve the geology section and, together with my assistant supervisor, we developed a formulation for calculating the potential energy storage capacity. With the help of the co-authors, we improved the clarity of the text.

III I participated in the marine seismic acquisition cruise on the Baltic Sea. I performed the seismic processing of profile 25 of the ALKOR data. For the seismic refraction method, I applied a processing flow (developed by my main supervisor) to an extensive part of the OPAB marine seismic dataset. I performed all interpretations of the data and wrote the first draft. I worked closely with Mikael Erlström to improve the geology section. The paper was later improved with the collaboration of my co-authors by clarifying the text.
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<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>CDP</td>
<td>Common Depth Point</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>KHz</td>
<td>Kilohertz</td>
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<tr>
<td>km</td>
<td>Kilometre</td>
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<tr>
<td>m</td>
<td>Metre</td>
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<tr>
<td>mBSL</td>
<td>Metre Below Sea Level</td>
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<tr>
<td>MCS</td>
<td>Multichannel Seismic</td>
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<td>mD</td>
<td>Millidarcy</td>
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<tr>
<td>MWh</td>
<td>Mega Watts per Hour</td>
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<td>ms</td>
<td>Milliseconds</td>
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<td>m/s</td>
<td>Metre per second</td>
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<tr>
<td>Ohmm</td>
<td>Ohm metre</td>
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<tr>
<td>OPAB</td>
<td>Oljeprospektering AB (Swedish oil prospecting company)</td>
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<tr>
<td>s</td>
<td>Seconds</td>
</tr>
<tr>
<td>SEGY</td>
<td>Society of Exploration Geophysicists – revision Y</td>
</tr>
<tr>
<td>SkyTEM</td>
<td>Helicopter-borne time-domain electromagnetics</td>
</tr>
<tr>
<td>SGU</td>
<td>Geological Survey of Sweden (Sveriges geologiska undersökning)</td>
</tr>
<tr>
<td>TIFF</td>
<td>Tagged Image File Format</td>
</tr>
<tr>
<td>VLF</td>
<td>Very Low Frequency (Helicopter-borne time-domain electromagnetics)</td>
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1. Introduction

Carbonate build-ups such as reefs and carbonate mud mounds are considered to be areas on the sea floor that were previously colonized by algae and other creatures. Over time, the deposition of small shell debris and organic remains lead to the development of topographic highs. Environmental factors such as sea level change and climate change affect the development of these mounds and reefs. Furthermore, biotic factors and post depositional erosion have been important in controlling their present day geometry. During the Late Ordovician -Early Silurian, Baltica moved northwards, towards the equator (e.g. Jaanusson 1973, Webby 1984, 2002, Cocks and Torsvik 2005, Kröger et al., 2017 with references therein). This shift brought upon low latitudes, relatively warm sea temperatures and the presence of a shallow marine environment, which led to the development of carbonate build-ups on the southern margin of Baltica. Locations where these carbonate build-ups can be found today include the Palaeozoic sequence offshore and beneath the island of Gotland in Sweden.

Ordovician and Silurian carbonate build-ups have previously been studied throughout the Baltic Basin. To date, most of the work within the Baltic Basin is based on observations in wells and outcrops. Carbonate mud mounds have been studied in outcrops within the Ordovician successions of western Estonia (Vormsi Island) and in the Siljan area of central Sweden (Kröger et al., 2017). These build-ups have also been identified in numerous drill cores from the Estonian and Swedish mainlands as well as in western Latvia and central Lithuania, and on islands such as Saaremaa and Hiiumaa (in Estonia) and Gotland (in Sweden) (Tuuling and Flodén, 2000). The first description of the Silurian reefs on Gotland was given by Murchison (1847). On- and offshore Gotland, within the Swedish sector of the Baltic Basin, carbonate build-ups have previously been investigated by 2D reflection seismic studies, outcrops and well drillings within both the Ordovician and Silurian successions (Flodén, 1980; Riding, 1981; Flodén et al., 1995; Tuuling and Flodén, 2000; Flodén et al., 2001; Bjerkèus and Eriksson, 2001; Sivhed et al., 2004; Tuuling and Flodén, 2007; Tuuling and Flodén, 2009; Sopher and Juhlin., 2013; Sopher et al., 2016; Kröger et al., 2017 among others).

In another context, according to the Intergovernmental Panel on Climate Change (IPCC), global temperatures continue to rise with the increase in CO₂
emissions largely related to human activities (IPCC, 2013). Alternative solutions for a sustainable future include the development of renewable and sustainable energy systems. Recently, the municipality of Gotland has established goals on having a climate neutral energy supply. The current plan for the region of Gotland is to produce 100% of its energy needs from renewable sources by 2025 (Region Gotland, 2014). Presently, a large portion of Gotland’s renewable energy is provided by wind turbines (Byman, 2015). The strong dependence of the wind energy on the weather conditions and the possible variability of the wind power has created the needs for energy storage planning. There is a vast amount of energy storage techniques available (Luo et al., 2015) however, one of the possibilities on Gotland is to utilize compressed air energy storage. Furthermore, greenhouse emissions for the area surrounding the Baltic Sea account for 2-5% of global emissions. Therefore, to reduce the CO₂ emissions, another potential option is carbon capture and storage, whereby, the sedimentary structures beneath Gotland have previously been investigated for their suitability of CO₂ storage (e.g., Erlström et al., 2011; Vernon et al., 2013; Sopher et al., 2014; SLR and Uppsala University 2014; Lothe et al., 2015; Yang et al., 2015).

The discovery of hydrocarbons by Oljeprospektering AB (OPAB), during the 1970’s and 1980’s, led to geological exploration and production of oil in the lower Palaeozoic sequence on Gotland, typically within the carbonate mounds. OPAB thus collected a vast dataset on- and offshore Gotland which is currently hosted at the Geological Survey of Sweden (SGU). This dataset is mainly unpublished and consists of marine and land seismic data covering areas over 33,000 km and 2,000 km respectively. The dataset also includes over 300 wells. In 1981, a 3D seismic survey was conducted by Horizon Exploration Ltd (Newman and White, 1981) over a carbonate mud mound as part of an investigation aiming to increasing the hydrocarbon production rates. Furthermore, recent investigations for groundwater have led to the acquisition of helicopter-borne electromagnetic data (SkyTEM and VLF) on the Swedish islands Gotland and Öland. Moreover, in 2017, new multichannel seismic (MCS) data were acquired during the cruise MSM52, by Hamburg University, on research vessel ALKOR in order to better understand the geology of the Baltic Basin.

To date, the main methods brought forward in scientific literature for investigating carbonate build-ups are through well data and outcrops. As a result, this vintage dataset (OPAB), together with the newly acquired seismic marine data (ALKOR), act as a platform to utilize seismic reflection and refraction methods to better image and interpret carbonate build-ups within the Swedish sector of the Baltic Basin.
In this thesis, the available extensive dataset mentioned above, provides a rare opportunity to map out and characterize carbonate build-ups across a wide area. This will provide valuable information about the distribution of the reefal systems across the Baltic Basin as these systems played an important role in the Late Ordovician carbonate factory within the Baltic Basin. Improved knowledge of the reefal systems could potentially provide insight into eustatic sea-level changes and global climate change during the Late Ordovician. In addition, the Ordovician carbonate mounds are today of interest as potential reservoirs for energy storage in the form of compressed air. In order to investigate this potential, it is important to map their extent and characterize their reservoir properties.

The main objectives of the thesis and the three papers presented are as follows:

1) To utilize the extensive OPAB dataset in mapping and characterizing Ordovician carbonate mud mounds onshore Gotland and improve our knowledge of the carbonate production in the Baltic region.
2) To share new insight of an investigation into a mound in 3D showcasing its reservoir properties as a potential preliminary assessment for compressed air energy storage.
3) To map the seismic velocity of the bedrock using seismic refractions in combination with the OPAB dataset and newly acquired marine seismic. These velocities are then combined with helicopter-borne resistivity data to map and gain a better understanding of the Silurian reefal systems both onshore and offshore Gotland.

This thesis is outlined in a specific way that provides a detailed summary of the work presented in the following papers as summarized below:

Paper I: The paper utilizes the OPAB dataset onshore Gotland, consisting of over 2,000 km of seismic data and data from over 300 wells. The location of the carbonate mud mounds is mapped within the Ordovician sequence beneath Gotland. In this context, the paper introduces carbonate mud mounds on a regional scale and attempts to relate them on a local scale within the Baltic Basin. The interpretation of carbonate mud mounds is mainly based on seismic reflection methods using the extensive (OPAB) dataset to perform a quantitative estimate of their distribution and geometry for the first time and provides detailed structural depth maps of the top and base of the Ordovician succession beneath Gotland.

Paper II: In this paper, for the first time, a carbonate mound on Gotland is imaged in 3D. Paper II exploits an unpublished vintage 3D seismic dataset acquired in 1981 to better understand the geology and structure of a carbonate mound. Depth structure and thickness maps are interpreted as well as cross
sections illustrating the stratigraphy/geology of a carbonate mound. An assessment of the reservoir properties for a carbonate mound is presented, according to previous studies on the structural constraints for energy storage. Furthermore, a preliminary assessment for compressed air energy storage within a carbonate mound is performed.

Paper III: This paper deals with part of the OPAB dataset, consisting of over 33,000 km of marine seismic, together with newly acquired multichannel seismic data (ALKOR) collected in 2017. Together with helicopter-borne SkyTEM and VLF electromagnetic data, the Silurian barrier reef succession on- and offshore Gotland are investigated. The barrier reefs are identified by an automated refraction velocity analysis of the first arrivals in the marine seismic data, after which a velocity map of the Swedish sector of the Baltic Basin is generated. The interpreted velocities are further used to distinguish between the different lithologies presented offshore Gotland. This study also presents a correlation of the Silurian barrier reefs onshore Gotland, with those found offshore Gotland, based on a new method which utilizes the refraction velocities.
2. Geology

The Baltic Basin is a synclinal structure located in the southwestern part of the East European Craton (EEC). The basin is confined to the northwest by the highlands of the Scandinavian Caledonides, situated between two major tectonic regional units: the eastern and the western European platforms (Harff et al., 2011). Towards the north, east and southeast, the syncline is bounded by the Baltic Shield, the Latvian Saddle and Byelorussian Anticline, respectively (Brangulis et al., 1993) and bounded in the southwest by the Trans-European Suture Zone (TESZ). Deposition within the basin began in the late Proterozoic to earliest Palaeozoic during the breakup of the Rodinia supercontinent.

Figure 1. Regional marine geology of the Baltic Basin along with the more detailed surface geology of Gotland, Sweden (modified from Sopher and Juhlin, 2013).
2.1 Structure

The Baltic Basin developed during the Late Vendian tectonic subsidence (Poprawa et al., 1999) which is related to the detachment of Baltica from Rodinia. The event is characterized by the formation of the Tornquist Sea, as well as the SW-NE Trending Baltic Depression (Poprawa et al., 1999). The basin was successively filled with Lower Palaeozoic deposits, starting with deposition during an Early–Middle Cambrian marine transgression. A sequence of sandstones, siltstones and claystones were deposited during the early Cambrian (Vernon et al., 2013). During periods of decreased subsidence rate, during the early-middle Cambrian, the Baltic Basin expanded. The Late Cambrian indicates a passive margin evolution consisting of deep-water proximal greywackes, arkoses and black shales (e.g. Dadlez, 1978; Katzung et al., 1993; Giese et al., 1994). During the Early Ordovician, the progressive narrowing of the western part of the Tornquist Sea resulted from the separation of Avalonia from Gondwana. During the Ordovician, Baltica shifted northwards towards the equator, where Baltica experienced a gradual rise of sea temperatures. This is inferred by Jaanusson (1973) who notes that the thin-bedded Early Ordovician limestones, in the east Baltic area, have an origin from cooler water conditions. The youngest Ordovician carbonate mounds, in the Baltic region, are observed in St Petersburg, Russia and described by Fedorov (2003), who suggests that these mud mounds built up around accumulations of siliceous sponges and formed in cool water environments. During the late Ordovician, Baltica was situated at low latitudes, attested by the absence of glaciogenic sediments during the latest Ordovician global glacial interval (Cocks and Torsvik, 2005). The decreasing palaeolatitudes and increase in temperatures, gave rise to deposition of Ashgill facies. This was followed by the deposition of middle Ashgill carbonate mud mounds, such as the Boda Limestone formation within Sweden. The collision between Baltica and Avalonia, at the Ordovician-Silurian boundary, and the collision between Baltica and Laurentia, resulted in forming much of the British and Irish Caledonides to the west and the Scandian Caledonides to the east (Cocks and Torsvik, 2005). The sedimentary infill of the Baltic Basin indicated a regional regression at the end of the Ordovician to the beginning of the Silurian which is recorded as breaks in sedimentation or minor erosion (Poprawa et al., 1999). During the Early Silurian, deeper sea, dark shales, developed in the southwest and along the Baltic Basin, while shallower, nearshore, marls, carbonate limestones and claystones developed on the northern and eastern basin flanks. The Late Ordovician-Early Silurian Baltic Basin is referred to as a foreland development involving lithosphere flexure (e.g. Angevine et al., 1990; King, 1994). A thick sedimentary succession of deep water laminated siltstones and mudstones indicate very high sedimentation rates and a collisional tectonic setting (Teller, 1974; Dadlez, 1978). The eastern part of the basin shows evidence of compressional deformation due to subsidence and sedimentation. Interbedded
marly-carbonates and sandstones conforms the rest of the Devonian sequence. However, the western part of the basin shows no evidence of Early Devonian basin development (Tomczykowa, 1988), which could indicate a tectonic up-lift according to Poprawa et al. (1999). The tectonic upliftment during the Carboniferous and Permian resulted in widespread erosion of the Palaeozoic sediments of the Baltic Basin (Šliaupa and Hoth, 2011).

During the late Carboniferous-Early Permian, transtensional faulting occurred in the Torquish Zone, which led to a series of pull-apart basins where sediments were deposited (Vejbaek et al., 1994). This tectonic activity led to strike-slip and reverse faulting with additional NW-SE trending faults. Most of the tectonic processes ceased during the Middle Permian, however, increased during the Late Cretaceous, mostly in the southwestern part of the Baltic Basin. The Mesozoic faulting was related to the reactivation of the Per-Permian fault system (Šliaupa and Hoth, 2011). The Sorgenfrei–Tornquist zone continued to experience tectonic activity in Triassic and Middle Jurassic times. The zone has experienced an uplift during the Late Cretaceous to Early Tertiary inversion tectonic phase and the Late Tertiary regional uplift of Fennoscandia. This particular time was known as the inversion phase (Šliaupa and Hoth, 2011).

2.2 Stratigraphy
The stratigraphy of this thesis is localized to the Swedish sector of the Baltic Basin. The main areas of interest include the Ordovician and Silurian sedimentary cover on- and offshore Gotland. The stratigraphy on Gotland is composed of Palaeozoic sediments overlaying the Precambrian basement. Formations and lithologies mentioned in this section have been identified from cutting samples, cores and wireline logs interpreted mainly from the OPAB well reports together with the exploration reports dated to 1976 (OPAB unpublished report, 1976).

The Precambrian Basement consists of metamorphosed quartz and biotite in the Viklau-1 and Skäggs-1 wells (OPAB unpublished reports, 1976). The Lower Cambrian sequences, namely the Viklau Fm, När Fm and Ölandicus Fm are up to 150 m thick (Sivhed et al., 2004) and are comprised of alternating sandstones and shale units. The Middle Cambrian has two main members, the Tessini Fm and the Faludden Sandstone Fm. The Tessini Fm is a sandy shale sequence. The sand is grey to white in colour and interbedded with a grey to greenish shale. The shale member of the Tessini Fm is mainly shale with thin layers of sandstone, often silty, siltstones are also present. The Faludden Sandstone Fm is a clean porous sandstone with good reservoir characteristics in the southern part of Gotland and is comprised of white quartz sandstone, very fine
to medium grained, with streaks of pyrite fragments. The Upper Cambrian consists of the Alum Shale Fm. This formation has a high uranium content which is recognized on the gamma ray log. The shale is brown to black in colour with a thickness of 0 m to 4.5 m (OPAB unpublished report, 1976).

The Ordovician has three main formations, namely the Bentonitic Fm, Kvarne Fm and the Klasen Fm. The Bentonitic Limestone formation thickness increases from north to south over Gotland. This formation is generally characterized by white grey-white limestone with occasional grey-green bands. The middle section of the Bentonitic formation is red to brown in colour due to its association with red brown claystones. The limestone is commonly microcrystalline and dense with traces of fossils. Bentonite is common in this formation, however, it occurs less frequently with depth. The Kvarne formation is characterized by a grey to light grey thin clay section typically less than 10 m in thickness. The thickness of this formation decreases towards the southern part of the island and in the northern most parts, which is around 11 m. Grey-white limestones are usually interbedded with the claystones. The Upper Ordovician sequence, the Klasen formation, named by OPAB, is dominated by variably argillaceous limestones and mudstones with thin beds of shale. The interbedded limestones are typically microcrystalline and dense. The thickness of the Upper Ordovician sediments on the island varies between 22 m and 74 m. Beneath Gotland, the overall thickness of the Ordovician ranges from 80-125 m (Erlström and Sopher, 2019), thinning towards the south of the island. In this context, the top of the Ordovician is found between 150 m and 250 m depth in the north and 500 m in the south. Besides the OPAB stratigraphic division, Kjellström (1971) based their studies on microplankton within the Grötlingbo-1 core. The Ordovician–Silurian boundary layers of the latter core were also divided in detail based on a conodont study by Männik et al. (2015), which indicated that the Ordovician-Silurian boundary lies slightly deeper than that noted in the OPAB well reports. Erlström and Sopher (2019) confirmed this based on a major shift from marlstone to limestone and shale, the top Ordovician occurs deeper than noted in the OPAB stratigraphic division. Within the Upper Ordovician succession, carbonate mud mounds occur more frequently at three stratigraphic levels namely, the Kullsbergs mounds (Late Sandbian-Early Katian), the Nabala/Rakvere mounds (Middle Katian), and the Boda mounds (Late Katian). The mud mounds at these stratigraphic levels beneath and around Gotland, are mostly confined to the Klasen formation informally classified by OPAB (Fig 2). The seismic interval between O4-5 and S1 (between the Upper Ordovician Fjäcka Shale and the base of the Silurian) as defined by Tuuling and Flodén (2000) correlates well with the File Formation defined by Bergström et al. (2004) and also with the OPAB Klasen limestones. The distribution of these mounds, on Gotland, reflect a general decrease in sea level to the north of the basin, between Gotland and the southwestern parts of Finland. This area contains the majority of the carbonate mud
mounds and is considered to indicate an area of relatively shallow conditions during the Ordovician.

The Silurian sequence can be found mainly in outcrops on Gotland. According to the OPAB dataset, from cores and wireline logs, the sequence is comprised of limestone, marlstone and siltstone. The thickness varies from 200 m in the north to 500 m in the south. These rocks contain vugs and voids which have been found to contain hydrocarbon residues (Sivhed et al., 2004). The stratigraphic subdivision prone for its reefal developments include the Llandovery, Wenlock and Ludlow units (Fig 2). The first is the Lower Wenlock Högklint–Tofta–Slite reefs, the second includes an east northeast oriented Upper Wenlock and lowermost Ludlow Klinteberg–Hemse reef complex, and finally the third complex is the upper Ludlow Sundre reefs (Mantén 1971). The lithology throughout the Llandovery represents a shelf environment (Flodén, 1980). During the Wenlock times, reefal banks dominate the Högklint, Slite and Fröjel beds however, an alternation between the reef banks and shelf environment occurs where the Slite marls consisting of siltstone represents more of a transition zone (Flodén, 1980). The area of interest for this thesis lies commonly within the Ludlow times. Here, the offshore continuation of the reef complexes on central and southern Gotland have previously been investigated using seismics by Flodén (1980) east of Gotland. The lower units of the Ludlovian contains elongated reefal barrier structures confined within the Burgsvik, Hamra and Sundre beds. Although the Silurian stratigraphy is relatively undefined according to the OPAB dataset, the Silurian lithologies have previously been studied in detail dating back to the 1800’s. The stratigraphic framework of the Silurian succession on Gotland was first described by Hede (1960) and successively refined by several geologists since then (see review by Calner et al., 2004.) The table below (Table 1) best describes a summary of the Silurian stratigraphic beds and their lithology.
Table 1. *A simplified lithological description of the stratigraphic beds found within the Silurian sequence on Gotland, Sweden. Modified after Laufeld and Basset (1981).* Refer to Figure 2 for stratigraphy chart.

<table>
<thead>
<tr>
<th>Stratigraphic bed</th>
<th>Lithology</th>
<th>Reefal build-ups</th>
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<tr>
<td>Sundre</td>
<td>Limestones</td>
<td>Reefs</td>
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<tr>
<td>Hamra</td>
<td>Limestones</td>
<td>Reefs and mounds</td>
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<tr>
<td>Burgsvik</td>
<td>Sandstones with intercalations of shales and marlstones</td>
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<tr>
<td>Eke</td>
<td>Limestones and marlstones</td>
<td>Reefs and mounds</td>
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<tr>
<td>Hemse</td>
<td>Marlstones and ripped limestones</td>
<td>Mounds</td>
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<td>Mulde</td>
<td>Fossiliferous limestones and interbedded limestones</td>
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<td>Halla</td>
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<td>Reefs interbedded</td>
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<td>Upper Visby</td>
<td>limestones with shale and mudstones intercalations</td>
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<tr>
<td>Lower Visby</td>
<td>Calcareous mudstones with thin argillaceous limestones.</td>
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</tbody>
</table>
Figure 2. A) Simplified stratigraphic chart of the Palaeozoic sedimentary succession within the Swedish sector of the Baltic Basin. Seismic stratigraphy of the Baltic sea taken from Flodén (1980). The Silurian barrier reefs are taken from Flodén (1980); Bjerkèus and Eriksson (2001). B) Well data and stratigraphic information from the Linhatte-1 well, located on south-east Gotland. Stratigraphy and key lithostratigraphy units, named according to OPAB’s informal stratigraphic scheme (1970, 1980), also shown are sonic and gamma ray logs. A synthetic seismogram is shown which was calculated using the P sonic log and a constant density of 2.6 g/cc. Seismic data from Line P74-5 are shown. The dotted line (red) correlates key seismic events with the well data.
Ordovician carbonate mud mounds are less well known than the Silurian reefs. These mounds are presumably associated with the palaeolatitudinal shift of Baltica towards the equator during the Late Ordovician (e.g. Jaanusson, 1973; Webby, 1984, 2002; Cocks and Torsvik, 2005). Today, the distribution of these mounds has been influenced by the Cenozoic river erosional escarpment i.e., the Baltic Klint (Tuuling and Flodén, 2016) and are located in regions close to the Baltic Klint and in isolated areas on the Fennoscandian shield north and west of the Baltic Klint (Kröger et al., 2017). Bergström et al. (2004) recognized two generations of mounds beneath Gotland. The Rakveran-Nabalan Liste mounds and the Piruan Klasen mounds. The dimensions of mounds have previously been illustrated by drill cores, outcrops and as measurements on seismic profiles (Flodén, 1980; Flodén, 1994; Tuuling and Flodén, 2000; Sivhed et al., 2004). According to Tuuling and Flodén (2000), the geometry of these mounds is strongly related to their height and length ratio. Onshore Gotland, carbonate mud mounds have a diameter of 800 m and a relief of 25 m (Sivhed et al., 2004). Offshore Gotland, larger mounds of up to 2 km in diameter exists (Tuuling and Flodén, 2000).

During the Late Ordovician, Baltica underwent a change in the tectonic regime from a passive margin to a foreland basin caused presumably due to the collision of Avalonia and Baltica (Poprawa et al., 1999). Gotland therefore was affected during the Ludlow time, thus having an impact on its depositional sequence. Carbonate build-ups, such as reef complexes, are commonly found outcropping in the Silurian sequence on Gotland and barrier reefs associated with lagoonal, biohermal slope and sediments towards the east offshore Gotland. From the uppermost Llandovery to the Ludlow times, these units were displaced towards the south as a result of the regressive development and the infilling of the basin (Flodén et al., 2001). The barrier reefs are also considered to have developed subparallel to the ancient shorelines (Flodén, 1980). The reefs on- and offshore Gotland have been discussed in detail by many authors (e.g. Flodén et al., 1994, 2001; Bjerkéus and Eriksson, 2001; Tuuling et al., 1995, 1997; Tuuling and Flodén, 2000, 2007, 2009, 2011, 2013). According to Tuuling and Flodén (2013), the growth of various reef-building organisms occurred in the middle of the broad carbonate shelf, where there is a high energy, shoal area up to a depth of 10–12 m (Nestor, 1995; fig. 3). Several Silurian reefs around the Baltic Sea have up to 10 km wide reef tracts (see Nestor, 1995; fig. 2).
3. Data and methodology

3.1 OPAB dataset
This chapter includes a summary of the data utilized in each paper. Most of the data in this thesis was acquired from an old exploration company, Oljeprospektering AB (OPAB), during the 1970’s and 1980’s. Since 2011, the OPAB database is situated at SGU (Geological Survey of Sweden) and has recently become available for research purposes. This dataset consists of seismic profiles, well data and reports. Included in the OPAB dataset, there is an unpublished 3D seismic survey, which was conducted by Horizon Exploration Ltd (Newman and White, 1981) over the Fardume mound, northern Gotland (Fig. 3).
Figure 3. Base map of the study area. Large map shows the offshore seismic profiles utilized in this thesis. Zoom in of Gotland illustrating onshore seismic profiles and 3D seismic survey.
3.1.1 Well data
The well data obtained from the OPAB dataset consists of over 300 wells, mostly situated onshore Gotland. However, in this study we have focused primarily on 38 of these which contained sonic, density, natural gamma wireline logs, as well as lithological descriptions (see Fig. 3 for the well locations). Formation tops, check shot data, bottom hole temperature readings and completion reports were also available for some of these wells.

3.1.2 Seismic data
The seismic data acquired by OPAB consist of land and marine data. In this thesis over 500 2D seismic lines from 11 different surveys, onshore Gotland were utilized. The combined length of all the profiles onshore Gotland exceeds 2,000 km. These seismic surveys are P77, P75, P74, MS85, MS84, MS82, MS80, MS79, MS78, MS77 and MC81 (Fig. 3). A Vibrosies or mini-SOSIE source was used to acquire the land data, typically with a relatively low fold (12 fold). The shot interval for each survey had a spacing of 30 m. The recorded length was either 1 s or 0.5 s and the sampling interval was either 1 ms or 0.5 ms. Out of the twenty different offshore OPAB seismic surveys, only seven are utilized in this thesis, D72, HR74, GA74, DS75, NA80, NA79 and ZA80 (Fig. 3). These surveys were acquired with a single streamer. The marine reflection data were mainly available as pre-stack data. Depending on the survey, the number of channels differs from 24 to 36. With a station interval of 25 m or 50 m and shot interval of 25 m or 12.5 m. The 3D seismic survey consists mainly of a series of 2D parallel lines over a mound onshore Gotland. A total of 28 seismic lines were surveyed covering about 1 km², with N-S and E-W dimensions of 1110 m and 810 m, respectively (Fig. 3). Nominal fold of 6 and with 30 m and 15 m CDP spacing in the E-W and N-S directions.

3.1.3 Resistivity and marine seismic data
In addition to the OPAB dataset, Gotland has recently become a target for groundwater exploration. SGU has therefore conducted a helicopter-borne electromagnetic survey (SkyTEM) on the Swedish islands Öland and Gotland (Dahlqvist et al., 2015, 2017; Jørgensen et al., 2018). Prior to this, helicopter-borne electromagnetic (VLF) data was collected over the island of Gotland in 2006, also by SGU. These data have been made available for research purposes and are partly included in this thesis (Paper III). Moreover, multichannel marine seismic reflection data were acquired onboard research vessels ALKOR during years 2016 and 2017, respectively, by Hamburg University (see Fig. 3 for the location of the 2017 seismic survey). The 2017 ALKOR seismic data were acquired using 1 or 2 GI-Guns, a shot interval of 41 m and an active
digital seismic streamer length of 600 m. The processing steps for the ALKOR
2017 data can be found in Table 2.

### 3.2 Vectorization

Much of land seismic data were only available as TIFF images. The seismic
images within the OPAB’s dataset are shown as a black and white wiggle trace
format. In order to import these data, they first had to be converted (vector-
ized) to SEGY format. For that, we used the WIGGLE2SEGY algorithm (Sop-
pher 2016, 2017), so that the data can be imported into modern seismic inter-
pretation software. Well data, from the OPAB dataset, were also only availa-
ble as scanned tiff images of the hard copies of the log data. Therefore, these
data also had to be digitized, this was done manually, using Engauge, an open
source software. After digitization, the well logs can be visualized and corre-
lated and then synthetic seismograms can be calculated.

### 3.3 Synthetic seismograms

Seismograms were generated for all of the wells where p-wave sonic logs were
available (38 wells). Well-seismic ties allow well data, measured in units of
depth, to be compared to seismic data, measured in units of time. After the
well-tie process stratigraphic markers identified in a well can be related to
specific reflections on the seismic section (Fig. 2). To generate a synthetic
seismogram a velocity and/or density log is required (Paper I & II).

### 3.4 Process flows

A generalized processing flow for the OPAB dataset, ALKOR marine data
and tau-p process can be found in Table 2. The digital SEGY formatted marine
data were utilized to generate a velocity map by performing a tau-p based pro-
cess flow to automatically detect the refraction velocities along every profile
(Paper III).
3.5 Method for identifying carbonate build-ups

Carbonate build-ups have previously been interpreted mainly through cuttings, cores and wireline log data, as mentioned previously. However, this thesis focuses on utilizing seismic reflection data. The carbonate mud mounds on Gotland, can typically be interpreted by two characteristics within the seismic reflection data. Firstly, they appear as a dome-like feature at the top of the Ordovician (Fig. 4) and sometimes within the Ordovician sequence. Secondly, mounds affect the gross thickness of the Ordovician succession at the mound location. A local horizon is then interpreted which follows the uppermost domal reflection in the data, at the mound location, as the top of the mound. The base of the mound was not possible to identify for interpretation due to inconsistent reflections.
Figure 4. Identified carbonate mud mound in the seismic profile P75-64 (A) and its schematic interpretation (B). The red line indicates the top of the mound. Left of the legend shows the location of the seismic profile on Gotland, Sweden.

Whilst processing the marine seismic lines, which pass through the Silurian reef systems (mapped previously by Flodén, 1980; Bjerkéus and Eriksson, 2001), offshore Gotland, it was apparent that the reefs were associated with higher seabed velocities. These changes in velocity are likely to be associated with changes in lithology within the Silurian strata. Barrier reefs (limestone rich) therefore give rise to a higher velocity than the surrounding strata. These reefs commonly outcrop at the seabed and are separated by lagoonal sedimentary deposits that form depressions visible on the seismic reflection profiles (Fig. 5).
3.6 Energy storage assessment

This section provides a brief summary of compressed air energy storage (CAES) as a potential subsurface storage technique. For CAES to be feasible, some general requirements are necessary. According to Succar and Williams (2008), key parameters are related to the porosity, permeability and pressure of the reservoir. The reservoir should have a suitable structural closure such as a dome or anticline and an impermeable caprock. The geometry of the reservoir may also play an important role for possible energy storage. Carbonate mounds onshore Gotland are previously known for their ability to act as a hydrocarbon reservoir therefore in this thesis we address the potential to calculate the energy storage capacity of a single mound located at the Fardume oil field, northern Gotland. The following table below (Table 3) summarizes...
the key parameters needed for CAES storage within a porous medium according to Succar and Williams (2008).

Table 3. Score based criteria system for storage sites.

<table>
<thead>
<tr>
<th>Score Interpretation</th>
<th>Score</th>
<th>Interpretation</th>
<th>Score</th>
<th>Interpretation</th>
<th>Score</th>
<th>Interpretation</th>
</tr>
</thead>
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<td>Unstable</td>
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<td>Marginal</td>
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<td>&lt;100</td>
<td>100-200</td>
<td>200-300</td>
<td>300-500</td>
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<td></td>
</tr>
<tr>
<td>Porosity (%)</td>
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<td>7-10</td>
<td>10-13</td>
<td>13-16</td>
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<td>0.75-0.95</td>
<td>0.95-1.0</td>
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<tr>
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<td>0.5-0.75</td>
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<tr>
<td>Total Closure Rating (h/H)</td>
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<td>0.5-0.75</td>
<td>0.75-0.95</td>
<td>0.95-1.0</td>
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<tr>
<td>Depth to Top of Reservoir (m)</td>
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<td>&lt;137 or &gt;760</td>
<td>142-170</td>
<td>170-260 or 670-760</td>
<td>260-430 or 550-670</td>
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<td></td>
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<td></td>
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<tr>
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<td>13-15</td>
<td>15-23 or 61-69</td>
<td>23-39 or 50-61</td>
<td>39-50</td>
<td></td>
<td></td>
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<tr>
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<tr>
<td>Highly discontinuous</td>
<td></td>
<td>Moderately vugular limestone and dolomite</td>
<td>Reefs, highly vugular limestone and dolomite</td>
<td>Channel sandstones</td>
<td>Blanket sands</td>
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<td>1-5%</td>
<td></td>
<td>&lt;1%</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Leakage evident</td>
<td></td>
<td>No data available</td>
<td></td>
<td>Pump tests show no signs of leakage</td>
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<td>&lt;10&lt;sup&gt;-5&lt;/sup&gt;</td>
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</tr>
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<td>&gt;55</td>
<td></td>
</tr>
<tr>
<td>Caprock thickness (m)</td>
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<td>&lt;6</td>
<td></td>
<td>&gt;6</td>
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4. Summary of papers

4.1 Paper I: Ordovician carbonate mud mounds of the Baltoscandian Basin in time and space – a geophysical approach

4.1.1 Summary

Ordovician carbonate mud mounds are commonly carbonate mud-dominated deposits that contain stromatactis, which represent a cavity filled with marine cements. These mounds developed mostly during the Upper Ordovician within the Baltoscandian Basin, specifically within three stratigraphic levels, namely the Kullsberg mounds (late Sandbian to early Katian), the Nabala/Rakvere mounds (middle Katian) and the Boda mounds (late Katian). On Gotland, Bergström et al. (2004) describe two generations of mounds, the Liste mounds (Nabala/Rakvere stage) and the younger Klasen mounds (Pirgu stage). Carbonate mud mounds of the Baltoscandian Basin are commonly linked, and well known in the literature to have first developed due to the northwards drift of Baltica from high latitudes (cold, cool and temperate environments) in the Early Ordovician to low latitudes close to the equator in the Late Ordovician (e.g. Jaanusson, 1973; Webby; 1984, 2002; Cocks and Torsvik, 2005, see Kröger et al., 2017 with references therein). The sedimentary record of the Baltoscandian Basin during this time can be studied for the sea-level changes, palaeoclimate changes, faunal communities and most importantly to investigate reef ecosystems and the formation of mounds in different settings on the shelf. Carbonate mud mounds are thus of interest as they display a range of different sizes depending on the water depth and palaeogeographic position on the shelf. Most studies on carbonate mud mounds have mainly been through drill cores from Estonia and Sweden (Tuuling and Flodén, 2000), outcrops in the Ordovician succession of western Estonia and in the Siljan area of Sweden and well data. Previously, carbonate mud mounds have been investigated using offshore seismic data in the Baltic Basin (e.g. Flodén, 1980; Tuuling and Flodén, 2000, 2007; Sopher, 2016) and onshore Gotland, a detailed review of carbonate mud mounds was performed by Sivhed et al. (2004) mainly using well data. To date, no extensive study utilizing onshore seismic data has been presented. Therefore, in this paper, the OPAB dataset, which is largely unpublished and consists of over 500 seismic lines (2,000 km) of land seismic data (Fig. 6) and data from over 300 wells,
provides a rare opportunity to map the structure of the Ordovician strata across Gotland and to characterize the distribution and geometry of carbonate mud mounds within the Baltic Basin on Gotland, Sweden.

Figure 6. Locations of the seismic profiles interpreted in this study. Note that wells are correlated to the seismic profiles using synthetic traces. Dotted lines represent the MC and MS seismic surveys and the solid gray lines represent the P seismic surveys. The solid black line P–Q and M–N illustrate the location of two cross sections.

In this paper, we use the traditional OPAB stratigraphic divisions mainly due to the fact that the Palaeozoic sequence relies largely on the petrophysical properties and can be more easily correlated with the seismic data. Out of 300 wells, only 38 wells (for the location see Fig. 6) were utilized to generate synthetic seismograms as these wells included p-sonic velocity logs. This process was important in order to identify key seismic reflections in the data by performing a well tie between the wells (in depth) and seismic profiles (in time). Important regional markers appear as positive and negative reflections at the top and base of the Ordovician interval. This is due to the large acoustic impedance contrast between the Ordovician and lower Cambrian sequence and the overlaying Silurian succession. It is important to note that the strength of
the top of the Ordovician is less in the north of the island than in the south due to the increase of clay content in the upper Ordovician interval (Fig. 7).

Figure 7. Seismic lines A, MS77-209 and B, P74-5 acquired using a mini-soise (higher resolution) source and a Vibroseis source (lower resolution), respectively. Synthetic seismograms shown in both diagrams are represented by A, Skäggs-1 well, located in the north of Gotland and B, Linhattor-1 well, located in the south of Gotland. The dotted line (red) correlates key seismic events with the well data within the Ordovician. The map indicates the locations of seismic lines A and B.

Two cross sections, M-N and P-Q, located in the southern and northern part of Gotland (Fig. 6) have been interpreted and are shown in Fig. 8A and 8B, respectively. Efforts were made to interpret mounds within the seismic data. Typically, these mounds appeared as anticlinal or dome-like structures on the top of the Ordovician reflection. They represent erosional remnants of mounds on the top of the Ordovician sequence. The majority of mounds interpreted in the southern part of Gotland appeared as concave upward features on top of the Ordovician succession (Fig. 8A). In the northern part of the island, mounds commonly appeared within the Ordovician succession as dome-like features. It is important to note that the seismic data display erosional unconformities (Tuuling and Flodén, 2000, 2007, 2009; Erltröm and Sopher, 2019) in the Late Ordovician succession beneath and northeast of Gotland due to the sea-level fall during the Hirnantian glaciations.
Figure 8. Illustrated are two cross section profiles, M–N (8A) and P–Q (8B) with a length of 5.5 km and 28 km, located in the south and north of Gotland, respectively. Refer to Fig. 6 for the location of these profiles. Both profiles consist of an interpreted ‘Precambrian basement’ as well as a ‘Cambrian’ sequence. This is overlain by an ‘Ordovician’ sequence, and above this, the ‘Silurian’. Dashed red lines represent the key horizons interpreted. The black box in both profiles, highlights the position of a carbonate mud mound. The top of the mound horizon is indicated by a solid red line. The mound has also been interpreted in the close-up box. Note that the time and distance scales are different for the two profiles.

The Ordovician sequence beneath Gotland generally increases in thickness towards the northwest and can range between 100 m – 150 m (Unpublished OPAB reports 1970–1990; Sivhed et al., 2004). The thickness of the Klasen limestone on the island increases from about 22 m in the south to about 74 m in the north. The structure contour map (Fig. 9) was generated from the seismic profiles onshore Gotland. The top Ordovician generally dips gradually to the southeast. Over 150 mounds have been identified in the seismic data on Gotland where the concentration of mounds appears to be higher in the eastern part of Gotland and in the south.
Figure 9. The main map shows the depth (below sea level) to the top of the Ordovician succession. The contour interval is 25 m. The insert shows the Ordovician thickness map in meters. The thickness ranges from 50 m to 120 m. The projection used for the location map is RT90 2.5 GONV

In this paper, carbonate mud mound thicknesses and sizes on Gotland have been estimated by applying a statistical approach by using our seismic interpretation. Fig. 10 illustrates a schematic image of the reflections which were interpreted in the seismic data at each mound location. The width of a mound is measured by the lateral extent of the top mound reflection as interpreted. As we were unable to measure the base of the mound due to poor reflections, the thickness of a mound was thus estimated using the following equation:

\[ T = \frac{v (x_2 - x_1)}{2000} \]  

Where \( x_1 \) and \( x_2 \) denote the minimum and maximum two-way time interval in ms between the top mound reflection and base Ordovician reflection where the mound is present, respectively. An interval velocity (\( v \)) of 3200 m/s was assumed for this calculation. This velocity was obtained from the time depth
functions generated from the well tops to match the key seismic reflection of the Ordovician. We estimate the mound thickness to have a mean average of 19 m and a standard deviation of 5.1 m. The mound widths have a mean average of 640 m and a standard deviation of 160 m.

Figure 10. A) Schematic illustration showing the key seismic reflections interpreted at the location of a mound in this study. The top mound reflection and mound itself are shown as a thick dotted line and grey area, respectively. The key measurements used to calculate the mound width and thickness are annotated. B) Illustrates a map view image of a circular lenticular mound with the location of three 2D profiles D, E and F annotated as dashed lines. To the right of the image are the cross sections of the mound obtained from profiles D, E and F.

Furthermore, we combine the locations of our identified carbonate mud mounds on Gotland with those in the offshore area around the island of Gotland to make broad inferences about the depositional setting during their formation in the Late Ordovician (Fig. 11). We discuss the regional depositional environment during the Ordovician to provide a useful case study for comparison and evaluation of coeval mound complexes forming during sea-level highstands in the Late Ordovician and distinguish any changes in the mound geometry related to the palaeogeographic position on the Baltoscandian Shelf. Based on the discussion, the area north-northeast of Gotland appears to constitute an area of relatively shallow water during the Late Ordovician (Gotland-Gotska Sandön ridge; Flodén, 1980). Hence, a greater number of mounds developed in this part of the basin compared to areas to the south where the relative water depth was greater.
4.1.2 Conclusions

Seismic interpretations based on a vintage dataset proved to be feasible in characterizing the Ordovician strata and carbonate mud mounds beneath Gotland. The Ordovician strata dip gently towards the southeast. Mounds were observed more frequently on the northeast and south of Gotland. For the first time, a detailed structure contour map of the top Ordovician and a map of the location of mounds are presented. The mounds have been estimated to have a mean width and thickness of 640 m and 19 m, respectively. The Upper Ordovician Klasen formation hosts the majority of the carbonate mud mounds and can be related to the Late Katian (Late Ordovician) shelf succession. The mound formation on the Baltoscandian Shelf is strongly linked to global climate and sea-level changes.
4.2. Paper II: Investigation of an Ordovician carbonate mound beneath Gotland, Sweden, using 3D seismic and well data

4.2.1. Summary

During the Late Ordovician, the region around Gotland was part of a shallow epicratonic basin in the southern subtropics. Carbonate mounds developed in warm water environments close to the coastlines. These mounds on Gotland are particularly of interest due to their hydrocarbon content. In 1981, a 3D seismic survey was conducted by Horizon Exploration Ltd (Newman and White, 1981) to better define the structure, in order to increase the hydrocarbon production over the Fardume mound on northern Gotland. To date no results from these 3D data have been published in scientific literature. A total of 28 seismic lines were surveyed with a line spacing and receiver spacing of 30 m each. The survey was collected using 24-channel recording equipment where two parallel seismic profiles were obtained simultaneously (Fig. 12). The dataset used in this study not only contains the 3D seismic survey, but also 8 wells drilled within the Fardume field which are supported with well reports provided by OPAB. The typical mound diameters and thicknesses range from 200 m to 800 m and 10 m to 25 m, respectively (OPAB unpublished reports, 1970, 1980; Flodén, 1980; Sivhed et al., 2004; Levendal et al., 2019).

Additionally, the paper discusses the potential on using carbonate mounds for compressed air energy storage (CAES). CAES has recently become of interest when related to renewable energy. One of the disadvantages of wind energy, being one of the renewable sources of energy on Gotland, is the fluctuation in wind power. CAES therefore, can possibly help to regulate the electricity supply from wind energy.
A key step in interpreting the seismic data is to generate a synthetic seismogram, which provides means to understand the relationship between the seismic response and the geology. Of the 8 wells within the Fardume field, none could be used to generate a synthetic seismogram due to the lack of density and P-wave velocity well logs. Therefore, the Grötlingbo-1 well, located in the south of Gotland, was used since the key well logs are available and the entire Ordovician sequence is sampled. Since it was not possible to perform a well tie within the Fardume field wells, the interpretation from Paper I was used to identify the key seismic markers in the 3D data (top Ordovician and base Ordovician). The well markers from the Fardume field were, however, utilized by converting to seismic two-way-time using interval velocities of 3155 m/s and 3600 m/s for the Silurian and Ordovician intervals, respectively. Based on the correlation between the production well markers and the 2D data, the top Ordovician, base Ordovician and top mound reflections were mapped throughout the 3D survey. The cross section of in-line 12 (Fig. 13) illustrates the key seismic reflections and shows a clear anticlinal mound feature. Three time-slices are shown at 124 ms, 138 ms and 153 ms. The time-slice at 153 ms illustrates a clear circular form beneath the mound. The time-slice at 138 ms can be interpreted to intercept the base of the mound and the time-slice at 124 ms represents a strong negative event at the top of the mound. The key
horizons interpreted in the 3D survey were used to generate depth structure maps using the OpendTect software (Fig. 14). The horizons (in two-way-time) were smoothed using a 2D median filter after which they were converted to depth based the same interval velocities as mentioned above. The mound appears as a clear circular, dome-like feature. The mound has a diameter of 495 m and a relief of 21 m. In the northern part of the survey, a structural low is observed (Fig. 14B). A cross section of cross-line 19 (Fig. 15) passes through the structural low. This low is bounded in the east and west by two faults. Based on the interpretation of the top of the mound, the western part seems to have a gentle dip and the peak of the mound tends to be more towards the east and not the centre. Thus, mound development may have been affected by pre-existing sea-bottom morphology.
Figure 13. Seismic in-line 12 which passes through the F-10 well. The interpreted seismic horizons and well markers appear to be in good agreement. The regional line 12, highlighted in the red box, is shown below the seismic section as a geo-seismic section. Here the mound facies have been added schematically to the figure. Three time-slices taken at 153 ms, 138 ms and 124 ms are shown. The projection used for the time-slice maps are RT90 2.5 GONV.
Figure 14. Horizon maps interpreted in TWT using the OpendTect software and subsequently depth converted using an interval velocity of 3155 m/s for the top Ordovician and an interval velocity of 3600 m/s for the mound and base Ordovician. A) represents the top Ordovician horizon, B) represents the top mound horizon and C) represents the base Ordovician horizon. All figures have a contour interval of 3 m. The white dots indicate the location of wells in relation to the geographical location of the seismic survey. The projection used for the maps are RT90 2.5 GONV.

Figure 15. Cross section along cross-line 19 showing interpreted faults and structures. The projection used for the location map is RT90 2.5 GONV.
Furthermore, the 3D survey provided detailed information for the assessment of potential energy storage in a mound. We used the classification scheme for a porous formation from Succar and Williams (2008) who outlined general requirements for CAES. Firstly, porosity (>10 %), permeability (>200 md) and pressure (15-68 bar) measurements are desirable. The reservoir should be located in a structural closure, such as a dome/anticline with a thick and impermeable caprock. A scoping evaluation for the potential CAES capacity of the mound was performed based on a simple empirical approach since the key factors such as pressure and flow rates were not available in the data. The reservoir volume was estimated at 1,700,000 m³ (Table 4) based on the calculation of the gross rock volume within the closure of the Fardume mound using the top mound depth structure map (Fig. 14). We calculated a pore volume of about 174,000 m³ for the closure assuming a porosity of 10%. The potential energy storage capacity was calculated by the following equation:

\[ E = G \theta V \]  
(2)

Where \( E \) is the total energy storage capacity (kWh), \( G \) (m³) is the gross rock volume within the closure, \( \theta \) is the porosity and \( V \) (kWh/m³) is the energy stored per unit volume of pore space. Since \( V \) is a complex factor and requires dynamic reservoir simulation work and also knowledge on the CAES plant design (how much electricity will be produced by the plant) we, assumed a value of \( V \) to be 0.21 kWh/m³, which was taken from a previously published CAES assessment (EPRI, 2012). The total estimated energy storage capacity of the Fardume mound was 37 MWh.

Table 4. Key parameters of the Fardume carbonate mound structural closure. The structure is assessed based on the interpretation of the closure in the seismic reflection data.

<table>
<thead>
<tr>
<th>Closure</th>
<th>Fardume mound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to the crest of the Top Mound (mBSL)</td>
<td>-229</td>
</tr>
<tr>
<td>Depth to spill point closure (mBSL)</td>
<td>-252</td>
</tr>
<tr>
<td>Reservoir thickness in centre of closure (m)</td>
<td>42</td>
</tr>
<tr>
<td>Diameter of closure area (m)</td>
<td>495</td>
</tr>
<tr>
<td>Area of closure (m²)</td>
<td>195010</td>
</tr>
<tr>
<td>Gross rock volume (m³)</td>
<td>1739847</td>
</tr>
<tr>
<td>Pore rock volume (m³)</td>
<td>173984.7</td>
</tr>
<tr>
<td>Energy storage capacity (MWh)</td>
<td>37</td>
</tr>
</tbody>
</table>
4.2.2 Conclusions
In this paper, the first seismic 3D survey on Gotland, over a carbonate mound, was interpreted by mapping the top Ordovician, top mound, and base Ordovician seismic reflections to generate depth and thickness structure maps. The mound has a diameter of about 500 m and a relief of about 21 m. Further interpretation suggests that possible faulting in the area, which pre-dates the development of the mound, plays an important role in its geometry. Faulting led to an elevated sea-bed which promoted mound development. The preliminary evaluation of the CAES potential for the Fardume mound suggests that the mound would be OK to marginal for storage according to Succar and Williams (2008) assessment. The scoping estimate of the CAES capacity within the mound is 37 MWh.

4.3 Paper III: Geophysical mapping of Silurian reefs offshore and onshore Gotland, Sweden

4.3.1 Summary
Three major reef-dominated limestone complexes, extending SW–NE and WSW–ENE across the island of Gotland, are easily recognized as topographic highs. These are the Högklint–Tofta–Slite reef complex in the north, the Klinteberg–Hemse complex on central Gotland and the Hamra–Sundre reefs in the south (Mantén 1971, Riding 1981). These reef complexes extend offshore Gotland and have mainly been studied through 2D seismic surveys (Flodén 1980; Flodén et al., 1995; Tuuling & Flodén 2000; Flodén et al., 2001; Bjerkéus & Eriksson 2001), they are known as the Palaeozoic barrier reefs, namely the Klinte reef, Östergarn reef, Millklint reef and Burgsvik reef. As a precursor to these seismic reflection surveys, Flodén (1975) conducted a refraction sounding survey, using a sonobuoy technique, in the area around Gotland in order to better evaluate the single channel seismic reflection profiles. Here, Flodén (1975) determined a mean refraction velocity of 3100m/s for the Silurian succession in an area east of Gotland.

In this study, the bulk of the data used to identify and interpret these barrier reefs were acquired by the Swedish Oil Prospecting CO (OPAB) in the 1970’s and 1980’s. The offshore data collected by OPAB, together with newly acquired multichannel seismic data, collected in 2017, Hamburg University (ALKOR), provides an opportunity to perform a geophysical seismic refraction technique for mapping the velocities of the Silurian reefs offshore Gotland. Furthermore, the subsurface of Gotland has been the target of helicopter-borne electromagnetic investigations by SGU (SkyTEM and Very Low Frequency (VLF)). Therefore, the combination of these data is used to produce regional attribute maps, in order to delineate the lithology of the bedrock
across a large area and to map the extent of these Silurian barrier reefs (refer to Fig. 3 for the location of the marine dataset used in this paper).

The Silurian succession consists mainly of mudstones, marlstones and limestones. About 15 on- and offshore wells, derived from the OPAB dataset, have been utilized to generate a statistical analysis of the velocities of different lithologies in the Palaeozoic sequence of the Baltic Basin (Fig. 16). The histograms show a clear difference in velocity between the marls (Fig. 16A) and the limestones (Fig. 16B) which comprise the Silurian succession, displaying an average velocity of 3300 m/s and 5200 m/s, respectively. The Cambrian sequence shows average velocities of 3500 m/s, 3800 m/s and 4200 m/s for the shales, siltstones and sandstones, respectively.

*Figure 16.* Illustration of different velocities according to the lithologies within the Baltic Basin. A) Marl (marl / calcareous siltstone / calcareous claystone), B) limestone, C) Shale (non calcareous - i.e. Cambrian), D) siltstone (non calcareous - i.e. Cambrian), E) Sandstone (non calcareous - i.e. Cambrian).

High resistivity values based on the helicopter-borne VLF measurements are observed on the island of Gotland in three northeast-southwest zones, perpendicular to the dip of the geology. These zones correlate to (A) the Hamra-
Sundre complex in the south of the island, (B) the Klinteberg-Hemse complex in the middle, and (C) the Högklint-Tofta-Slite complex in the north of the island (see Fig.6 in Paper III). A clear signature of the Ordovician/Silurian boundary is present in the refraction velocities as shown by the high velocity linear belt that separates dense Ordovician limestones from Silurian fine clastic deposits in the western part of the Baltic Basin (see Fig.6 in Paper III). The high refraction velocities noted in the marine areas close to Gotland illustrate a strong correlation with the onshore high-resistive reefal limestone complexes. The barrier reefs correlate with velocity values greater than 4500 m/s. According to Flodén (1980) and Bjerkéus and Eriksson (2001), the high velocity reef barrier successions southeast of Gotland correspond to, which they refer to as the Burgsvik reef (B4). The middle northeast-southwest striking high velocity zones, located east of Gotland can be separated into two reefal developments, which are referred to as the Östergarn reef (B2) and the Klinte reef (B1), respectively. Besides this, there are locally occurring high velocity anomalies found between these major complexes that are interpreted as representing smaller patch reef areas (see Fig.6 in Paper III).

A geological interpretation of the raw velocity and resistivity data is presented in Fig.7, in Paper III. The paper attempts to classify the velocity of the data into limestone (> 4500 m/s), transitional (4000 - 4500 m/s) and marls (< 4000 m/s). Similarly, classifications for the resistivity data on Öland and Gotland have been generated where high resistivity values, corresponding to limestone, are found. The seabed geology of the Baltic Basin has been superimposed on the figure (see Fig.7A in Paper III) as lines. The checked polygons (see Fig.7A and 7B in Paper III) are interpreted as the Silurian reefs. Here, we have interpreted the length and width of these barrier reefs (B1, B2, B4) according to the representative velocities / resistivities and additionally, we have included singular reefs (patch reefs) located near the barrier reefs (see Fig.7, in Paper III). Also highlighted, is the extension of these barrier reefs onshore Gotland (A, B, C). According to our classification scheme, these structures are composed of reefal limestone. These zones are separated by low velocity zones dominated by marlstone, mudstone and wackestone zones, highlighted by dotted polygons (see Figs. 7A and 7B in Paper III). Fig. 7B, in Paper III, shows a close-up of Gotland and surrounding areas focusing on the interpreted outline of the barrier reefs, east offshore Gotland. A detailed surface geology of Gotland’s stratigraphy has been superimposed.

The final stack of seismic profile P-25, derived from the ALKOR dataset, is approximately 108 km and passes through the reef barrier successions in the Baltic Sea in a south-north direction (Fig. 17). The seismic reflections indicate a southeast dipping sedimentary sequence. The Cambrian, consisting of alternating layers of sandstone and shale, has a constant thickness throughout the profile. Strong seismic events are associated with the overlying Ordovician limestone intervals for the first 2400 CDPs (0 km - 60 km) with a relatively
constant thickness. Reflections of the top basement, Cambrian and Ordovician are weak and discontinuous from CDP 2400 to the end of the profile (60 km to 108 km). This is possibly due to the acoustic waves being trapped in the water layer above the hard, Silurian limestones. The Silurian succession wedges out with an increase in thickness towards the south of the profile (Fig. 17B). Within the Silurian sequence, many reflections can be identified as erosional truncations dipping towards the southeast. These truncations are more evident between CDPs 800 and 2400 (20 km – 60 km) (Fig. 17A and 17B), possibly due to the seismic waves propagating through softer material representing Silurian marlstone fine clastic rocks, which have an average velocity of 3000 m/s (Fig. 17C). In areas where there is a lack of truncations, a harder, reefal limestone lithology, constricting the travel path of the seismic waves may be present. Profile 25 cuts across the B1 (Klinte reef), the B2 (Östergarn reef) and the B4 (Burgsvik reef) barrier reefs towards the north of the profile.

Fig. 17C clearly indicates a sharp increase in velocity which can be associated with the reef limestones, interpreted barrier reefs affirms higher velocities of 4000 m/s or greater compared to the marlstones. An additional possible barrier reef (B5) can be seen in the south of the profile, at CDP 600 (15 km), which is exposed at the sea floor. This barrier reef could be related to the B5 barrier reef structure mentioned in Bjerkéus & Eriksson (2001). Wedge-like sequences of glacial/postglacial sediments overlaying the B4 barrier reef whilst the first 400 CDPs (0 km – 10 km), at 0.3-0.2 s, could possibly indicate the lower Devonian. A sheet-like layer of Quaternary sediments overlies the Palaeozoic sequences and minor faults are interpreted within the Silurian sequence (Fig. 17B).
Figure 17. S-N cross section of seismic profile 25 obtained from the ALKOR 2017 dataset. A) Processed seismic profile in TWT. B) Geological interpreted cross section of profile 25 in TWT. C) Refraction velocity below the seabed based on profile 25.
4.3.2 Conclusions

Elongated barrier reefs offshore Gotland have been identified and interpreted. A top bedrock velocity map over a large portion of the Swedish sector, of the Baltic Sea, is presented for the first time, using seismic refraction velocities based on an automated tau-p process. Velocities greater than 4500 m/s are associated with the Silurian barrier reefs compared to the Silurian near-seabed velocity of 3200 m/s. Petrophysical results are consistent with the velocity map indicating Silurian mudstones, marlstones and limestones to have an average velocity of 3200 m/s and 5200 m/s, respectively. This study provides information about the placement and geometry of the Silurian reefal complexes. Three barrier reef structures have been identified, namely the Klinte reef (B1), Östergarn reef (B2) and the Burgsvik reef (B4). Furthermore, an additional barrier reef, B5, has also been interpreted from the cross section of profile 25.
5. Conclusions and outlook

5.1 Conclusions

A geophysical investigation over carbonate build-ups on- and offshore Gotland, within the Swedish sector of the Baltic Basin, has been carried out using vintage and new seismic data, well data, helicopter-borne VLF and SkyTEM data.

Papers I and II, were devoted mainly to carbonate mud mound build-ups onshore Gotland. The objectives were to map and characterize the geometry of carbonate mud mounds. Carbonate mounds were thus studied in detail through seismic reflection data acquired by OPAB (Paper I) and Horizon Exploration Ltd. (Paper II) together with the OPAB well dataset. In Paper I, the top and base Ordovician seismic reflections were mapped across Gotland resulting in a thickness map of the Ordovician succession. The Ordovician interval on Gotland dips gently to the southeast, due to its position on the north-western flank of the Baltic Basin. In addition, the OPAB dataset was utilized to map the location and distribution of carbonate mounds from seismic profiles onshore Gotland. For the first time, over 150 mounds were identified, mostly located on the eastern and southern parts of Gotland. The seismic observations and interpretations gave a mean mound width and thickness of 640 m and 19 m, respectively. Paper I highlights the use of the seismic reflection method as a powerful tool to characterize large scale structures like mound complexes on local and regional scales. The mound limestones constitute large volumes of carbonate production with characteristic features of Katian (Late Ordovician) shelf successions. The extensive distribution of mud mounds and their formation on the Baltoscandian Shelf is strongly linked to global climate and sea-level changes within the Ordovician.

Paper II showcases the first 3D characterization of a Late Ordovician carbonate mound on Gotland and, hence, provides a better understanding of its structure and stratigraphic position. There top and base Ordovician reflections interpreted in Paper I were utilized in Paper II to generate depth and thickness structure maps from the 3D seismic survey. In addition, it was possible to characterize the geometry and reservoir parameters for potential compressed air energy storage (CAES) within a carbonate mound. The analyzed carbonate mound in Paper II appears to have a circular, domelike geometry with a diam-
eter of about 500 m and a maximum relief of 21 m. The geological interpretation suggests that faulting led to an elevated sea-bed which promoted the mound development. Furthermore, the preliminary CAES assessment suggested that there is some potential for energy storage within the mound. A scoping estimate of the CAES capacity within this carbonate mound on Gotland is 37 MWh.

Paper III focuses mainly on the Silurian reefs. Paper III utilizes the vintage OPAB marine seismic data, well data, newly acquired multichannel seismic (MCS) and resistivity data to gain a better understanding of the Silurian reefs offshore Gotland. From a statistical point of view, the physical properties, inferred from geophysical well data, associated different velocities to the lithologies within the Palaeozoic sequence below the Baltic Sea. The Silurian succession, displayed an average velocity of 3300 m/s and 5200 m/s for the marlstones and limestones, respectively. The Cambrian sequence shows average velocities of 3500 m/s, 3800 m/s and 4200 m/s for the shales, siltstones and sandstones, respectively. For the first time, by using an automated refraction velocity technique of the first arrivals in the marine seismic data, a large scale velocity map was generated. Three barrier reef structures have been identified, namely the Klinte reef (B1), Östergarn reef (B2) and the Burgsvik reef (B4) based on their high velocities in comparison to the surrounding Silurian marlstones. Paper III therefore provides a feasible case study on utilizing seismic refraction velocities together with helicopter-borne resistivity data to interpret and identify reefal build-ups on a large scale.

5.2. Outlook

The Late Ordovician mass extinction is cited as the second most devastating extinction to marine communities in earth history where much of the reef building organisms perished. One of the theories behind this mass extinction is the glaciation event of Gondwana which caused lowering of the sea levels (Elewa, 2008). The sea-level fall exposed the shallow shelf areas which led to karstification of carbonate areas and the formation of channels (Brenchley and Newall 1984; Brenchley 1988).

Channels form during the glaciation cycle by the flow of sub-ice meltwater during periods of regression and are highly erosive. According to Smart (2000), channels can be terminated with sediment bodies due to back-fill. Smart (2000) further notes that these back-fills could be the origin of upper Ordovician mounds. The sedimentary record in the Baltoscandian Basin provides a great possibility to study sea-level changes, shifts in palaeoclimate and changes in palaeoenvironments.
The OPAB dataset consists of over 2,000 km of seismic data and over 300 well data onshore Gotland and the analysis of it has only started. Therefore, a next step to utilize this extensive dataset would be to study the palaeo-channels within the Ordovician beneath Gotland. These channels have previously been linked to the Global Ordovician glaciation.

Figure 18. Seismic profiles MS85-706 and MS84-624 illustrating possible channels within the Ordovician onshore Gotland. Below each seismic profile is the geological schematic displaying onlaps, truncations and possible channel fill.

Detailed mapping of the late Ordovician succession beneath Gotland can provide opportunities for improving the understanding of the depositional environment of the Ordovician within the Baltic Basin and give new insight into the late Ordovician glacial period and its effect on the Baltoscandian Basin, how the sea floor might have looked like during different times of trans- or regressions and/or subaerial exposure.

Upphöjda karbonatformationer från Ordovicium och Silur har studerats sedan en tid tillbaka i hela Östersjön, men merparten av tidigare arbete är baserat på observationer från brunnar och berghällar. Potentiellt höga halter av kolväten i de ordoviciska karbonatformationerna på Gotland gjorde dem till mål för oljeprospektering under 70- och 80-talet, där företaget Oljeprospektering AB (OPAB) samlade in en stor mängd data från seismiska undersökningar och brunnsshörningar. Dessa data är fortfarande till största delen opublicerade och inkluderar, i området, ca 33 000 linjekilometer reflektionsseismiska data från marina mätningar, 2 000 linjekilometer seismiska data från mätningar på land, samt mer än 300 borrhål. 1980 genomfördes en seismisk 3D-undersökning av Horizon Exploration Ltd. över Fardume-formationen på norra Gotland. Inga uppgifter från denna undersökning har tidigare publicerats i vetenskaplig litteratur. Dessutom har Gotland och Öland under senare år varit föremål för en större satsning på grundvattenundersökningar under ledning av Sveriges geologiska undersökning (SGU) där man utfört luftburna elektromagnetiska mätningar (SkyTEM och VLF). Under 2017 samlades dessutom nya reflektionsseismiska data in med hjälp av forskningsfartyget ALKOR för att komplettera OPAB:s data i vissa regioner.

Till skillnad från tidigare studier, som begränsats till observationer från borrhålsdata och berghäll, erbjuder det omfattande dataset som beskrivs ovan en möjlighet att generera regionala kartor av seismiska attribut som kan hjälpa
till att beskriva de geologiska systemen. I denna avhandling presenteras en detaljerad tolkning av 3D seismiska data som samlats in över en upphöjd karbonatformation under Gotland, vilket ger en unik inblick i dessa formationers 3D struktur. I avhandlingen undersöks även dessa karbonatformationers geometri och geografiska utbredningen, samt deras reservoaregenskaper. Dessutom har de äldre dataseten (OPAB) kombinerats med de nya (ALKOR) för att skapa en bas utifrån vilken reflektionsseismiska och refraktionsseismiska metoder kan användas för att avbilda och tolka karbonatformationer inom den svenska sektorn av den Baltiska bassängen. De huvudsakliga målen som utgör kärnan i denna avhandling och de tre vetenskapliga publikationerna som den baseras på, kan sammanfattas som:

1) Kartläggning och karaktärisering av de ordoviciska karbonatstenskul- larna på Gotland, samt en förbättring av kunskapen om produktionen av karbonat i den Baltiska regionen, med hjälp av OPAB:s omfattande datasetet.

2) Detaljstudier av en specifik karbonatstenskulle i 3D med speciellt fo- kus på dess struktur och reservoaregenskaper samt en utvärdering av dess potential för framtida energilagring (Compressed Air Energy Storage, CAES).

3) Kartläggning av berggrundens seismiska hastigheter med hjälp av re- fraktionseismik baserat på den combinerade datamängden från de äldre (OPAB) och de nya (ALKOR) seismiska mätningarna. Dessa hastigheter har kombinerats med resistivitetsdata från flygburna mät- ningar för att kartlägga, och öka kunskapen om, de siluriska rev-sy- stemen på Gotland och utanför dess kust.

Denna avhandling bygger på tre vetenskapliga artiklarna som återfinns mot slutet av avhandlingen. Här följer en kort sammanfattning.

150 karbonatstenskullar kunde identifieras. De flesta av dessa återfinns i Gotlands östra och södra delar. En sammanställning av observationer och tolkning utifrån de seismiska data visar att karbonatstenskullarna, i genomsnitt, har en bredd på 640 m och tjocklek på 19 m. En mycket stor del av karbonatformationerna inom den orдовiskas sekvensen består av kalksten med karaktäristiska drag från avsättning på continentalsockeln under Katy-perioden (sena orдовicum). Karbonatstenskullarnas stora utbredning och deras formation på Baltiska continentalsockeln är starkt kopplad till det globala klimatet och förändringar i havsnivå under orдовicum. Artikel II presenteras den första 3D karaktäriseringen av karbonatstenskullar från sena orдовium på Gotland och bidrar därmed till en utökad kunskap om deras struktur och stratigrafiska läge. Reflektionerna från toppen och botten av den orдовiskas sekvensen har tolkats utifrån de 3D seismiska mätningarna och används för att generera kartor över djupet till den orдовiska sekvens och dess variation i tjocklek. Den karbonatstenskulle som beskrivs i detalj i artikel II är en cirkulär, kupol-liknande struktur med en diameter på ca 500 m och en maximal höjd på 21 m. Högens nuvarande struktur tyder på att avsättningen av karbonatlera vid dess formation har främjats av en lokal förhöjning av havsbotten vid en förkastning. Det var också möjligt att utvärdera karbonathögarnas potential för energilagring i form av högtrycksluft (CAES). De preliminära resultaten tyder på att denna gotländska karbonathög kan ha en god potential för denna typ av energilagring med en uppskattad CAES kapacitet på 37 MWh.

Artikel III fokuserar på att ge en ökad kunskap om de siluriska revformationerna utanför Gotlands kust, inom den svenska sektorn av Baltiska bassängen, genom att kombinera äldre och nya seismiska data från marina undersökningar, borrhållsdata, samt resistivitetsdata från flygmätningar. Borrehålsdata visar på en variation av seismiska hastigheter genom den paleoziskas lagerföljen i området och genom statistiska analyser av de geofysiska datamängderna har hastigheterna för de olika sekvenserna kunnat bestämmas. Inom den siluriska sedimentsekvensen har hastigheterna för kalksten och mögel uppmätts till 5200 m/s respektive 3300 m/s. Den kambriska sekvensen består av lerskiffer, siltsten och sandsten som har hastigheter på 3500 m/s, 3800 m/s respektive 4200 m/s. Genom att använda en automatisk teknik för beräkning av seismiska hastigheter utifrån den första ankomsten av refrakterade vågor i marinseismiskt data har, för första gången, en regional karta över seismiska hastigheter kunnat skapas. De tre barriärrevformationerna Klinterevet (B1), Östergarnrevet (B2) och Burgsviksvetsrevet (B4) har kunnat identifierats då de seismiska hastigheterna är mycket högre i dessa än i omkringliggande mögel. Denna studie visar därmed styrkan med att kombinera hastigheter som fås från refractionseismik med resistivitetsdata från flygmätningar för storskalig kartläggnings tolkning av revformationer.
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Mesmerised, here I stand.
As the wind picks up the oceans scent.
Gliding across my sun-kissed face.
Or could it be the melatonin engraved,
deeper within.
Here I stand,
on the soles of my feet, buried under the
iron rich sands.
Strong and firm, holding my weight from
collapsed diamond mines.

Here I stand, with a God given talent and a universal charm.
Marking my way, my territory, my gifts.

Tegan Corinne Levendal, Uppsala, November 2019
References


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