GEUS Bulletin

RESEARCH ARTICLE

Seismic investigations of eight geological structures for potential storage of CO_2 in Denmark: an introduction

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Abstract

In June 2021, a novel Danish national carbon capture and storage strategy was ratified by the Danish Parliament, and this was followed by the initiation of the project 'CCS2022–2024', led by the Geological Survey of Denmark and Greenland. In collaboration with other institutions, we acquired and interpreted new 2D seismic data between 2022 to 2024 to investigate and mature eight sites for potential subsurface storage of CO_2 in Danish onshore and offshore areas. This Bulletin contains a series of papers that present important results of the work. In this introduction paper, we provide an overview of seismic acquisitions and the interpretation of seismic data together with existing deep wells. The study sites selected are large subsurface structures located in onshore Jylland, Sjælland and Lolland and offshore Denmark in the eastern North Sea. The onshore targets are the Gassum, Havnsø, Rødby, Stenlille and Thorning structures, while the offshore sites comprise the Inez, Jammerbugt and Lisa structures. The project work comprises a series of reports regarding extensive seismic acquisition, processing and interpretation of the new and pre-existing seismic data as well as other publications emanating from the project. This Bulletin and the technical reports present an improved understanding of the formation, composition and geometry of the investigated structures. The studies include the mapping of the reservoir and seal formations, identification of principal faults, interpretation of the stratigraphic and structural development, reservoir and seal characterisation and estimates of the static storage capacity. Hence, this research provides a significant step forward concerning characterisation of the geology and maturation of the potential storage sites. In addition, it has inspired new ideas, including an updated regional stratigraphic interpretation of the Triassic succession of the Danish Basin and correlation with adjacent basins.

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Edited by: Jon R Ineson (Geological Survey of Denmark and Greenland, Denmark)

Reviewed by: Daniel Sopher (Geological Survey of Sweden), Alvar Braathen (University of Oslo, Norway)

Funding: see page 26

Competing interests: None declared

Additional files: None provided

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Received: 27 Nov 2024
Revised: 04 Mar 2025
Accepted: 06 03 2025
Published: 21 May 2025

Keywords: carbon capture and storage (CCS), CO_2 storage, Denmark, Gassum Formation, seismic acquisition

Abbreviations:
bmsl: below mean sea level
BGR: German Federal Institute for Geosciences and Natural Resources
CCS: Carbon Capture and Storage
DB: Danish Basin
ECU: Early Cimmerian Unconformity
Fm: Formation
GEUS: Geological Survey of Denmark and Greenland
Gp: Group
GRV: Gross Rock Volume
MCU: Mid-Cimmerian Unconformity
MEMS: Micro Electronic Mechanical Systems
N/G: average ratio of net sand to gross reservoir volume
NGB: North German Basin
OBS: ocean bottom seismometers
RFH: Ringkøbing–Fyn High
RTS: Realtimeseismic
SC: storage capacity
STZ: Sorgenfrei–Tornquist Zone
TWT: two-way travel time

1. Introduction

The need for reduction of greenhouse gas emissions to the atmosphere to counter further climate deterioration is becoming increasingly urgent. Carbon Capture and Storage (CCS) is an important strategy for considerably lowering atmospheric CO_2 emissions (IPCC 2005), and is currently implemented in a growing number of countries since the first projects were initiated more than 25 years ago, for example at the Sleipner Field offshore Norway (the SACS project; Chadwick *et al.* 2004; Gregersen & Johannessen 2007). In the Danish sector of the North Sea, the first pilot geological storage of CO_2 started in March 2023 (the Greensand project; Szabados & Poulsen 2023).

The Danish subsurface has been considered highly suitable for geological CO_2 storage for many years, and screening studies document a large geological storage potential that is widely distributed onshore and offshore (e.g. Larsen *et al*. 2003; Anthonsen *et al.* 2014; Hjelm *et al.* 2022). Detailed and site-specific studies based on thorough interpretation of new subsurface data from eight selected structures (Fig. 1) conducted by the CCS2022–2024 project (Gregersen *et al.* 2023a, 2023b; Abramovitz *et al.* 2024; Bjerager *et al.* 2024; Fyhn *et al.* 2024; Keiding *et al.* 2024) suggest a reduction in expected static storage capacity compared to previous estimates (Hjelm *et al*. 2022). The significant Danish CO_2 storage potential is based on the favourable geology that includes good reservoir properties of regionally distributed reservoirs, thick seals, large structures and relatively quiescent present tectonic activity. The storage potential is contained within sandstone reservoirs (saline aquifers), and the Danish onshore and nearshore areas contain several structures with significant CO_2 storage potential. Eight structures were investigated in the CCS2022–2024 project led by the Geological Survey of Denmark and Greenland (GEUS). Five sites are onshore structures (the Gassum, Havnsø, Rødby, Stenlille and Thorning structures), and three are offshore structures (the Inez, Jammerbugt and Lisa structures; Fig. 1). New interpretations of seismic and well data were made for the eight structures. For six of the structures, new seismic surveys were acquired, whereas for the Lisa and Inez structures sufficient pre-existing data were available. The focus has been on integrating the new seismic data with the

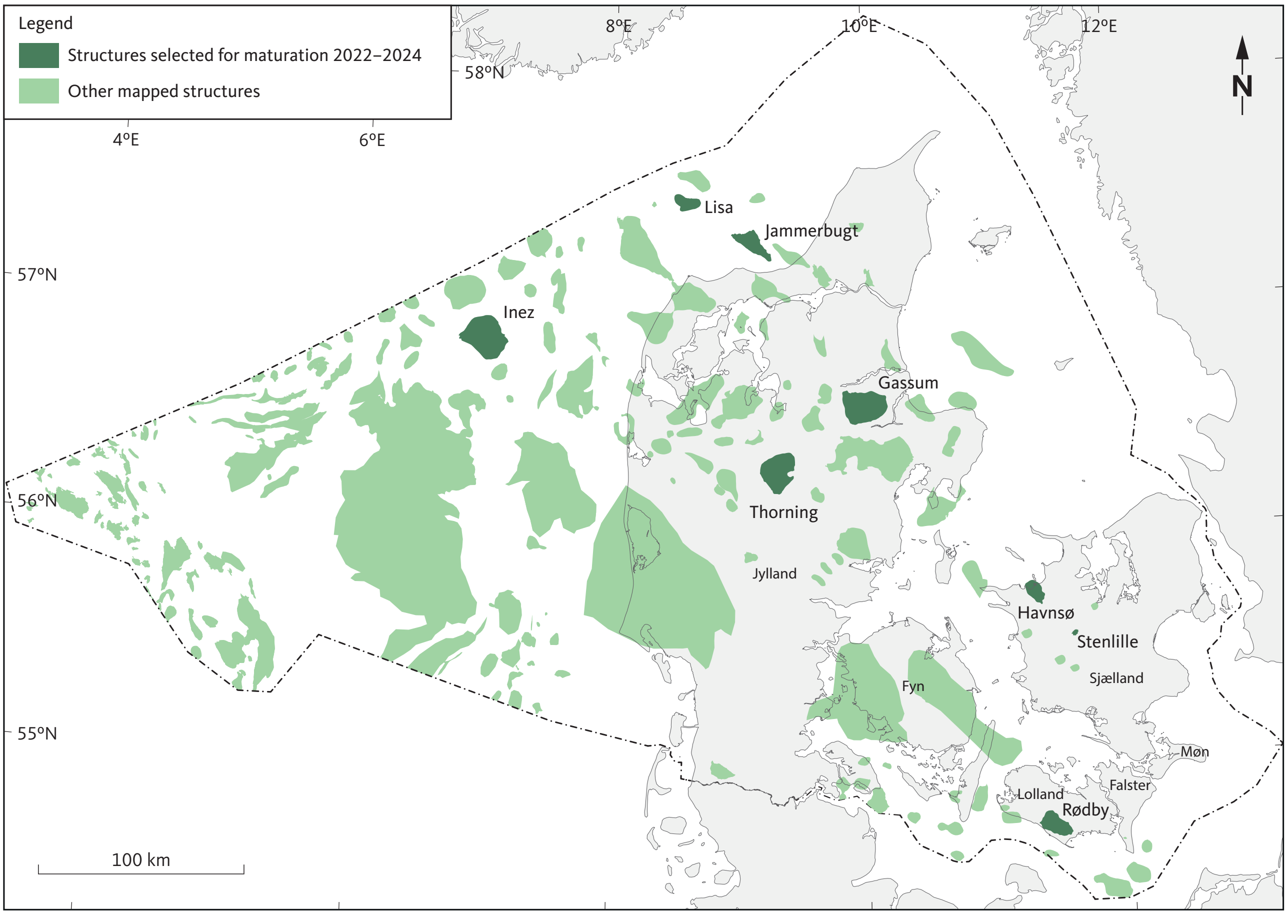

Fig. 1 Map of the Danish structures with potential for geological storage of CO_2 from the GEUS-led CCS2022–2024 project. The dark green structures (Stenlille, Havnsø, Rødby, Gassum, Thorning, Jammerbugt, Lisa and Inez structures) are mapped in the project. Outlines of the Lisa and Inez structures are modified from Hjelm *et al*. (2022). The **dark green shading** shows the extent of the deepest mapped closure of the Top Gassum Fm surface, except in the Rødby structure, where the deepest closure of the Top Bunter Sandstone Fm is delineated. The **light green shading** shows outlines of other structures, which may have potential for geological storage of CO_2.

previously acquired seismic and well data. The six seismic surveys were acquired in 2022 and 2023. The first seismic survey was acquired in 2022 at the NE flank of the Stenlille structure as a small test survey and was upscaled for the other onshore surveys (e.g. Papadopoulou *et al*. 2023, 2024).

Uppsala University was contracted by GEUS for the onshore seismic acquisition. The German Federal Institute for Geosciences and Natural Resources (BGR) and Aarhus University performed the marine seismic acquisition of the Jammerbugt structure for GEUS. For the Havnsø structure, Aarhus University also acquired data in the marine strait between Sjælland and Nekselø, recording signals from the vibro-truck sources onshore near the coast. Consultancy firm COWI assisted with the logistics, applications and communication, while students from Copenhagen, Uppsala, Aarhus and UniLaSalle universities supported the seismic field work.

The scope of this special issue of GEUS Bulletin is to provide an overview of the many results of the CCS2022–2024 project, including the context, purpose and methods that have improved the geological understanding and maturation of the eight selected structures for potential CO_2 storage. The Bulletin contains ten individual research papers. This first introductory paper includes the context, aim and summary of methods and key results of the project, and provides a common reference for the remaining papers of the Bulletin. Six papers focus on the investigated structures. The Inez, Gassum, Rødby and Thorning structures are described in individual papers. However, due to their proximity and similar geological development, the Stenlille and Havnsø structures are grouped and described together in a single paper, as are the Jammerbugt and Lisa structures. Three papers are topic-specific in which common elements of the structures such as the reservoir properties, their potential static storage capacity, brine composition and seal capacity are described and discussed.

2. Geological setting

The Danish Basin trends WNW−ESE between the Ringkøbing–Fyn High to the south and the Sorgenfrei–Tornquist Zone and the Skagerrak–Kattegat Platform to the north (Figs 2, 3). The North German Basin is situated south of the Ringkøbing–Fyn High. The Danish Basin is the eastern part of the larger Norwegian–Danish Basin extending from the Norwegian North Sea in the northwest to Sjælland in the east. The Danish Basin is an intracratonic basin that developed since the late Palaeozoic when it was initiated by late Carboniferous – Early Permian crustal extension reflected in normal faulting associated with widespread magmatism (Ziegler 1990; Michelsen & Nielsen 1991, 1993; Vejbæk 1997; Abramovitz *et al.* 1998, 2000).

Pre-dating the Danish Basin, the oldest documented sedimentary successions resting on crystalline basement are Lower Palaeozoic rocks known from a few deep wells and from outcrops and wells on Bornholm

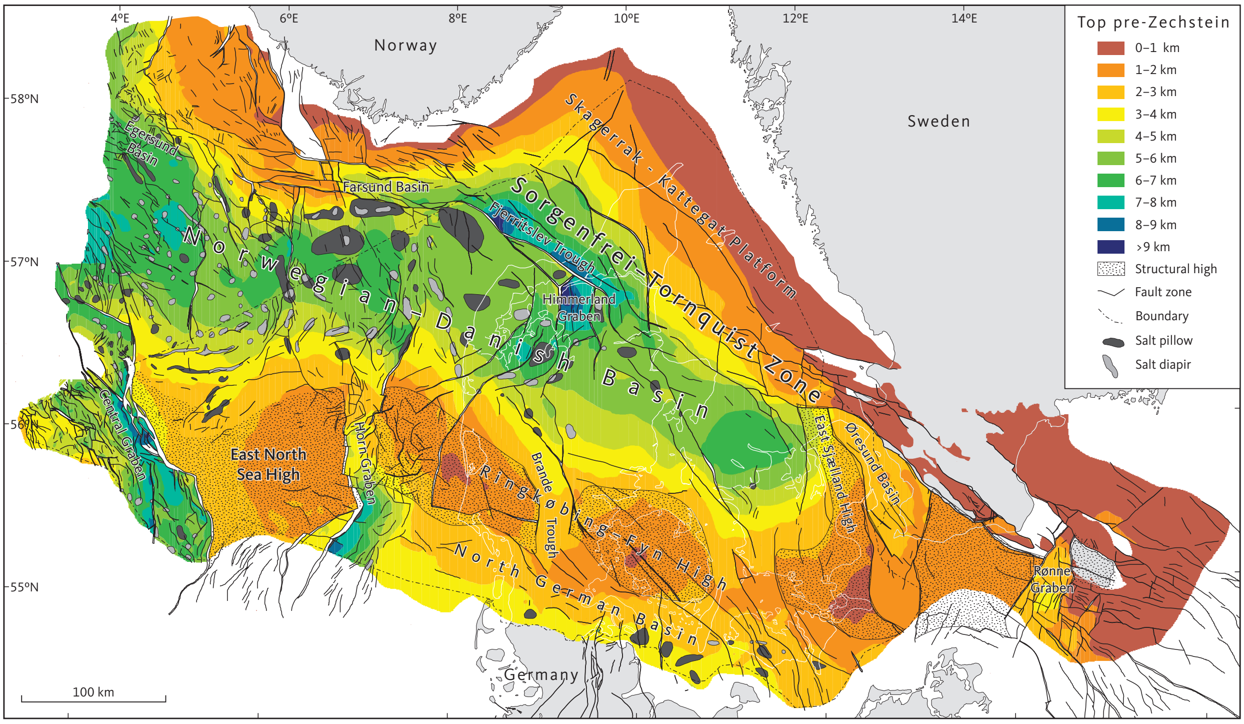

Fig. 2 Top pre-Zechstein map of the main structural elements onshore and offshore Denmark, including highs, basins and main faults. The elements include the Norwegian–Danish Basin, the eastern part of which is named the Danish Basin, the Sorgenfrei–Tornquist Zone, the Skagerrak–Kattegat Platform, the Ringkøbing–Fyn High and the northern part of the North German Basin. Modified from Vejbæk (1997).

and in Kattegat, and adjacent regions in southern Sweden and Norway (Nielsen & Japsen 1991; Erlström *et al.* 1997; Erlström & Sivhed 2012; Schovsbo *et al.* 2016; Nielsen & Klitten 2023). The oldest sedimentary rocks comprise Cambrian sandstones and mudstones representing continental and near-shore deposition in a shallow epicontinental sea. Later Cambrian and Ordovician deposition of organic-rich mud and carbonates resulted from continued transgression. Subsequently, a thick interval of organic-rich Silurian shale was deposited within a deepening foreland basin (Nielsen & Schovsbo 2011, 2015; Schovsbo *et al*. 2016).

The Danish Basin is located north of the E–W-striking Caledonian Deformation Front straddling southern Denmark, along which the East Avalonia microcontinent collided with the Baltica plate (including Scandinavia) during the Ordovician to Early Devonian Caledonian orogeny (Ziegler 1990; BABEL Working Group 1993; Abramovitz *et al.* 1998). During the Caledonian orogeny, northwards movements of East Avalonia resulted in thrusting and deformation of the lower Palaeozoic succession in SE Denmark and the SW Baltic Sea (Lassen *et al.* 2001).

The Norwegian–Danish and North German basins started to form in response to lithospheric stretching and rifting in the Carboniferous−Permian. The Ringkøbing–Fyn High, located between the two basins (Fig. 2), evolved during the same period, forming broad horsts with lesser extension compared with the adjacent basins (Vejbæk 1997). Extensional faulting was associated with volcanism and led to the formation of large, rotated fault blocks, extensive erosion, and widespread, mostly coarse siliciclastic deposition (Carboniferous and overlying Rotliegend Group; Gp; Michelsen & Nielsen 1991, 1993; Vejbæk 1997; Stemmerik *et al.* 2000; Nielsen 2003). In some places, the Rotliegend Gp forms discrete syn-rift wedges on rotated fault blocks (Michelsen & Nielsen 1991; Vejbæk 1997). The region farther to the east (Bornholm and southern Sweden) forms part of the major Sorgenfrei–Tornquist Zone (Fig. 2), where complex strike-slip tectonism and pull-apart basins evolved (Erlström *et al.* 1997; Vejbæk 1997).

The Top pre-Zechstein surface (top of the Rotliegend Gp where the group is preserved, see Fig. 3) is in part a significant unconformity and represents one of the deepest regionally mappable levels from seismic data onshore and offshore Denmark. This surface outlines the main structural elements described above (Figs 2, 3; Vejbæk 1997). In the late Permian (Zechstein), late-rift thermal subsidence dominated, and major basins with restricted seaway connections developed. The Northern and Southern Permian basins (see outlines in Peryt *et al.* 2010) were partially separated by the Ringkøbing–Fyn High and are mainly characterised by deposition of evaporites and carbonates included in the Zechstein Gp (Fig. 3; Stemmerik & Frykman 1989; Stemmerik *et al.* 2000; Peryt *et al.* 2010).

Following the Permian, regional subsidence continued, and a thick Triassic siliciclastic-dominated succession accumulated, comprising sandstones and mudstones with subordinate carbonates and evaporite intervals. The Triassic lithostratigraphic subdivision adopted in this study (Bunter Shale, Bunter Sandstone, Ørslev, Falster, Tønder, Oddesund and Vinding Formations) follows Bertelsen (1978, 1980). The Triassic climate was warm and with some exceptions arid. Deposition of the Bunter Shale and Bunter Sandstone Formations (Fms) occurred in fluvio-limnic and continental dominated environments with desert sand plains and sabkhas during deposition of the Bunter Sandstone Fm (Bertelsen 1980; Clemmensen 1986; Bachmann *et al*. 2010). At the same time, the Skagerrak Fm developed farther to the north reflecting the fluvially-alluvially dominated environment that bordered the Scandinavian Craton (Olsen 1988).

During the Early Triassic, especially in southern Denmark, deposition occurred in large lakes, sabkhas, playas and maybe even short-lived shallow seas (Ørslev Fm, equivalent to Röt Fm in the North German Basin, see Fig. 3; Bertelsen 1980). Meanwhile, deposition farther to the north remained continental in character.

The connection to the Tethys Sea and the North European epicontinental sea in the south increased during the Anisian (early Middle Triassic) and mudstones and carbonates were deposited. Limestone beds are frequent in the Falster Fm, which is equivalent to the Muschelkalk Fm in the North German Basin (Fig. 3; Bertelsen 1980; Lindström *et al*. 2017). Marine-influenced interludes can be traced far into the Norwegian–Danish Basin that was otherwise dominated by continental deposition (Michelsen & Clausen 2002). During the Ladinian (late Middle Triassic), the epicontinental sea retreated to the south and coastal plains and playas developed (Bertelsen 1980). Later, deposits became more sand-prone, influenced by fluvial processes and interbedded with finer-grained sediments. The nature of the sedimentary regime and the presence of plant remains in the upper Tønder Fm, and time-equivalent deposits in the Danish Basin and Scania are indicative of slightly more humid conditions at this time (Bertelsen 1980; Lindström *et al.* 2017).

Lateral thickness variations and faulting within the Tønder Fm in southern Denmark suggest active tectonism and extension along the northern margin of the North German Basin. Salt mobilisation occurred simultaneously with the extension. Following the Carnian (early Late Triassic), tectonism and uplift resulted in the establishment of the Early Cimmerian Unconformity

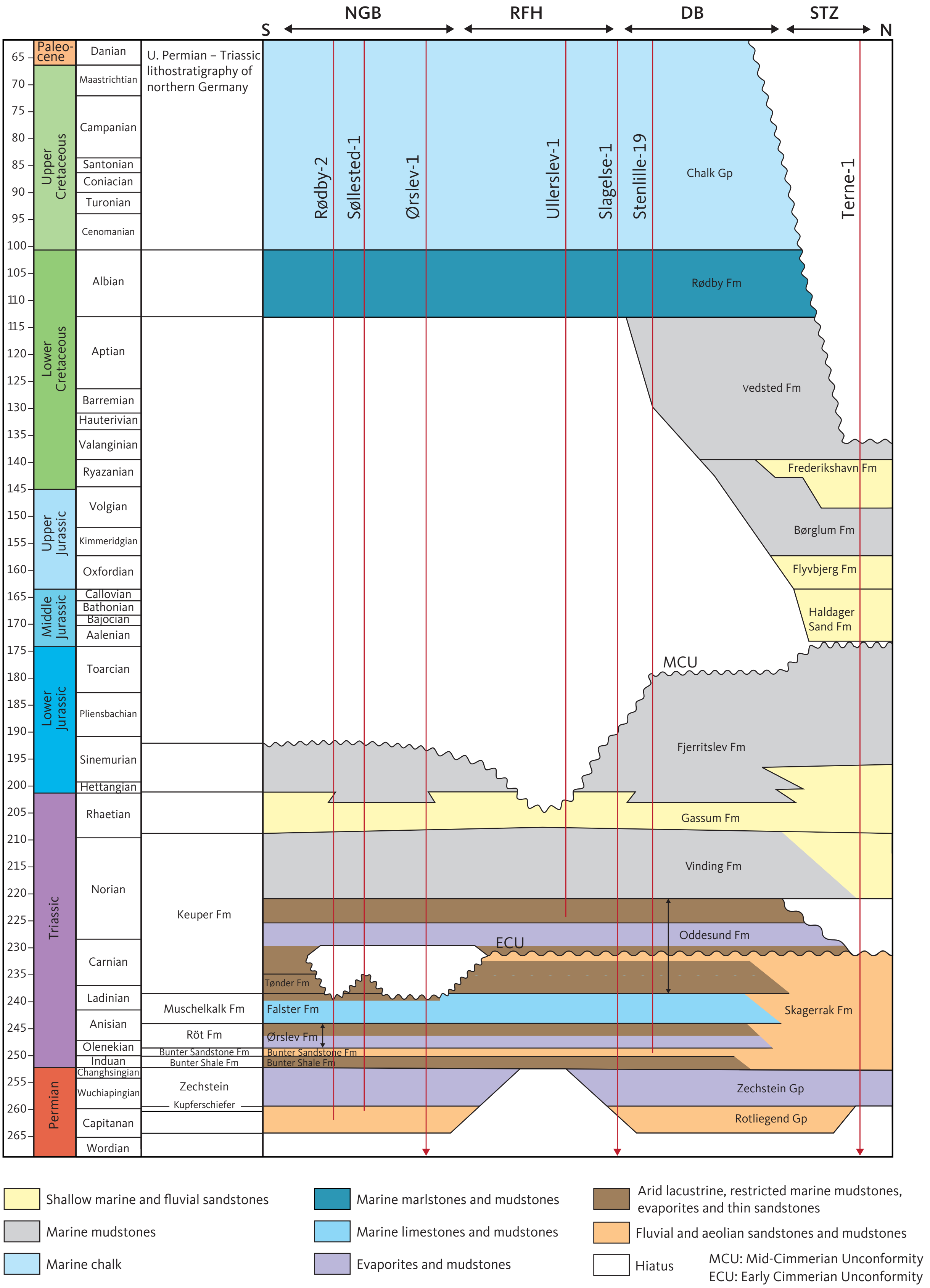

Fig. 3 Schematic stratigraphic diagram oriented from north to south including wells in the Sorgenfrei–Tornquist Zone (**STZ**), the eastern part of the Danish Basin (**DB**), Ringkøbing–Fyn High (**RFH**) and the North German Basin (**NGB**), compiled in this study. The well sections are from north to south located geographically in the Kattegat sea (Terne-1), and on the islands of Sjælland (Stenlille-19, Slagelse-1), Fyn (Ullerslev-1), Falster (Ørslev-1) and Lolland (Søllested-1, Rødby-2) shown by **red vertical lines** (arrows indicate where well termination, Total Depth, is located below the figure). Well locations are shown in Fig. 4. The lithostratigraphy is based on available well sections (Nielsen & Japsen 1991 and references therein) and new research from this project using wells and seismic data. Similar groups and formations occur in Jylland, and the figure is used as a reference for the current Danish lithostratigraphy (incl. Bertelsen 1978, 1980; Michelsen *et al*. 2003; Nielsen 2003). The upper Permian-Triassic lithostratigraphy of northern Germany is also shown. Modified from Abramovitz *et al.* (2024).

(ECU) described in the North German Basin and over the Ringkøbing–Fyn High (Clausen & Pedersen 1999; Ahlrichs *et al.* 2020), but presumably also existing over part of the Danish Basin (Fig. 3). A significant hiatus characterised by the absence of large parts of the Carnian is recorded in southern Danish wells in the North German Basin (e.g. Lolland, Falster and southern Jylland; Fig. 3).

During the Late Triassic, deposition of mudstones and evaporites, mainly in the middle of the Oddesund Fm (Fig. 3) indicate a return to mainly arid conditions, separated by episodes of more humid conditions. In some places, sand was also deposited (Bertelsen 1980).

In the Danish Basin, mobilisation of Zechstein salt into salt pillows was initiated regionally during the deposition of the Oddesund Fm due to differential loading, deep-seated tectonism and faulting (Boldreel 1985; Geil 1991). The Oddesund Fm therefore shows large variations in thickness throughout much of the Danish Basin governed by salt migration, rifting and differential subsidence across the basin. Thickness variations are most distinct towards NW Jylland, in the Fjerritslev Trough and within the Himmerland Graben (Fig. 2). Some of the salt pillows evolved into salt diapirs and other types of salt structures (e.g. salt walls) in the North German Basin, the western Danish Basin (NW Jylland) and farther west in the Norwegian–Danish Basin (North Sea; Boldreel 1985; Sørensen 1998).

During the uppermost Late Triassic (late Norian to Rhaetian), more humid conditions were established, and the Danish Basin became marine-influenced (Bertelsen 1980). Mud-dominated sediments with calcareous and sandy interbeds (Vinding Fm) were deposited in shallow, brackish-marine environments in the deeper parts of the basin, while sand-dominated deposition was initiated at the margins (Fig. 3; Bertelsen 1980).

During the latest Triassic (Rhaetian) and into the earliest Jurassic (Hettangian – early Sinemurian), coastal to continental areas were repeatedly overstepped by the sea, and fluvial, coastal and shallow marine sand interbedded with offshore mud were deposited, which now constitute the widely distributed Gassum Fm (Bertelsen 1978; Nielsen 2003). The Gassum Fm is the key reservoir formation for potential CO_2 storage within the structures located in the Danish Basin, which are described in this Bulletin. Continued rise in relative sea level, on a regional scale, during the Early Jurassic resulted in widespread deposition of thick clay-dominated successions with more silty and sandy interludes (Fjerritslev Fm). The Gassum and Fjerritslev Fms have been subdivided sequence-stratigraphically into sequences and systems tracts, which can be correlated throughout the basin (Nielsen 2003).

Middle−Late Jurassic regional uplift related to the Mid-Cimmerian tectonic phase led to major erosion in large parts of the Danish Basin (Mid-Cimmerian Unconformity, see Fig. 3), in places enhanced by vertical salt movement. The hiatus expands towards the Ringkøbing–Fyn High and the North German Basin (Figs 2, 3; Nielsen 2003). The Middle Jurassic to earliest Cretaceous tectonism and uplift probably contributed to sand-rich deposition (Haldager Sand and Frederikshavn Fms), mainly from the north across the Skagerrak–Kattegat Platform and Sorgenfrei–Tornquist Zone, and southwards into the Danish Basin (Figs 2, 3). Pauses in tectonism and renewed subsidence during the Late Jurassic to Early Cretaceous caused increased clay- and mud-rich deposition (Flyvbjerg and Børglum Fms; Nielsen 2003).

Mud-dominated deposition (Vedsted Fm) continued during the Early Cretaceous (Valanginian to Aptian) and became more calcareous with marl and chalk units during the Albian (Rødby Fm). Upper Cretaceous chalk was deposited throughout the Danish Basin followed by Danian limestone, together constituting the Chalk Gp (Fig. 3).

S–N- and SW–NE-oriented Alpine Orogeny compression led to episodes of Late Cretaceous to Paleocene regional inversion, which affected large parts of Northern Europe. Inversion tectonism also impacted the Danish Basin and the Sorgenfrei–Tornquist Zone (Ziegler 1990; Vejbæk 1997).

In the early part of the Cenozoic, deposition in the Danish Basin was influenced by post-rift thermal subsidence combined with the opening of the North Atlantic Ocean. The hemipelagic sediments consist of fully marine clay and marl and, locally, diatomite and ash layers (Ziegler 1990; Heilmann-Clausen 1995; Schiøler *et al.* 2007 and references therein). Subsequent uplift of the Danish Basin occurred during the Late Oligocene and Early Miocene, and at the same time parts of Fennoscandia were inverted (Ziegler 1990; Japsen & Bidstrup 1999; Japsen *et al.* 2007; Rasmussen *et al.* 2008, 2010). This resulted in the development of large sand-rich fluvio-deltaic systems in present-day Jylland. Glacioeustatic sea-level changes also influenced the sedimentation pattern. Also, during the Miocene many salt structures were active in the Central Graben and most likely also in the Norwegian–Danish Basin. After the Early Miocene, a new tectonic regime formed (Rasmussen 2009).

During the Middle Miocene, accelerated subsidence of the North Sea Basin, including the Danish area, occurred. The delta plains were flooded, and the fluvio-deltaic successions were overlain by fully marine mud (Rasmussen *et al.* 2010). Mud deposition continued during the Late Miocene, although uplift was initiated in the late Tortonian. Deposits from the Pliocene are not present onshore Denmark.

Uplift and tilting towards the SW occurred during the Quaternary, resulting in erosion of older deposits (Rasmussen *et al*. 2005). Hence, in the eastern part of the Danish area, Quaternary deposits overlie Upper Cretaceous chalk and Danian limestone, while in the south-western part of Jylland, the youngest pre-Quaternary deposits are of Tortonian (Late Miocene) age (Sorgenfrei & Bertelsen 1954; Rasmussen *et al.* 2010). Processes during the Quaternary, predominantly associated with glaciations and de-glaciations, deformed and altered large areas of Denmark (Houmark-Nielsen 1987, 2004).

3. Database and methods

3.1. Database

An important part of the CCS2022–2024 project was the acquisition of new seismic data to improve the understanding of the potential for CO_2 storage within the eight selected structures (Fig. 1). The pre-existing database of the study includes wells (Fig. 4) and seismic data (Fig. 5) of the structures.

Vintage seismic profiles provide the basis for mapping structures selected for maturation (Figs 5, 6). A review of vintage seismic data and of the structures was used for planning of new seismic profiles of the structures for updated mapping (maturation) in this project.

The acquisitions of new seismic surveys (Figs 5, 6) were carried out during 2022–2023 and were focused over the six structures: Gassum, Havnsø, Jammerbugt, Rødby, Stenlille and Thorning (Figs 1, 5). A few seismic lines were also acquired over the Lisa structure to tie to the Jammerbugt structure, but apart from these lines, sufficient legacy seismic lines cover the Lisa and Inez structures to map these areas. In addition, deep wells in nearby structures (Fig. 4) were also used to tie well data (lithology, formations, ages etc.) and to consider reservoir and seal properties.

In total, 2093 km of 2D seismic profiles were acquired in the project. A total of 643 km profiles were acquired

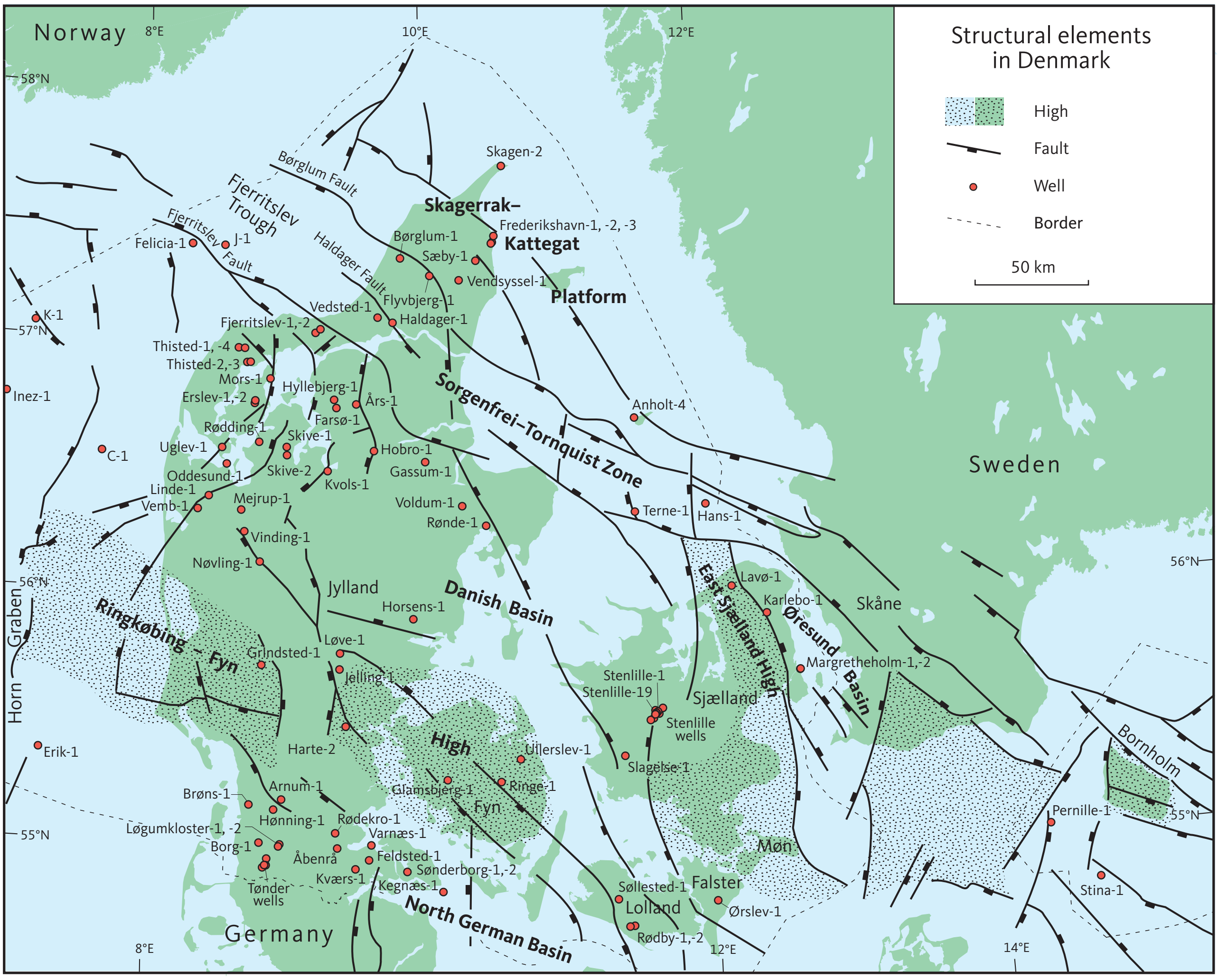

Fig. 4 Locations of Danish wells (**red circles**) and outlines of regional structural elements, including structural highs, basins, fault zones and faults. Modified from Nielsen (2003).

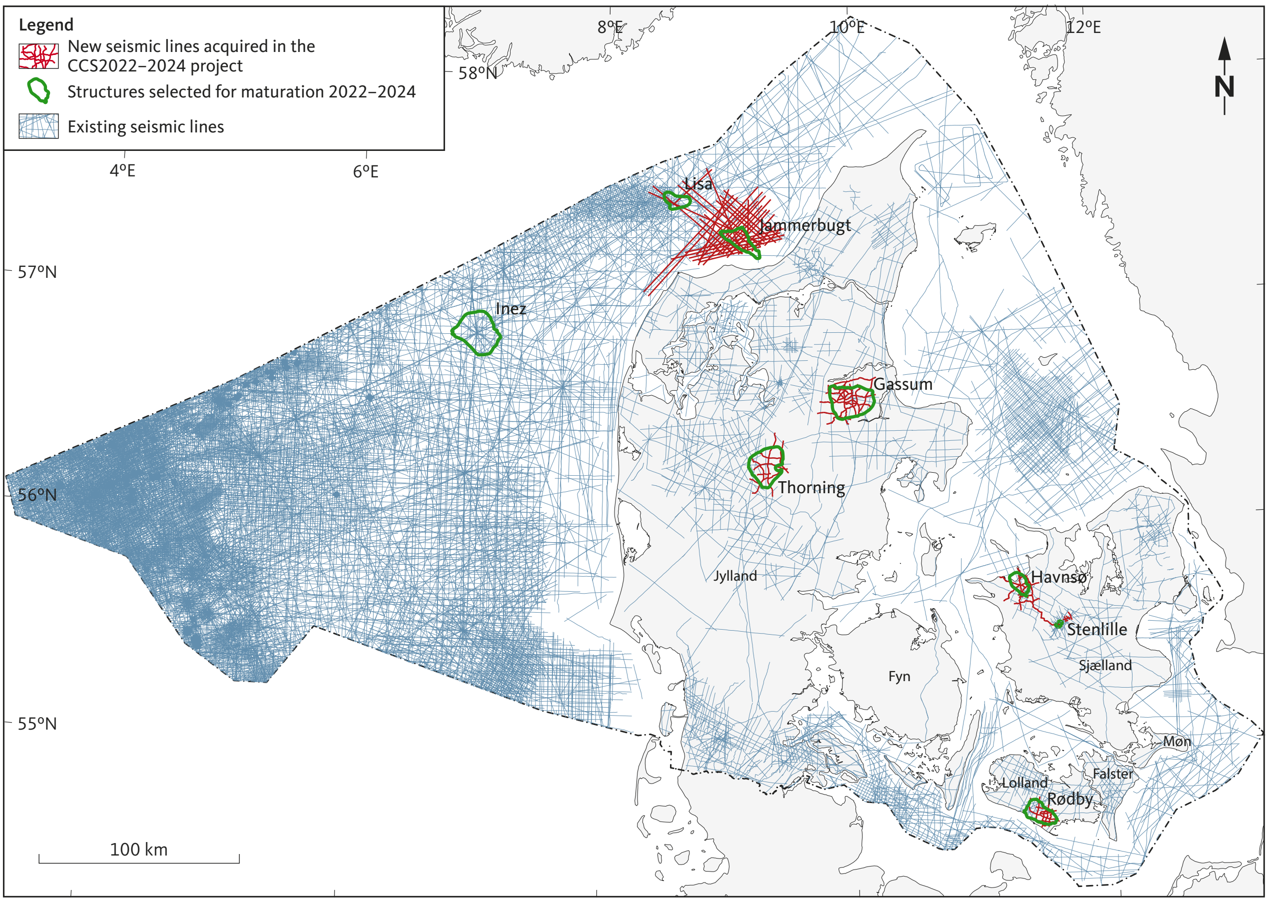

Fig. 5 Locations of the new seismic lines (**red**) acquired in 2022 and 2023, and outlines (**green**) of the structures that were mapped as part of this project (CCS2022–2024). Older seismic lines are shown in **blue**.

over the onshore structures (including a few kilometres in the marine strait at Havnsø) while 1450 km were acquired offshore, centred over the Jammerbugt structure (Table 1). Examples of vintage seismic data and new seismic data of this project from onshore and offshore areas are shown in Fig. 6.

3.2. Onshore seismic acquisition

The existing seismic database over the selected onshore structures consisted mostly of sparse and poor-quality seismic data acquired during hydrocarbon exploration between the 1960s and the 1980s (e.g. Fig. 6a, c). These older data typically have relatively low vertical resolution, a poor signal-to-noise ratio and discontinuous seismic reflections affected by noise. This means that stratigraphic and structural details are often uncertain and not clearly observable in these data compared to more recent data (Fig. 6). Furthermore, the coverage of these older data is often low (large and irregular spacing between profiles); only a few legacy seismic lines are available over the Thorning, Gassum, Havnsø structures, the central to eastern Rødby structure, and the north-eastern flank of the Stenlille structure. A 3D seismic survey from 1997 and more recent 2D lines were available over the central part of the Stenlille structure.

As a result, new 2D seismic profiles were acquired in some areas over these structures. GEUS contracted Uppsala University (Sweden) to acquire and process the five onshore seismic surveys at the Stenlille, Havnsø, Rødby, Gassum and Thorning structures. The seismic source was provided by Geopartner Geofizyka (Poland). COWI coordinated permissions and logistics. The surveys had field assistance by students from Copenhagen, Aarhus, and UniLaSalle universities.

The seismic data were collected along roads using vibroseis trucks and a dual recording system (Fig. 7). Two 12t vibroseis trucks generated the seismic source at shot points with 10 m intervals, with a peak force of 95 kN and synchronised sweeps with a linear frequency increasing from 10 Hz to 140 Hz in 18 s. At every shot-point location, this sweep was repeated three times to improve the signal-to-noise ratio in the processing. The record length was set to 25 s after each shot. On average, 2.5–3.0 km of seismic data were acquired per day.

The dual recording system consisted of a land-streamer towed behind the rear truck and wireless geophones placed along the profile (Fig. 7). It is designed and

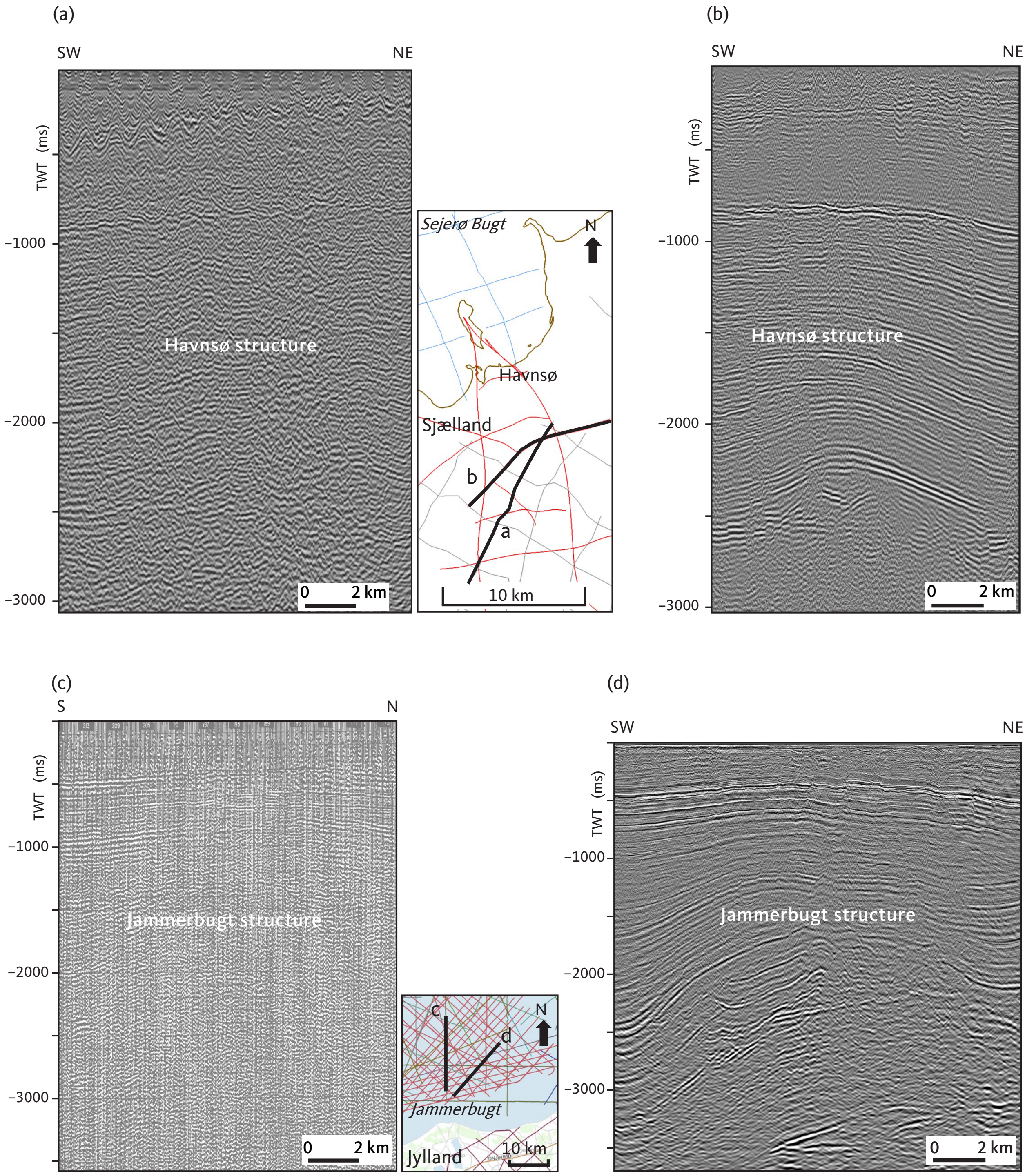

Fig. 6 Examples of vintage and newly acquired 2D seismic data shown with vertical scale in two-way travel (**TWT**) time in milliseconds (**ms**). Example from onshore seismic data across the Havnsø structure with (**a**) vintage seismic data (Ref: SSL6267-R12) and (**b**) new seismic data acquired and processed by Uppsala University (Ref: GEUS22-HVN-P7). Example from offshore seismic data across the Jammerbugt structure with (**c**) vintage seismic data (Ref: WGC64A-39970) and (**d**) newly acquired seismic data by the Federal Institute for Geosciences and Natural Resources (BGR) and Aarhus University, and that was subsequently reprocessed by Realtimeseismic (RTS; Ref: GEUS23-JB-15 from the reprocessed survey GEUS2023-JAMMERBUGT-RE2023).

tested to produce two complementary high-resolution data sets for an improved imaging of both the shallow and the deeper subsurface (Malehmir *et al*. 2022; Zappalá *et al*. 2022). The SeisMove® landstreamer, developed by Uppsala University, has Micro Electronic Mechanical Systems (MEMS) sensors mounted 2 m apart and with a 1 ms sampling interval. The landstreamer is comprised of 40 m segments that are attached end-to-end, providing a flexible length of 40 to 240 m. Adjustment of the streamer length depended on the logistical complexity of the given day's traverse due to road bends, buildings and traffic. The wireless geophones were placed along roads at 10 m intervals (nodal system), and they have a natural frequency of 10 Hz with a 2 ms sampling interval.

Table 1 Seismic data (2D) acquired 2022 and 2023 during the CCS2022–2024 project and pre-exisiting data.

Geological structure	Line acquired	Pre-existing wells and seismic data
Stenlille structure	13 km (5 profiles)	20 Stenlille wells, one 3D seismic survey (1997) and *c.* 20 seismic profiles (of 2D seismic surveys from 1962–1967, 1972–73, 1981, 1987, 1994)
Havnsø structure	131 km (9 profiles)	No wells, *c.* 20 seismic profiles (of 2D seismic surveys from 1962–1967, 1972–73, 1974)
Gassum structure	259 km (14 profiles)	Gassum-1 well, 6 seismic profiles (of 2D seismic surveys from 1962–1967, 1973–74, 1981–1983)
Rødby structure	106 km (12 profiles)	Rødby-1 & -2 wells, *c.* 12 seismic profiles (of 2D seismic surveys from 1962–1967, 1979–1981) & a few more recent lines from a shallow seismic survey
Thorning structure	134 km (8 profiles)	No wells, 2 seismic profiles (of a 2D seismic survey from 1973–74)
Acquired onshore	643 km	
Acquired offshore for the Jammerbugt structure	1450 km (39 profiles)	No wells, 3 seismic profiles (of 2D surveys from 1964, 1982), partly over the structure
Total acquired	**2093 km**	

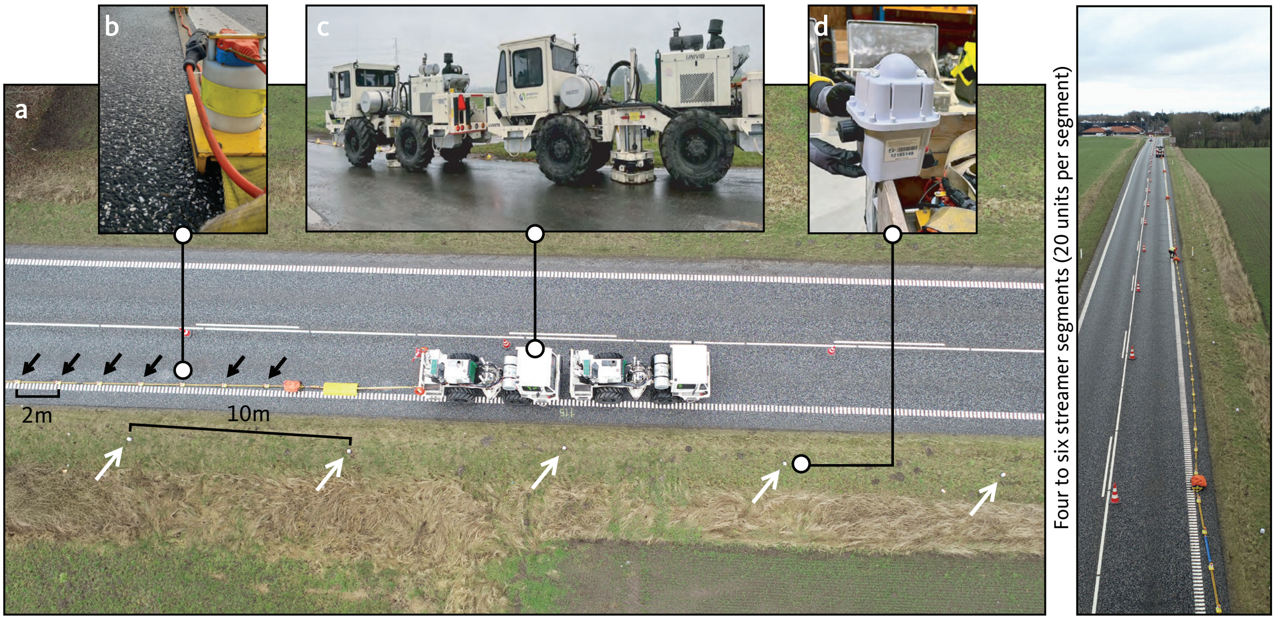

Fig. 7 Photographs from the seismic acquisition with the two vibroseis trucks, landstreamer and geophones. (**a**) Operational setup of field equipment. (**b**) MEMS sensors mounted at 2 m intervals on a landstreamer towed behind the rear vibroseis truck. (**c**) Two vibroseis trucks are operated with synchronised vibrations. (**d**) Wireless geophones are deployed every 10 m along the profile. Reproduced from Malehmir & Westgate (2023).

Geophone positions were derived using Differential GPS measurements with an accuracy of 10–30 cm. Both the operational zone and the active spread for each recording system changed each day during the acquisition, with mostly a 200 m spread length for the landstreamer, and typically 5–9 km spread length for the nodal system.

Each seismic profile was independently processed; the overall processing flow was kept consistent, however, with only minor variations in the input parameters per profile. The processing steps are thoroughly described in the acquisition and processing reports (Malehmir & Papadopoulou 2022, 2023; Malehmir & Westgate 2023; Malehmir & Markovic 2024; Putnaite & Malehmir 2024). The landstreamer and nodal data were processed independently, yielding final stacked and migrated sections. Furthermore, the data sets were merged in the pre-stack domain, rebalanced and jointly stacked and migrated to produce a third section per profile. Merging the wireless geophone data and the landstreamer data unites each data set configuration's benefits and optimises the merged data set's signal-to-noise ratio (e.g. Papadopoulou *et al.* 2022; Malehmir *et al.* 2025).

In addition, the data were reprocessed by Realtimeseismic (2023a, b; 2024a, b, c, d) to further enhance the resolution of the data and ensure optimal ties between the seismic lines. Particular effort was put into the reprocessing to understand and suppress crooked-line artefacts caused by the irregular source locations along roads with bends (Abramovitz *et al.* 2024).

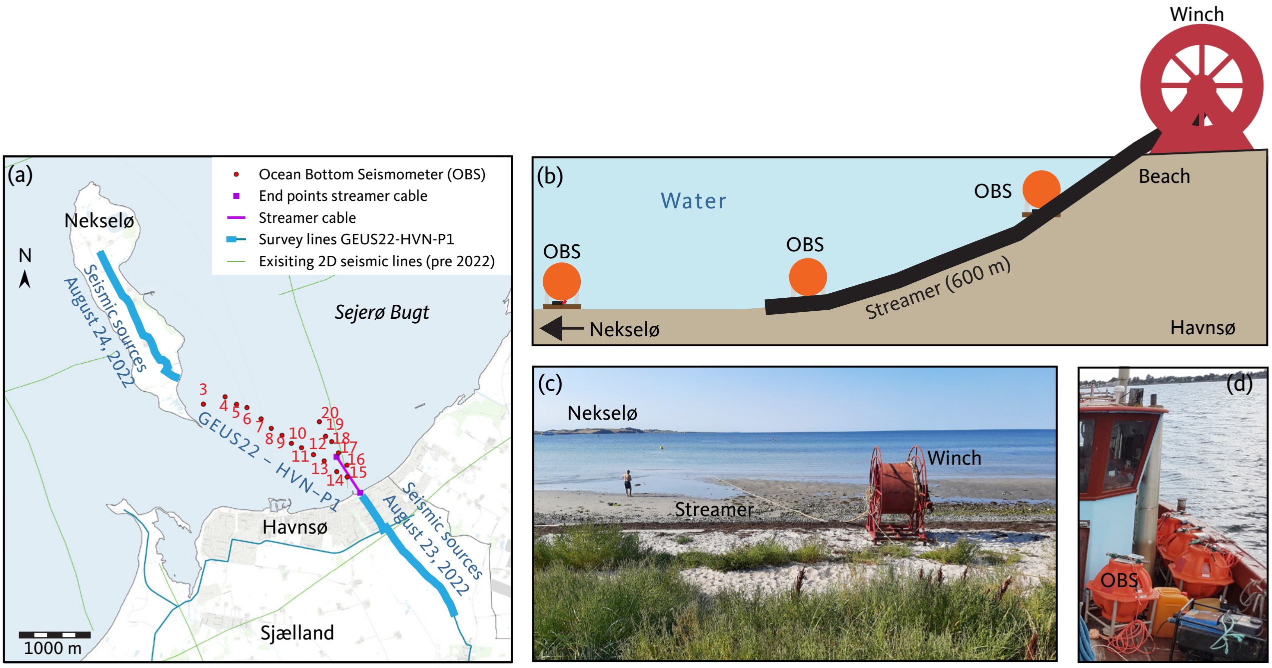

Fig. 8 Overview of the Havnsø seismic acquisition from Havnsø to Nekselø. (**a**) Location map showing the onshore seismic sources (Vibroseis) and the marine receivers (**OBS**: Ocean bottom seismometers, and streamer cable) used along the northern portion of seismic line GEUS22-HVN-P1. (**b**) Schematic cross-section of the marine receivers. (**c**) The streamer winch on the beach at Havnsø with 600 m of streamer cable deployed at the seafloor towards Nekselø. (Photograph by Per Trinhammer 2022) (**d**) Four of the retrieved OBS on board a local fishing vessel that was used for the marine operation. (Photograph by Egon Nørmark 2022).

3.3. Offshore seismic acquisition

3.3.1. Havnsø–Nekselø seismic acquisition

To map the northern extent of the Havnsø structure, the onshore seismic survey included a profile (GEUS22-HVN-P1) that extends offshore (Fig. 8; Funck & Nørmark 2023; Malehmir & Papadopoulou 2023). This line took advantage of the nearby island of Nekselø that is separated from Sjælland by a 2 km wide shallow marine strait.

Due to the shallow water depth and the protection status as a Natura2000 area, no seismic sources could be employed offshore. Instead, seismic receivers were deployed in the marine strait to record the onshore Vibroseis sweeps both on Sjælland and Nekselø.

While shallow reflectivity cannot be traced continuously across the marine strait because of the marine source restrictions, deeper structures that are relevant for the assessment of the Havnsø structure can be mapped from Sjælland to Nekselø.

For the offshore recording, 18 ocean bottom seismometers (OBS) of the type Sercel micrOBS were deployed at the seafloor between Havnsø and Nekselø in August 2022 (Fig. 8). These instruments are equipped with three-component geophones and a hydrophone; the latter provided better data quality in this experiment. The OBS recorded the seismic signals that were initiated on the road towards Havnsø, and subsequently on Nekselø. Some OBS stopped recording prior to the completion of the line. However, the data quality of the recorded signals is good. After correlation with the source sweep, reflections can be seen from depths below 2 s two-way-travel time (TWT).

A second type of receiver was used close to Havnsø, where a 600 m long marine streamer with 96 channels was deployed from the shore and seaward (Fig. 8). Additional weights kept the streamer at the seafloor. Motion transferred from the recovery buoy resulted in poorer data at the tail end of the streamer. A complete account of the marine acquisition component and the initial processing of the data is provided by Funck & Nørmark (2023), and Malehmir & Papadopoulou (2023) describe the merging with the land data.

3.3.2. Jammerbugt seismic acquisition

Prior to this study, the seismic data coverage of the Jammerbugt structure was very limited, where only three pre-existing seismic lines were available. Hence, the acquisition of additional data to allow for a proper assessment of the structure's suitability for underground CO_2 storage was required. Therefore, 1450 km of 2D seismic data were acquired in April 2023 covering most of the Jammerbugt structure in a denser line spacing (*c.* 2–3 km) and systematic grid than existed previously (Figs 5, 6, 9). The survey was carried out using the Faroese research vessel Jákup Sverri (Fig. 10) in a collaboration between GEUS, Aarhus University and the BGR in Germany. Data acquisition was limited to water depths greater than 10 m, and a 10 km distance had to be kept from the Natura2000 marine protected areas. The design of the survey ensured ties to the existing legacy seismic grid and to the J-1 well on the Lisa structure.

Thirty-nine seismic lines (GEUS23-JB-1 to 39; Fig. 9) were acquired using a 2100 m long Sercel Sentinel SSRD streamer (Fig. 10) with 336 channels and a group spacing of 6.25 m. The seismic source was changed after acquisition of the first ten lines to provide better penetration into the hard subsurface with shallow chalk. Initially, two 150 cubic inch (2.4 L) GI guns were used at a shot rate of 6 s. Later, two GI guns with a volume of 355 cubic inch (5.8 L) each were employed for which a shot rate between 10 and 12 s could be maintained. The pressure was 135 bar (13.5 MPa). More details on the acquisition can be found in Funck *et al*. (2023).

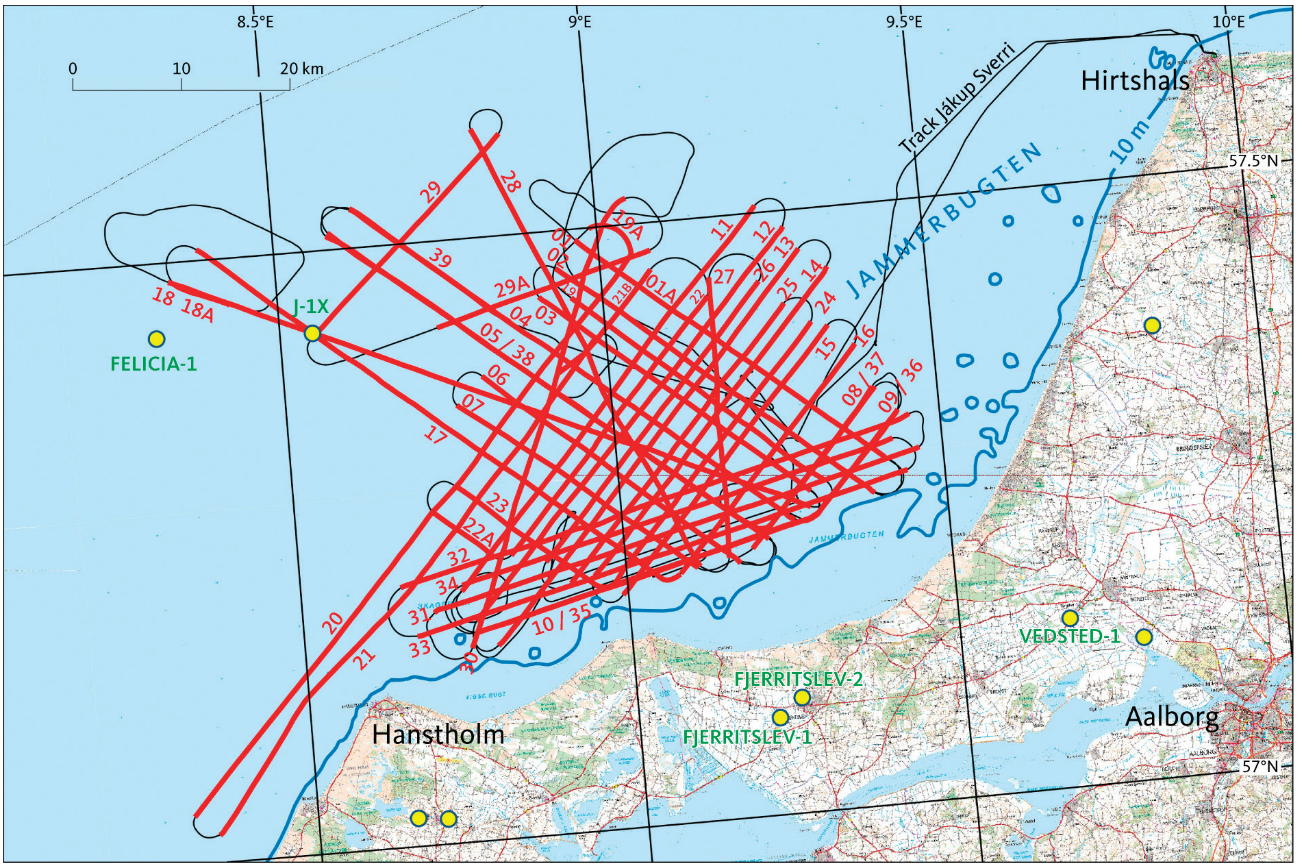

Fig. 9 Topographic map with the location of the acquired seismic lines of the GEUS23-JB survey (**red lines**). **Yellow circles** indicate the positions of wells, the **black line** marks the track of the acquisition vessel Jákup Sverri, **blue lines** indicate the 10 m depth contour.

Fig. 10 Photographs from the Jammerbugt seismic acquisition. (**a**) The Faroese research vessel Jákup Sverri about to leave Hirtshals harbour (northern Jylland) for the seismic acquisition. (**b**) Deployment of the streamer tail buoy. In the foreground, one of the two winches with the solid-state streamer cable (Sercel Sentinel SSRD; yellow cable). Photographs: Thomas Funck.

3.4. Seismic interpretation and mapping

Within the project the geological development and stratigraphy of each of the eight structures were investigated and evaluated, with a focus on the reservoir-seal pairs most important for CO_2 storage. To do this, we used wells and new and legacy seismic data.

Petrel™ software was used for establishing the database with wells and seismic data and for well-to-seismic ties, seismic interpretation and maps. Key wells in and close to structures were examined, and we mainly used the lithostratigraphy (formation tops) from Nielsen & Japsen (1991). If needed, the well-log lithology and ages of successions from biostratigraphy were revised, and the resulting updated well-log figures were reported (see e.g. Gregersen *et al*. 2023a, appendix B).

To use well-log data and well tops (depth domain) for the interpretation of the seismic data (time domain), seismic-well tie procedure was performed on wells that contained sonic and density logs. We used well-to-seismic ties with synthetic seismograms to relate geology to seismic response, and time-to-depth relationships in the wells were mostly from Nielsen & Japsen (1991; see more details e.g. in Gregersen *et al*. 2023a).

The most significant reflections were tied from wells to seismic sections and include for most structures near to base and near to top (here simply base and top) of formations or groups: top and base Chalk (Gp), top Fjerritslev (Fm), top and base Gassum (Fm), top Bunter Sandstone (Fm), top Zechstein (Gp), and top pre-Zechstein. 'Fm' or 'Gp' are omitted in the seismic horizon names. A strong amplitude reflection with the associated acoustic impedance change (velocity and density decrease) at the base Chalk Gp (e.g. Fig. 6b: *c.* 900 ms) was used as a key for interpretation of seismic sections and is indicative for the polarity of the data.

Seismic reflections, seismic successions and seismic facies were identified and interpreted (e.g. Gregersen *et al*. 2022, 2023a; Smit *et al*. 2022). The workflow for this process was to start by interpreting the most significant seismic reflections and relate these to well-tied formation tops. The well-to-seismic ties with synthetic seismograms were used to more exactly select a trough or a peak reflection that corresponded to the formation tops. Then the auto-track function was specified for each horizon to be interpreted. If the auto-tracking could not be used (e.g. where reflections were discontinuous or weak), then interpretation was performed manually. Different seismic data displays were used for interpretation. The displays include various colour scales (black-white and different colour displays including black-white-red) and different seismic attributes. Seismic stratigraphic relationships such as onlaps, downlaps and truncations were used to interpret seismic units and boundaries (e.g. unconformities). Faults, salt structures and folds were also identified and mapped together with thickness patterns. Horizon flattening of seismic profiles, faults and maps were used for the structural and tectonostratigraphic interpretation.

Mapping and interpretation focused particularly on the horizons and faults related to the successions of the primary reservoir (Gassum Fm or Bunter Sandstone Fm) and their primary seals (Fjerritslev Fm or Ørslev Fm, respectively). In addition, the Gassum Fm is described in more detail in studies of sequence stratigraphy applying well-logs and seismic lines to better predict reservoir properties. Reservoir properties, mapped reservoir formation thicknesses and top reservoir closure areas are included for calculations of static storage capacity of CO_2.

Methods for preparing time-to-depth conversion of maps include the compilation of a regional velocity model constructed to convert the interpreted horizons from the time domain to the depth domain. The model area was defined so that the velocity model included a significant buffer around the structure. The data used were: (1) TWT seismic horizons of the main stratigraphic units, using the seismic survey lines, gridded to 250 × 250 m and adjusted to the wells in the structure; (2) well top markers; and (3) seismic migration (root mean square, RMS) velocities from the 2D lines, which were converted to average velocities using the Dix formula. More details are available in Gregersen *et al*. (2023a) and Abramovitz *et al.* (2024).

3.5. Investigation of reservoir and seal

The geology of the reservoir and seal successions are described in the individual, structure-specific project reports (e.g. Gregersen *et al*. 2023a; Abramovitz *et al.* 2024; Keiding *et al*. 2024) and briefly in the Bulletin papers of this volume using well completion reports, publications and in-house studies of well logs and geological samples from wells (mainly from cores). In addition, some studies focusing on description of lithology and biostratigraphy are described (e.g. Gregersen *et al*. 2023a; Abramovitz *et al.* 2024; Keiding *et al*. 2024). The data used are from the wells in or closest to the relevant structure.

The aim of these studies is to provide a more detailed understanding of the reservoir and seal characteristics for each structure. Reservoir characteristics are derived mainly from acquired wireline logs, that are calibrated against conventional core analysis, descriptions of cuttings and sidewall cores. Similarly, the wireline logs are used to estimate thicknesses and identify mudstone sealing sections. The specific method of the seal characterisation depends on the availability of logs in each well. Key reservoir parameters are also investigated and used for storage capacity calculations.

3.6. Storage capacity

To compare the potential CO_2 storage of the structures, we use a simple equation for saline aquifers (e.g. Goodman *et al.* 2011), where static theoretical storage capacity of reservoir units with buoyant trapping is estimated by:

$$SC = GRV * N/G * \varphi * \rho_{CO2R} * S_{Eff} \qquad (1)$$

SC is the storage capacity in mass of CO_2 (Mt). *GRV* is based on seismic interpretation and depth conversion, and is the gross rock volume confined by the upper and lower boundaries of the gross reservoir interval, where thickness and outline area of the structure is defined by the top point depth and the deepest closing contour depth constrained by the spill-point depth (Fig. 11). *N/G* is the average ratio of net sand to gross reservoir volume for the aquifer being investigated. This is based on the petrophysical and geological understanding of the thicknesses derived from the nearest wells and transformed into structure-specific geological-based average values. ϕ is the average effective reservoir porosity of the reservoir within the *GRV*, and ρ_{CO2R} is the average CO_2 density at reservoir pressure and temperature where the density is estimated using the 'Calculation of thermodynamic state variables of carbon dioxide' web tool essentially based on Span & Wagner (1996), and Wischnewski (2007). For this calculation, we assume hydrostatic pressure and geothermal gradients between 27°C/km and 30°C/km (Fuchs *et al.* 2020). The storage efficiency factor (S_{Eff}) relates to the fraction of the total available pore volume that can store CO_2 within the *GRV*. This fraction depends on many subsurface aspects including the size of storage domain, heterogeneity of the formation, compartmentalisation, permeability, porosity, pressure increase, temperature, salinity and compressibility, but is also strongly influenced by different well configurations, injection schemes and displacement efficiency (e.g. Wang *et al.* 2013).

Evaluation and estimation of the static CO_2 storage capacity in deep saline aquifers is complex, and accurate estimations of storage capacity are only reasonable at local site-specific scales. The estimated CO_2 storage capacity is the maximum amount that theoretically can be injected until it reaches the boundaries (i.e. deepest closing contour; Fig. 11). Estimation of CO_2 storage capacity is uncertain due to a lack of knowledge on the storage efficiency factor that is used to reduce the storage capacity to a more realistic estimation (e.g. Bachu *et al.* 2007; Hall 2008; Gorecki *et al.* 2009; Goodman *et al*. 2011). The Stenlille structure is the best-known case in the Danish onshore area, and in previous studies, a fixed storage efficiency factor of 0.4 was used (e.g. Hjelm *et al.* 2022). This value represents a geologically excellent and well-described Gassum Formation sandstone reservoir with a well-defined four-way dip closure without significant cross-cutting faults offsetting the reservoir and overlying seal. For all other potential structures and reservoirs in the Danish onshore area, a reduced factor of 0.1 is selected based on limited well data, geological understanding and the presence of cross-cutting faults.

To address uncertainty related to the reservoir data, depth conversion, reservoir thickness estimates and CO_2 density ranges, simple Monte Carlo simulation was carried out (Fig. 11). Even though this methodology is simple, the purpose is to assess and illustrate the variation of the estimated CO_2 storage capacities as a supplement to the mean calculated values. The method is used in all structures of the CCS2022–2024 project.

Estimation of storage capacity assumes a static approach where the pores in the trap are expected to be 100% connected. It does not include dynamic pressure build-up, solubility of CO_2 in brine, CO_2 mineralisation reactions, presence of salt with possible movement of CO_2 and in-place brine (water) in the saline aquifer, neither inside nor outside the trap. Detailed dynamic reservoir simulation must take these factors into account and will obviously produce different and more realistic CO_2 storage capacity results than those estimated with the static method used

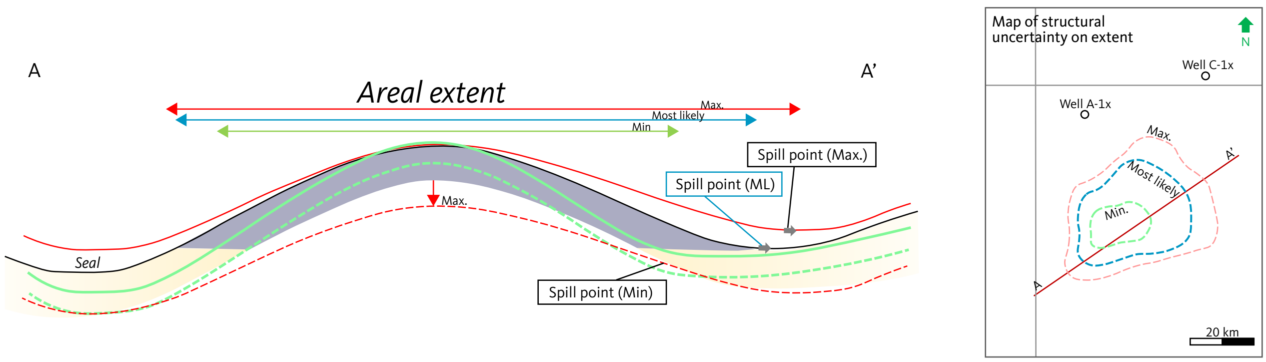

Fig. 11 Conceptual profile (***A***–***A'***) across a potential structure. The uncertainty in mapping the structure results in the hypothetical minimum (**Min.**) and maximum (**Max.**) scenarios that are very different from the most likely mapped scenario. Variance in area and in gross thickness (***t***) will affect the Gross Rock Volume (*GRV*) of the structure. The uncertainty is addressed by applying uncertainty on the resulting *GRV* and other parameters and by conducting simple Monte Carlo simulation to calculate 90, 50 and 10% percentiles (e.g. Burruss *et al.* 2009; Heidug *et al*. 2013).

here – see Schovsbo *et al.* (2025, this volume) for further discussion. A more detailed realistic dynamic reservoir simulation including well design and injection strategy is normally carried out by the awarded license holders and operators.

4. Results of seismic interpretation and storage capacity estimation

The seismic interpretation carried out in the CCS2022–2024 project used both the newly acquired and legacy seismic data, as well as information from deep wells. The project focused on initial maturation and de-risking by mapping and describing mainly the reservoir and seal formations, the largest faults and the geometry of structural closure, and by outlining the stratigraphic and structural development of the structures, as summarised below.

4.1. Stratigraphy, geometry and geological development of individual structures

4.1.1. Stenlille structure

The Stenlille structure is a four-way dip closure, elongated in a SW–NE direction, located in the eastern part of the Danish Basin, in central-west Sjælland (Figs 1, 12a). The main influence on the structure is a salt pillow, which predominantly impacts the dome-shaped overlying Triassic and Jurassic successions and slightly affects the Cretaceous succession (Fig. 12a). The salt pillow was mapped, described and defined by Gregersen *et al*. (2023a), and is subsequently referred to as the Stenlille Salt Pillow. The structure is penetrated by 20 wells and covered by both 2D and 3D seismic data, thereby offering the most comprehensive database of all the investigated structures. Thus, only a small survey with five lines was acquired in 2022 on the NE flank, just outside the area covered by the 3D seismic survey. The new data increased the overall coverage of modern, high-quality data in this part of the structure (Gregersen *et al.* 2022, 2023a; Papadopoulou *et al.* 2022, 2023; Fig. 5).

Through the work in this study, a greatly improved understanding of the structure has been achieved, particularly concerning the understanding of the primary reservoir-seal pair of the Rhaetian Gassum Fm and the uppermost Rhaetian to Lower Jurassic Fjerritslev Fm (Gregersen *et al.* 2023a). A geological cross section of the structure is shown in Fig. 12a. Deep below the Gassum Fm reservoirs and mudstones are secondary reservoirs consisting of Triassic sandstones of the Oddesund Fm (Carnian to Norian) and the Bunter Sandstone Fm (Olenekian to Anisian).

The Gassum Fm consists of six reservoir zones with sandstones. Details on reservoir properties and geophysical modelling of these zones are given by Bredesen *et al.* (2022, 2023) and Gregersen *et al.* (2023a). The zones have good reservoir properties with the deepest zones (zones 5 and 6) showing the highest average effective reservoir porosities (approximately 25 and 27%, respectively), which decrease slightly in the upper zones (zones 1–4; Gregersen *et al.* 2023a).

Natural gas is stored by Gas Storage Denmark A/S within the Gassum Fm of the Stenlille structure and extracted for consumers as needed. The storage of gas has been operated safely for more than 30 years, proving the caprock integrity of the Stenlille structure.

The uppermost reservoir sandstones of the Gassum Fm in the Stenlille structure are overlain by a 240–300 m thick section of mudstones of the Fjerritslev Fm. The Gassum Fm is on average 150 m (140–160 m) thick within the structure with the top at *c.* 1450 m below mean sea level (bmsl). The deepest closure of the Gassum Fm top surface is at 1475 m bmsl, outlining an area of 5.4 km^2 (Gregersen *et al.* 2023a).

The Stenlille structure mainly evolved by the growth of a salt pillow, which led to the formation of an anticlinal dome structure in the overlying strata. The structure developed predominantly during the burial of the thick Fjerritslev Fm. The salt pillow overlies pre-Zechstein successions that form the base of the present Stenlille structure. The pre-Zechstein successions were mainly faulted during the Carboniferous – early Permian, and some of the faults were probably reactivated during the Triassic to Jurassic. Renewed faulting probably triggered salt migration over the inclined pre-Zechstein succession (near top of the Rotliegend Gp) leading to the formation of the domal salt pillow in the Stenlille structure (Fig. 12a). Continued growth of the salt pillow elevated the overburden, particularly during the late Early Jurassic to earliest Cretaceous. Sedimentary successions of these ages are missing in the Stenlille wells (Fig. 3; Gregersen *et al.* 2023a).

Normal faults and, to a lesser extent, minor reverse faults, are observed in the Stenlille data. The faults were manually interpreted as well as outlined by machine learning, thereby increasing the understanding of the 3D fault network (Gregersen *et al.* 2020, 2022, 2023a; Lorentzen *et al.* 2022). The faults in the Gassum–Fjerritslev levels show NE−SW trends. The Top Fjerritslev Fm unconformity (Mid-Cimmerian Unconformity, MCU; Fig 3) is onlapped by a succession including the Vedsted and Rødby Fms, which are overlain by the Chalk Gp (Figs 3, 12a). Shallower faults in the Chalk Gp have predominant strikes in three directions: NW−SE, WNW−ESE and NE−SW, and may be related to renewed episodes of uplift.

4.1.2. Havnsø structure

The Havnsø structure is a four-way dip closure, elongated in a SE–NW direction, located in the eastern part of the Danish Basin, in western Sjælland (Figs 1, 2,

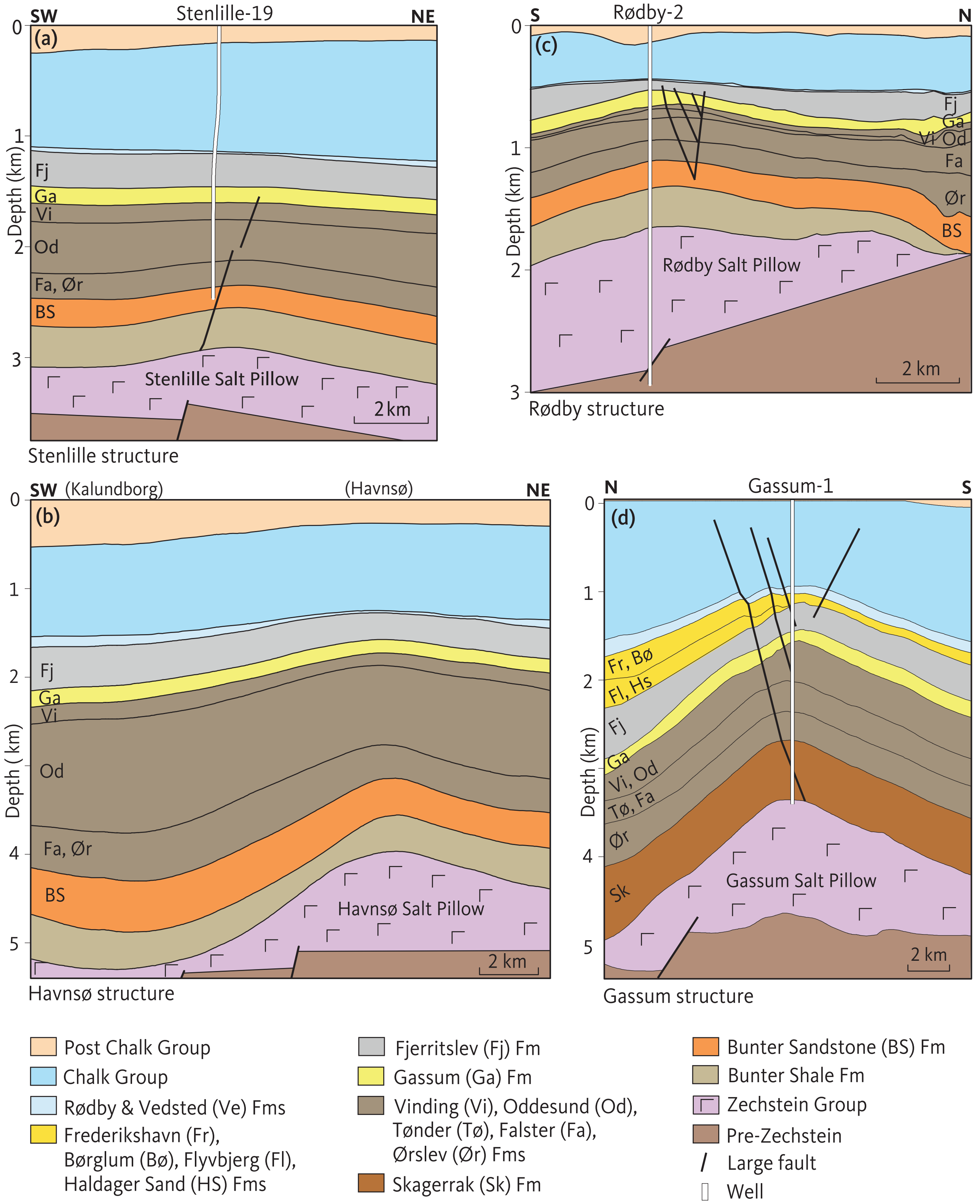

Fig. 12 Simplified geological cross sections through the eight structures investigated in this study. The approximate locations of the largest faults are shown. The primary reservoir formation is the Gassum Fm for all structures except for the Rødby structure (c), where it the primary reservoir formation is the Bunter Sandstone Fm. (**a**) Stenlille structure. (**b**) Havnsø structure. (**c**) Rødby structure. (**d**) Gassum structure. (**e**) Thorning structure. (**f**) Jammerbugt structure. (**g**) Lisa structure. (**h**) Inez structure. Note that the sections have different vertical and horizontal scales. Continues on next page.

12b); new seismic data were acquired over the structure in 2022. The deep, central part of the Havnsø structure has recently been described, mapped and defined as a large salt pillow – the Havnsø Salt Pillow – based on the new and legacy seismic data (Gregersen *et al.* 2023b). Development of the salt pillow caused the doming of the overlying Triassic and Jurassic successions (Fig. 12b).

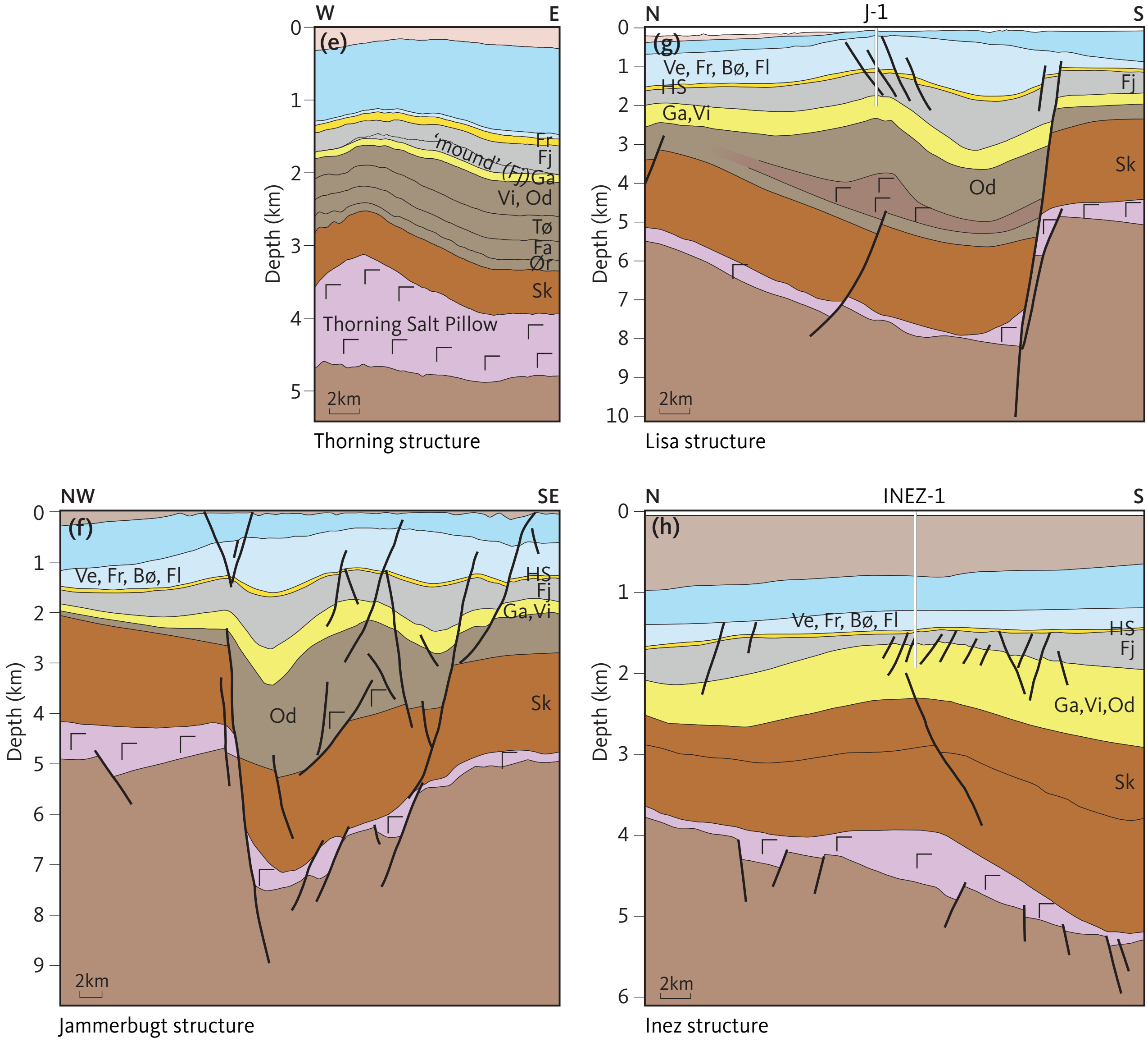

Fig. 12 *(continued)* Simplified geological cross sections through the eight structures investigated in this study. The approximate locations of the largest faults are shown. The primary reservoir formation is the Gassum Fm for all structures except for the Rødby structure (c), where it the primary reservoir formation is the Bunter Sandstone Fm. (**a**) Stenlille structure. (**b**) Havnsø structure. (**c**) Rødby structure. (**d**) Gassum structure. (**e**) Thorning structure. (**f**) Jammerbugt structure. (**g**) Lisa structure. (**h**) Inez structure. Note that the sections have different vertical and horizontal scales.

No wells have been drilled in the structure, and the new seismic data acquired in 2022 (Fig. 5) are thus tied to the deepest well in the nearby Stenlille structure (the Stenlille-19 well, see Fig. 3). The seismic acquisition also included the crossing of a marine strait to connect with the small island Nekselø (Figs 4, 6; Section 3.3.1). The interpretation of the Havnsø structure and its reservoir and seal formations were largely based on correlation to the Stenlille structure (Gregersen *et al.* 2023b; Papadopoulou *et al*. 2023, 2024; Zappalá *et al*. 2024). Hence, further investigations are required to address uncertainties with the seal, faults, near surface geology and velocity models (Gregersen *et al.* 2023b; Kucinskaite *et al.* 2023).

The primary reservoir-seal pair in both the Stenlille and Havnsø structures comprises the Gassum and Fjerritslev Fms (Gregersen *et al.* 2023b). A geological cross section through the Havnsø structure is shown in Figure 12b. Deeper-lying sandstones of the Oddesund Fm and the Bunter Sandstone Fm, known from the Stenlille structure, may form secondary reservoirs in the Havnsø structure. The Gassum Fm is on average 150 m thick (with variations between 130 and 170 m) and has its top at 1550 m bmsl. The deepest closure is at 1710 m bmsl, outlining an area of 70 km^2 (Gregersen *et al.* 2023b). The reservoir properties are mainly prognosed from the nearby Stenlille wells, where three scenarios are considered: (1) the reservoir properties are directly extrapolated from the nearby Stenlille wells; (2) average reservoir property values from Stenlille wells (Stenlille-1 & -19) and selected surrounding wells are assumed; and (3) the reservoir properties are extrapolated from the nearby Stenlille wells, taking into account the stratigraphy inferred from the seismic interpretation. The interpretation indicates that mainly sequences 4 through 6 with sand-prone lowstand system tracts reached the Havnsø area, whereas upper sequences of the Gassum Fm may be more mudstone-dominated. This interpretation is supported by acoustic impedance modelling and differentiated seismic velocities (Gregersen *et al*. 2023b). The interpretation of the available data suggests that good reservoir properties can be expected in all three scenarios.

The Havnsø structure formed in a similar way to the Stenlille structure and is also underlain by a salt pillow; salt movement was initiated during the Triassic. This most likely occurred after deposition of the Falster Fm and at the same time as the deposition of the lower part of the Oddesund Fm (possibly during the Early–Middle Carnian). At this time, a significant succession of sand was deposited (Intra Oddesund Sandstone beds observed in Stenlille-19 well; Gregersen *et al.* 2023a, 2023b). These sands were probably associated with the onset of tectonism that culminated in the development of an erosional unconformity. This unconformity can probably be correlated to an unconformity and a significant hiatus (Carnian age) recognised farther to the south, close to the top of the Tønder Fm in the Søllested-1 well. This event is probably equivalent to the Early Cimmerian Unconformity (ECU; Fig. 3), known more regionally from, for example, the North German Basin (Ahlrichs *et al.* 2020).

The salt pillow mainly developed during Jurassic to Early Cretaceous times, when burial by a thick sedimentary succession and episodic tectonic activity probably triggered salt migration. Nearly all successions overlying the salt pillow form four-way dip closures. The salt pillow is underlain by a slightly inclined pre-Zechstein succession (Rotliegend Gp and older), which is faulted. New faulting and reactivation of pre-existing faults probably occurred during the Triassic and Jurassic and may have triggered salt migration.

There are apparently no large faults through the Mesozoic in the Havnsø structure, based on the present seismic database (Gregersen *et al.* 2023b). However, the newly acquired 2D and legacy seismic surveys have a relatively wide line spacing, and a new, denser data set (preferentially a 3D survey) is needed to investigate whether critical faults are present in the structure. A denser grid would provide possibilities for more accurate evaluation of the extent, throw and pathways of faults in the seal and near-surface succession for de-risking, but would also result in improved facies analysis to predict reservoirs.

Minor faults in the Mesozoic succession are recognised in the data and were developed during the growth of the salt pillow. The throw on these faults is typically small (mostly less than 15 ms), and the lateral extent of the faults is typically not more than a few kilometres. The faults typically trend NW−SE and SW−NE, parallel to the flanks of the structure.

Thinning of the Fjerritslev Fm over the top of the structure (Fig. 12b) indicate elevation of the structure and associated erosion during late Early Jurassic – Early Cretaceous. Onlap of the Lower Cretaceous Vedsted Fm on the Top Fjerritslev horizon marks a major hiatus related to the MCU (see Fig. 3), as observed in the Stenlille structure.

4.1.3. Rødby structure

The Rødby structure is a four-way dip closure, elongated in a NW–SE direction, near the town of Rødby in the south of the island of Lolland (Figs 1, 12c). The main influence on the structure is the Rødby Salt Pillow which gives rise to the dome-shaped geometry of the overlying Triassic and Jurassic successions (Fig. 12c; Abramovitz *et al*. 2024). The primary reservoir-seal pair in the Rødby structure is represented by the Bunter Sandstone Fm and the mudstone seal successions of the Ørslev and Falster Fms, which are shown in Figs 3 and 12c. The reservoir and seal successions in the Rødby structure are intersected by the Rødby-1 and Rødby-2 wells drilled in the 1950s (Figs 3, 4).

Legacy seismic data exist in the central and western part of the structure. New data were acquired over the central part and the eastern flank of the structure (Fig. 5). These new data significantly improved the data coverage and formed the basis for improved mapping and definition of the structure (Abramovitz *et al.* 2024; Malehmir *et al*. 2025). The Bunter Sandstone Fm is 200–260 m (on average 230 m) thick and contains three separate sandstone-dominated intervals. The formation top is at 1100 m bmsl with the deepest closure at 1415 m bmsl, outlining an area of 117 km^2 (Abramovitz *et al*. 2024). The Rødby-1 and Rødby-2 wells show fair to good reservoir properties within the Bunter Sandstone Fm, with average porosities of 17–32% and permeabilities of 293–2029 mD (Abramovitz *et al*. 2024).

The domed-shaped anticlinal structure evolved sequentially over at least three main episodes of salt migration (Abramovitz *et al.* 2024), namely: (1) Initial growth of the Rødby Salt Pillow, which began during deposition of the Falster and Tønder Fms as indicated by truncations along the southern flank. A thick sediment cover resulted in increased pressure and temperatures, which initiated movement of the salt, whereas faulting together with the inclined pre-Zechstein succession influenced the resultant movement (Top Rotliegend Gp; Fig. 12c). (2) Growth of the salt pillow during the Middle Jurassic to Early Cretaceous, triggered by tectonism and re-activated faulting during the mid-Cimmerian tectonic phase resulting in thickness variations of the Fjerritslev Fm. Salt pillow growth elevated the structure and was associated with erosion of the Fjerritslev Fm and perhaps later deposits. The Top Fjerritslev surface is equivalent to the MCU, separating the Lower Jurassic Fjerritslev Fm from the Lower Cretaceous Vedsted Fm (Fig. 3). This tectonism may also have formed the small faults at the top of the structure (Fig. 12c) slightly offsetting parts of the Fjerritslev Fm and older successions. (3) Final growth of the salt pillow and faulting after deposition of the Paleocene, probably up until recent times (hiatus until Quaternary), slightly doming the landscape above the structure.

Quaternary (glacial) valleys formed, in particular, north of the Rødby structure along zones of weakness that have nearly the same orientation as the deeper-seated faults (Lolland–Falster Fault Zone, see Abramovitz *et al*. 2024). The Lolland–Falster Fault Zone mainly developed during the Late Triassic and was reactivated during Middle Jurassic and Cenozoic times. The structural evolution leading to the outline of the present-day Rødby structure may have been triggered by reactivation of the deep-seated Palaeozoic faults below the Top pre-Zechstein at the base of the present-day Rødby structure.

4.1.4. Gassum structure

The Gassum structure is a four-way dip closure, elongated in an E–W direction, located centrally in the Danish Basin (Figs 1, 2), in eastern Jylland (Fig. 1). The main influence on the structure is the Gassum Salt Pillow, mapped and defined using the new seismic data by Keiding *et al*. (2024), which gives rise to the domal geometry in the overlying Triassic and Jurassic successions (Fig. 12d).

The reservoirs and seal successions of the Gassum structure are intersected by the Gassum-1 well, located centrally in the structure (Fig. 12d). Other nearby wells (e.g. Hobro-1 and Voldum-1; Fig. 4) are included in the interpretation to add further information on the geology of the structure. Only a few legacy seismic lines of poor quality covered the structure before the new survey was acquired in 2023 (Fig. 5). The newly acquired data provide much-improved data coverage for updated mapping (Westgate *et al*. 2023, 2024, 2025; Keiding *et al.* 2024) but also underline the need for further investigation of the seal, overburden and faults for site characterisation and risk assessment (Konstantinidis *et al*. 2023; Keiding *et al.* 2024).

The primary reservoir-seal pair in the Gassum structure consists of the Gassum and Fjerritslev Fms (Fig. 12d; Keiding *et al.* 2024). A deeper-situated, secondary reservoir-seal pair consists of the sandstone-rich Skagerrak Fm overlain by the Lower to lowermost Upper Triassic mudstone seal succession of the Ørslev–Falster–Tønder Fms. The ages of these formations are shown in Fig. 3. In addition, a secondary, shallower reservoir-seal pair consists of the uppermost Upper Jurassic to Lower Cretaceous Frederikshavn and Lower Cretaceous Vedsted Fms. Although not present in the Gassum-1 well, the Middle Jurassic Haldager Sand and Upper Jurassic Flyvbjerg Fms (Fig. 3) possibly form additional reservoirs in the structure, as these seem to be present and thicken downdip at the northern flank of the structure, where they are overlain by a potential seal of the Børglum Fm mudstones and overlying successions (Fig. 12d). The secondary reservoirs may provide a significant upside to the estimated storage capacity of the Gassum Fm in the Gassum structure.

The Gassum Fm is *c.* 130–180 m thick in the structure and is overlain by a more than 300 m thick mudstone succession referred to the Fjerritslev Fm. The shallowest point of the Gassum Fm within the structure is 1375 m bmsl and the lowermost closing contour is at 2300 m bmsl, outlining an area of 280 km^2 (Keiding *et al.* 2024). The Gassum-1 well shows good reservoir properties for the Gassum Fm sandstones with an average effective reservoir porosity of 28.5% and an average permeability of 1500 mD (Keiding *et al*. 2024).

The uniform thickness of the Skagerrak Fm infers no or only minor syn-depositional faulting and salt tectonism. This also applies to the overlying Triassic succession (Keiding *et al.* 2024). Most of the Triassic succession, including the Gassum Fm, is intersected by E–W-trending faults, but faulting does not significantly affect the internal thicknesses. Consequently, faulting is interpreted to have occurred mainly after deposition of the Fjerritslev Fm. Minor movements during the Early Jurassic, however, are indicated by thickening of the Fjerritslev Fm towards the north.

Salt movements and uplift leading to development of the Gassum structure may have started during the Triassic, but renewed movement and uplift occurred after deposition of the Fjerritslev Fm. During these periods, parts of the Middle to Late Jurassic Haldager Sand and Flyvbjerg Fms may have been eroded or faulted out since they are not recorded in the Gassum-1 well (Fig. 12d; Keiding *et al.* 2024). It is possible that these formations occur as part of a wedge, which thins towards the northern top of the structure (Fig. 12d). This implies that the Gassum structure probably has secondary reservoir potential; the Haldager Sand and Flyvbjerg Fms are known from other wells (e.g. the Hobro-1 well to the west; Fig. 4).

The Lower Cretaceous Vedsted Fm forms a seal for the Frederikshavn Fm and thins towards the top of the structure (Fig. 12d). The Rødby Fm and most of the Vedsted Fm are missing in the Gassum-1 well, thereby revealing a major hiatus in the upper part of the structure and indicating uplift and erosion, likely related to salt movements (Keiding *et al.* 2024).

The prevailing E–W-striking faults offset the Jurassic to uppermost Cretaceous successions but can be recognised at all stratigraphic levels from the top of the Ørslev Fm to the Chalk Gp (Fig. 12d). Large-scale faults that pass through the seal and continue up to the shallow succession are observed. These faults can be a critical risk for CO_2 storage and must be addressed in further studies, which should include dense seismic acquisition and risk assessment. Additional investigation of the leakage risks associated with the old well should also be conducted. The faulting is interpreted to have been associated with salt migration, and consequently, the youngest salt movements must be Late Cretaceous or Cenozoic in age. The decreasing chalk thickness over the crest of the Gassum structure may have been caused by uplift and erosion, which has been ascribed to salt movement or structural inversion (Konstantinidis *et al*. 2023; Keiding *et al.* 2024; Westgate *et al.* 2024, 2025).

4.1.5. Thorning structure

The Thorning structure is a three-way dip closure, elongated in a SSW–NNE direction, located in central Jylland (Figs 1, 12e). The main influence on the structure is the Thorning Salt Pillow, which affects the overlying Triassic to Cretaceous successions (Fig. 12e). The salt pillow has recently been mapped and defined with the newly acquired data (Bjerager *et al.* 2024). There are no deep wells in the structure, and the new seismic data acquired in 2023 (Putnaite & Malehmir 2024) are thus correlated to nearby wells to the south-west (Nøvling-1 and Vinding-1) and to the north (Kvols-1) using legacy data. These wells are located some 30–40 km away from the Thorning structure (Figs 4, 5).

The primary reservoir-seal pair for the Thorning structure consists of the Gassum and Fjerritslev Fms (Hjelm *et al.* 2022; Bjerager *et al.* 2024). A geological cross-section through the Thorning structure is shown in Figure 12e.

Deeper sandstones of the Triassic Skagerrak and Tønder Fms and shallower reservoirs, possibly the uppermost Jurassic to Lower Cretaceous Frederikshavn Fm, known from wells to the north (e.g. Kvols-1, Hobro-1, Gassum-1; Fig. 4), may form secondary reservoirs in the structure (Bjerager *et al.* 2024). The Gassum Fm is *c.* 100 m thick on average, and the shallowest point of the reservoir within the structure is 1520 m bmsl. The lowest closing contour for the reservoir is at 1950 m bmsl, outlining an area of 235 km^2 (Bjerager *et al.* 2024). Reservoir properties of the Gassum Fm sandstones are inferred to be good from nearby wells surrounding the Thorning structure and from seismic interpretation estimated in three scenarios, showing an average effective reservoir porosity of *c.* 26–29% and an average permeability of *c.* 1000–1500 mD (Bjerager *et al.* 2024).

The Thorning structure overlies a salt pillow that began to form during the Triassic and developed through the Jurassic to Early Cretaceous, when continuous burial by thick sedimentary successions and tectonic activity probably triggered salt migration (Bjerager *et al.* 2024). The salt pillow overlies a slightly northward-dipping pre-Zechstein surface. A few extensional faults are observed in the Triassic to Cretaceous successions at the northern rim of the Thorning structure. These faults were probably formed during the Triassic and Jurassic as a result of salt movements. Compared with the earlier interpretation based on only a few seismic lines (Fig. 5), the updated interpretation using the newly acquired high-resolution seismic data shows a more elongate structure (Bjerager *et al*. 2024; Putnaite *et al*. *2025*). Specifically, the structure is narrower in the E–W direction and longer in the N–S direction than originally mapped (Hjelm *et al.* 2022; Fig. 1). Estimates of the size of the Thorning structure are similar to those derived in previous studies (Hjelm *et al.* 2022; Bjerager *et al.* 2024). Near-surface structures, including faults and palaeo valleys, are also revealed by the new seismic data (Putnaite *et al*. 2025).

A significant graben structure, with normal faults and a width of 5 km (south of the profile in Fig. 12e), is revealed in the new seismic data (lines P4 and P5) at the SW flank of the Thorning structure (see Bjerager *et al*. 2024). It probably formed due to salt withdrawal and collapse, resulting in a marked thickening of the Fjerritslev Fm in the fault zone. Large throws at the Top Gassum to Top Falster horizons indicate faulting during deposition of the Vinding Fm, which shows a clear increase in thickness near to the NE-dipping main boundary fault of the graben structure. This was most likely the result of salt withdrawal beneath the graben. A second phase of faulting and salt migration took place during deposition of the Fjerritslev Fm. The Top Fjerritslev to Base Chalk horizons show only minor faulting, which probably developed during the growth of the salt pillow, partly triggered by the Mid-Cimmerian tectonic phase. Thinning of the Fjerritslev Fm over the top of the structure may indicate elevation of the structure and associated erosion during the late Early Jurassic – Early Cretaceous. Onlap of the Lower Cretaceous Vedsted Fm onto the top of the Fjerritslev Fm marks a major hiatus at the MCU. The fault zone along the SW flank of the Thorning structure is close to the deepest closing contour, that is, the spill point for the top Gassum Fm of the structure. From the point of view of leakage risk, this is therefore less critical than if it had occurred at the top of the structure. The profiles in the new seismic survey are rather sparse; new and more tightly spaced seismic data are thus needed to further map and evaluate faults and determine their significance for seal integrity.

4.1.6. Jammerbugt structure

The Jammerbugt structure (Fig. 12f) is an elongated structure with a SE–NW direction located in the Fjerritslev Trough near the shore of the Jammerbugt bay, west of northern Jylland (Fig. 1). The structure outlines an undrilled, faulted, three-way closure. Prior to the new seismic survey in 2023, the structure was only covered by a few seismic lines of variable quality. The new acquisition added 1450 km of seismic lines to the database, covering the structure and the adjacent area in a systematic and dense grid (Figs 5, 9; Table 1). Three of the lines tie to the nearby J-1 well in the adjacent Lisa structure (Fig. 9). The new data permit a better delineation of the structure and an analysis of its geological evolution.

Extensional faults confine the north-western and north-eastern flanks of the Jammerbugt structure, while the opposite flanks are defined by the stratigraphic plunge (Fig. 12f; Fyhn *et al.* 2024). Seismic data are essentially lacking in the south-easternmost, landward part of the structure due to the low water depths there. The Jammerbugt structure developed together with the Fjerritslev Trough that formed in response to Mesozoic extension and down-throw across the Fjerritslev Fault. Similarly, the faults in the Jammerbugt structure developed in response to Triassic–Cretaceous pulses of deep-seated extension (Fyhn *et al*. 2024). In addition, detachment faults in Zechstein salt caused roll-over folding in the overlying Mesozoic section, which influenced the structural architecture giving rise to an anticlinal element in the closure geometry.

Apart from the confining faults, the stratigraphy within the Jammerbugt structure, including reservoirs and seals, is offset by faults rooted in the salt of the Oddesund Fm (indicated in Fig. 12f). Growth of a salt pillow within the Oddesund Fm under the north-western part of the structure contributed to the closure relief in the overlying section. Similarly, doming associated with Late Cretaceous to Palaeogene structural inversion of the Fjerritslev Trough contributed slightly to the closure relief. Correlation to wells drilled in the vicinity suggests the presence of two reservoir levels within the structural closure: (1) the Gassum Fm and (2) the Haldager Sand Fm. Depth-converted seismic mapping of the Jammerbugt structure places the shallowest point of the Gassum Fm at around 1620 m and the top of the Haldager Sand Fm at 1160 m. The area of the closures within the Gassum Fm and Haldager Sand Fm are mapped to be 119 km^2 and 142 km^2, respectively (Fyhn *et al*. 2024). By comparison to nearby wells, the Gassum Fm is estimated to have a thickness of around 200 m, whereas the Haldager Sand Fm is only estimated to have a thickness of around 20 m over the structure.

The two reservoir intervals are interpreted to be overlain by thick mudstone successions. Seismic mapping and comparison to nearby wells suggest that the mudstone-dominated Lower Jurassic Fjerritslev Fm, which overlies the Gassum Fm, has a thickness of a few hundred metres within the structure. The Fjerritslev Fm forms the primary seal for the Gassum Fm. The Haldager Sand Fm is interpreted to be overlain by Upper Jurassic Børglum Fm claystones that form a sealing unit. Information from nearby wells intersecting this fine-grained unit together with seismic mapping suggests a thickness of the Børglum Fm of *c.* 100 m in the Jammerbugt structure. A geological risk defined at this stage is associated with faulting of the reservoir and seal intervals, where some faults appear to terminate close to the seabed. These faults introduce a risk of reservoir leakage and compartmentalisation and hence the potential risk for leakage along fault planes needs further investigation. Other geological uncertainties include the local reservoir quality of the Gassum Fm within the structure and the risk that hydrocarbons, formed in the Fjerritslev Trough, have charged the undrilled structure.

4.1.7. Lisa structure

The Lisa structure is located in the Fjerritslev Trough, offshore northern Jylland (Fig. 1). It is a four-way dip closure elongated in a SE–NW direction; the structure is located above a salt pillow belonging to the Oddesund Fm (Fig. 12g). The structure was drilled by the J-1 well and is covered by a sparse grid of seismic data of variable quality acquired by both industry and academia. The most recently acquired data over the structure was acquired in 2023 as part of this study (Fig. 5). The J-1 well terminated in Rhaetian deposits after drilling 1952 m of Upper Cretaceous, Jurassic, and uppermost Triassic strata. The Lisa Salt Pillow is overlain by two reservoir-seal pairs, the Gassum Fm – Fjerritslev Fm and the Haldager Sand Fm – Børglum Fm, where four-way dip closures are present at both stratigraphic levels. The structures in the sequence overlying the salt developed in response to a combination of differential salt motion and Late Cretaceous to Palaeogene structural inversion of the Fjerritslev Trough.

The Rhaetian to Hettangian Gassum Fm forms the primary reservoir with a thickness of 199 m in the J-1 well. Based on calculations using the wireline logs from this well, the reservoir is estimated to have a net-to-gross of 0.45, an average effective reservoir porosity of 20% and an average permeability of 251 mD. The Gassum Fm is capped by 623 m of mudstone-dominated strata belonging to the Lower Jurassic Fjerritslev Fm of which the lower 120 m section, dominated by shale, is considered an excellent main seal for storage within the Gassum Fm. Despite an excellent average effective reservoir porosity of 25% and permeability of 1112 mD the shallower Middle Jurassic Haldager Sand Fm is considered a secondary reservoir due to its modest thickness and net-to-gross of 19 m and 0.24, respectively. The Haldager Sand Fm reservoir is overlain by 101 m of mudstones belonging to the Børglum Fm, which are considered to have excellent seal potential. Both reservoirs and seals are intersected by faults, some of which appear to terminate close to the seabed. Over part of the closure, faults are densely spaced, located at intervals of a few kilometres to a few hundred metres apart. These faults typically offset the geological layers by a few tens of metres but occasionally more. The primary geological risks for efficient and lasting CO_2 storage as identified at this stage are therefore associated with the presence of these minor faults offsetting both reservoirs and overlying seals. The faults introduce the risk of reservoir compartmentalisation and a mechanical weakening of the seal, which needs to be investigated with further data acquisition and analysis.

4.1.8. Inez structure

The Inez structure is situated *c.* 50 km offshore in the northern Danish North Sea (Fig.1). It is a four-way dip structure outlining one of the larger Danish geological structures with a promising storage potential. The Inez area is covered by a sparse 2D seismic grid of variable quality, and the structure was drilled in 1978 by the Inez-1 well.

The Inez structure (Fig. 12h) is a turtleback structure formed in response to Zechstein salt migration towards six large salt structures in the vicinity of the structure, where salt movement occurred predominantly during the Middle Triassic to Early Cretaceous. The associated differential subsidence resulted in laterally migrating rim synclines around the Inez structure generating a four-way dip closure at three reservoir levels: (1) Top Skagerrak Fm, (2) Top Gassum Fm and (3) Top Haldager Sand Fm (Fig. 12h). The Gassum and Haldager Sand Fms are intersected by the Inez-1 well and include sandstones with average effective porosities of 20.3% and 26.0%, respectively. Estimated average permeabilities of the Gassum and Haldager Sand Fms are 442 mD and 871 mD, respectively. The Rhaetian to Hettangian Gassum Fm, which formed in a near-shore environment, is interpreted to have a thickness of 148 m in the Inez-1 well. It has a net-to-gross ratio of around 0.59. The Middle Jurassic Haldager Sand Fm only measures 9 m in thickness, has a net-to-gross ratio around 0.32 and is therefore secondary to the Gassum Fm. The Gassum Fm is overlain by thick claystone intervals of the Fjerritslev Fm, which are observed to be 127 m thick in the Inez-1 well. Hence, the Fjerritslev Fm is considered the primary seal for the Gassum Fm reservoir. Similarly, the Jurassic sandstone interval (Haldager Sand Fm) is overlain by thick Upper Jurassic claystones of the Børglum Fm, which form a sealing unit.

In the Inez-1 well, the youngest Gassum Fm is lowermost Jurassic in age. The section downwards becomes increasingly arkosic in nature interpreted as an upper Triassic proximal facies belonging to the Gassum or Vinding Fms in which the well terminates. The Lower to lowermost Upper Triassic Skagerrak Fm is correlated seismically from the Felicia-1A well with the deeper part of the Inez structure. The thick and sand-rich Skagerrak Fm comprises another secondary reservoir in this structure. The shallowest point of the Skagerrak Fm within the structure is estimated to be of a depth of about 2500 m, which lies some 175 m above the lowest closing contour. The unit is not intersected in the Inez-1 well as the well terminated in the uppermost Triassic succession, but good reservoir properties are anticipated from analogues within Danish wells elsewhere that encounter the Skagerrak Fm. The Skagerrak Fm is interpreted to be overlain by fine-grained sediments and evaporites of the Oddesund Fm that probably provide a tight sealing unit for the reservoir.

A geological risk defined at this stage is associated with densely spaced faulting within the Gassum Fm; these faults typically offset the reservoir by a few tens of metres introducing a risk of reservoir compartmentalisation. The faults also continue upwards into the overlying Fjerritslev Fm seal succession. Therefore, although the Fjerritslev Fm seal thickness fully complies with the recommendations for CO_2 storage, the potential risk for leakage along fault planes needs further investigation.

4.2. New geological results and implications

The study of the eight structures in the CCS2022–2024 project has resulted in an improved geological understanding of the structures and basins, their tectonostratigraphic evolution and the regional correlation between the structures. It has also revealed several novel questions to be addressed in future work.

The newly acquired seismic data significantly improve the existing database and allow for a revised and much more detailed interpretation with a better physical definition of the structures, as well as new depth-structure maps of key horizons and thickness maps. The new data and interpretation also provide valuable additional information regarding the composition of reservoir and seal successions, faults and biostratigraphy, all of which are important for future work on the suitability of these structures for the purpose of CCS.

In all structures, the primary reservoir formations (storage formations) show a significant and relatively stable thickness, mostly between 100 and 200 m for the Gassum Fm and 200 to 250 m for the Bunter Sandstone Fm (Table 2). Good reservoir properties are demonstrated based on interpretation of well data in or near the structures. There are no wells drilled in the Havnsø, Thorning and Jammerbugt structures; the reservoir models of these structures are based on interpretation of data from the wells closest to the structures and interpretation from seismic tie-lines correlated from these wells. We interpreted seismic facies successions with subtle inclined reflections and troughs, suggestive of sandstone-dominated lowstand successions. This was particularly the case for the Havnsø structure, based on similar features and seismic correlation from the Stenlille area with wells and 3D seismic data (Gregersen *et al*. 2023b).

In all structures, the primary seal formation is based on wells in or near the structures and mapped from seismic data that demonstrate significant thicknesses. The Fjerritslev Fm is more than 250 m thick in most structures, except for the Inez structure, which has a thickness of 127 m. In the Rødby structure, the Ørslev Fm seal succession has a thickness of 175 m (Table 2).

The structures mainly formed through episodic salt tectonism triggered by deep-seated faulting. Further investigations of structures, reservoirs and seals are recommended to increase the understanding of their CO_2 storage potential.

Previously unobserved faults, most significantly in the Jammerbugt, Gassum, Rødby and Thorning structures, have been discovered in the new seismic data. However, faults are recognised in both new and vintage data in all structures. Therefore, all investigated structures require additional seismic and well data to perform an assessment of risks associated with potential CO_2 storage, in particular regarding faults, but also regarding old wells where they penetrate seal and reservoir successions.

Interpretation using regional seismic correlation between wells and analysis of well data during this project have revealed a need for updating the lithostratigraphy in the Triassic succession of the Danish Basin. Different formation names (e.g. the Skagerrak Fm and the Bunter Sandstone Fm) are in some cases used for equivalent stratigraphic intervals. In addition, regional lithofacies distribution (e.g. of Triassic reservoir sandstones) is not well understood, while existing lithostratigraphy is based on wells but not integrated with regional seismic correlations. Therefore, a revision of the Danish Triassic stratigraphy should be considered.

4.3. Storage capacity estimation

Using the new high-quality seismic data, the work in the CCS2022–2024 project has resulted in an improvement in the physical definition of the eight structures, their outline areas and GRVs (Fig. 12). The new geological knowledge of the structures has increased the understanding of the reservoir and seal successions. The new data and interpretations have also significantly improved the understanding of the geometry and distribution of faults. This improved knowledge is important for further CCS evaluation. In this study, updated well analysis and new depth conversions have also led to a greatly improved characterisation of key reservoirs and the geometry of the structures.

Evaluation and maturation of a CO_2 storage site include several steps. A maturation phase includes a static calculation of the theoretical storage capacity – primarily

Table 2 Area, depth and formation thicknesses of each of the structures in the CCS2022–2024 project.

Structure	Area	Top	Primary reservoir Fm		Primary seal Fm	
	(km^2 at top primary reservoir)	(m bmsl to top primary reservoir)	Formation	Thickness (m)	Formation	Thickness (m)
Stenlille	5.4 km^2	1449 m	Gassum Fm	150 m	Fjerritslev Fm	275 m
Havnsø	70 km^2	1550 m	Gassum Fm	150 m	Fjerritslev Fm	275 m
Rødby	117 km^2	1100 m	Bunter Sandstone Fm	230 m	Ørslev Fm	175 m
Gassum	280 km^2	1375 m	Gassum Fm	180 m	Fjerritslev Fm	325 m
Thorning	235 km^2	1520 m	Gassum Fm	94 m	Fjerritslev Fm	265 m
Jammerbugt	119 km^2	1620 m	Gassum Fm	200 m	Fjerritslev Fm	525 m
Lisa	not available	1623 m	Gassum Fm	199 m	Fjerritslev Fm	623 m
Inez	not available	1592 m	Gassum Fm	148 m	Fjerritslev Fm	127 m

'Area' refers to the area within the lowest closing contour for each respective structure, based on a depth-converted structure map of the top of the reservoir. 'Top' refers to the shallowest point of the primary reservoir within the structure. The table shows simplified single values to give an overview for comparison between the structures. The values are mostly averages from a ranges of scenarios, based on wells and mapping of the individual structures, which are more thoroughly described in the interpretation reports of the project (Gregersen *et al.* 2023a, 2023b; Abramovitz *et al*. 2024; Bjerager *et al*. 2024; Fyhn *et al.* 2024; Keiding *et al.* 2024). Note that the formation thicknesses from maps change across the structures and become thicker mainly from the top and towards the flanks of the structures (Fig. 12) as described in the interpretation reports of the project (see references above). Depth and thicknesses for each structure are from wells and maps, although the values for the Lisa and Inez structures were derived solely from the J-1 and Inez-1 wells, respectively.

based on *GRV*, reservoir sand thickness and average effective porosity, as well as density of the CO_2 (Section 3.6) but excluding permeability. The current maturation phase does not include dynamic capacity estimates of the potential CO_2 structures but focuses on identifying and assessing the extent and quality of the reservoir aquifers. Furthermore, no attempts are made to address seal capacity (i.e. CO_2 entry pressures), fault leakage, fault reactivation, solubility of CO_2 in brine, and CO_2 mineralisation reactions.

By using the static approach (described in Section 3.6), all the structures of this project have been re-evaluated since Hjelm *et al.* (2022). The Gassum Fm reservoirs have been the primary sandstone target with the Bunter Sandstone Fm reservoir in the Rødby structure being the exception. Sandstone reservoirs in the Frederikshavn, Haldager Sand and Skagerrak Fms may also possess considerable reservoir potential, but the storage potential of these units has not been evaluated. Combined, these units may provide a significant upside to the storage capacity.

In the storage capacity estimation, the *GRV* is corrected with the *N/G* ratio to achieve a more realistic reservoir sand volume. Extended and more detailed analysis of the log data show that the Gassum Fm in some wells has a number of discrete sandstone intervals, mainly in the lower part of the formation (e.g. the Havnsø and Thorning structures). However, these separate layers are not taken into account in these estimations.

To evaluate the uncertainty on the input parameters, minimum and maximum cases were also calculated by assigning a minimum, mode and maximum uncertainty range, mode being the data value that occurs most often in the data set. It is assumed that the assigned distribution of all the input parameters follow a Pert distribution defined by the minimum, mode and maximum values. The Pert distribution is believed to give suitable representation for naturally occurring events following the subjective input estimates (Clark 1962). The variation in *GRV*, amongst others, was inferred to cover uncertainty in interpretations, seismic well ties, mapping and depth conversion normally by defining the minimum and maximum of the distribution based on surrounding wells. Some variation of *N/G* and porosity are expected due to thickness and lateral variation of the lithologies owing to differences in facies distribution, depositional environment, diagenesis and poor quality of the well logs. Storage efficiency is heavily influenced by local geological subsurface factors, and an analogue storage efficiency database is not available for the Danish onshore area; accurate storage efficiency factor ranges are thus lacking at this early stage of maturation. A fixed factor value of 0.1 was used, assuming that the reservoir has reasonable reservoir characteristics, and that uncertainty is caused by the identification of faults on or near the apex or top point of the structures penetrating both the seal and the reservoir.

The results of Monte Carlo simulations for each of the structures, including the mean mass of CO_2 in megatons (Mt) that can be stored, are shown in Table 3. Together with the 90, 50 and 10% percentiles (P90, P50 and P10), the range corresponds to the chance for a given storage volume scenario to exceed the given storage capacity value. Mean values of the resultant outcome distribution is considered the 'best' single value representation for the entire distribution.

Without addressing the influence of the faults located on or near the apex or top point of several of the structures (e.g. the Gassum and Rødby structures), the mean unrisked static storage capacities for the investigated structures range between 8 and 498 Mt CO_2 for the Gassum Fm, and 107 Mt CO_2 for the Bunter Sandstone Fm (Table 3).

Due to the variability of the underlying factors, the estimated storage capacities have a significant range. The results are mainly linked to the use and uncertainty

Table 3 Unrisked theoretical storage capacity for structures investigated in the CCS2022–2024 project.

			Static CO_2 capacity			
Structure	Stratigraphic level	**Area** (km^2)	**Mean** (Mt CO_2)	**P90** (Mt CO_2)	**P50** (Mt CO_2)	**P10** (Mt CO_2)
Stenlille	Gassum Fm	5.4	8	1.7–4.7	2.5–7.7	3.2–11.8
Havnsø	Gassum Fm	70	50	22.1–41.3	33.5 – 62.8	48.8–90.4
Rødby	Bunter Sandstone Fm	117	107	69	104	149
Gassum	Gassum Fm	280	498	325	486	689
Thorning	Gassum Fm	235	125	81	122	174
Jammerbugt	Gassum Fm	119	199	122	191	289

The primary reservoir formation is the Gassum Fm except for the Rødby structure, where the Bunter Sandstone Fm is the primary reservoir formation. For the Stenlille structure, a fixed storage efficiency factor of 0.4 was used, whereas for all other structures, a fixed efficiency factor of 0.1 was used. The capacity ranges for the Stenlille and Havnsø structures cover different scenarios, and the mean values cover an average of scenarios: 6–10 Mt CO_2 and 35–65 Mt CO_2 for the Stenlille and Havnsø structures, respectively. Estimations for the Lisa and Inez structures are in progress and were not available at the time of publication. P90, P50 and P10: 90, 50 and 10% percentiles, respectively. See full estimations in the interpretation reports of the project (Gregersen *et al.* 2023a, 2023b; Abramovitz *et al*. 2024; Bjerager *et al*. 2024; Fyhn *et al.* 2024; Keiding *et al.* 2024).

of the storage efficiency factor, where the factor is 0.1 (minimum of 0.05 to a maximum of 0.2) compared to the previously used 0.4, thus reducing the overall CO_2 storage capacity compared to previous studies (see Hjelm *et al.* 2022).

The simple method used to obtain the estimated storage capacities in Table 3 is a means to benchmark and compare the structures during the initial screening across Denmark. It should be updated when more data are gathered. It is also recommended to apply more complex and detailed dynamic methods. Using a simple static CO_2 storage capacity calculation is, however, beneficial for several reasons. It only requires a few input parameters, making it easier to obtain first estimates on capacity. It is cost-effective, less expensive and less time-consuming than dynamic methods, which require more data and computational power. It is important to note that static methods do not account for fluid flow and more complex geological factors and facies configurations. Furthermore, static calculations do not account for all the dynamic processes that can affect CO_2 injection and storage over time.

5. Conclusions and perspectives

The CCS2022–2024 project has matured eight selected geological structures (the Gassum, Havnsø, Inez, Jammerbugt, Lisa, Rødby, Stenlille and Thorning structures) that were identified as suitable targets for potential storage of CO_2, facilitated by new seismic acquisition and hence enhanced interpretation.

The seismic acquisition of the project carried out in 2022 and 2023 is one of the most comprehensive public scientific acquisition campaigns ever conducted in Denmark, and it has significantly increased the data coverage with high-quality seismic data over the structures investigated. Within the project, a total of 2093 km of new 2D seismic profiles of good quality were acquired, where approximately 643 and 1450 km were acquired onshore and offshore, respectively. The data sets were initially processed and subsequently reprocessed to enhance more details. In addition, selected pre-existing legacy seismic data sets were reprocessed.

The new extended database was used to update the geological and seismic interpretation and structural mapping of the structures, providing both a better delineation of the investigated structures, including major faults, and an improved understanding of the geological and tectonostratigraphic evolution. Interpretation of seismic facies reflecting sandstone-dominated successions away from wells support the interpretation that storage formations are regional in extent. All new data along with the acquisition, processing and interpretation reports and a list of related publications from the CCS2022–2024 project are available on the GEUS website (*https://geus.dk/ccsdata*). Key results of the project and continued work are summarised within this Bulletin.

Unrisked theoretical static storage capacities of the structures were estimated based on the new data and interpretations performed in the project and are provided with ranges of uncertainty. The assessment of the static estimated storage capacities provides a good insight into the relative capacities of the structures. However, they do not address complex variations in the reservoir structure and properties. Hence, this highlights the need for further work, for example to identify volumes of the reservoir with high quality, connectivity and absence of cross-cutting faults. After this maturation phase, the reservoir units and the impact of identified faults must be assessed in more detail by dynamic 3D reservoir simulation models to ensure optimal development, injection, and filling of the storage reservoirs of the structures. In addition, the storage capacity should be determined with a lower uncertainty.

The results of the project also lay the foundation for developing new projects including seismic surveys for further evaluation of the structures for CCS and other purposes. New and more densely spaced data such as 3D seismic surveys are needed for the further maturation steps to fill in the data gaps and to address 3D complexities, such as to further resolve and describe the structural traps, reservoirs, seals, spill points, faults, storage capacity and to address potential risks. In addition, monitoring of for example seismicity, groundwater, wells, faults, elevation and other investigations are very important prior to, during and after CO_2 storage operations.

The project has revealed that not only site- and structure-specific work is required, but also that more regional geological studies should be carried out to revise the regional understanding of the depositional systems, including reservoir distribution, seal characterisation and tectonostratigraphic evolution across basins and large structures of the Danish Basin. In addition, the stratigraphy and geological evolution from the Danish Basin to adjacent regions should be investigated, southwards across the Ringkøbing–Fyn High, northwards into the Sorgenfrei–Tornquist Zone and Skagerrak–Kattegat Platform, eastwards into the Øresund Basin and westwards into the Norwegian–Danish Basin.

The new data and related research have resulted in numerous scientific publications and the completion of several PhD and Master theses, which benefited from using the new data and participating in the field work. This is also an outstanding societal contribution to the education of a new generation of geoscientists working to tackle climate issues, and to the green energy transition.

Acknowledgements

The enthusiastic and fruitful cooperation between the authors, and with the external parties of Geopartner Geofizyka (Poland) and COWI (Denmark) in connection with the seismic data acquisition is much acknowledged. We are grateful for the hard work of the field crews, including students from Uppsala University (Sweden), University of Copenhagen (Denmark), Aarhus University (Denmark) and UniLaSalle (France). We also thank Per Trinhammer for cooperation regarding the marine acquisition at Havnsø, Tomi A. Jusri and Rasmus Rasmussen for QC of the seismic data processing, and Lasse M. Rasmussen for data support. We appreciate the careful figure drafting by Carsten E. Thuesen. Annette Ryge is thanked for providing biostratigraphic preparations. We acknowledge the constructive and useful comments and suggestions by the two reviewers. This study is part of the CCS2022–2024 project for maturation of selected structures to potential CO_2 storage sites.

Additional information

Funding statement

The funding to GEUS for the maturation of the eight selected, potential CO_2 storage sites in Denmark (the CCS2022–2024 project) is provided by the 'Funding of Higher Education in Denmark' (Forskningsreserven 2022). The funding made the contracted seismic acquisition and the subsequent work including this publication possible.

Author contributions

UG: Conceptualisation; Writing- Original draft; Main Project Administration; Investigation; Writing – Review & Editing; AM, MKE: Main Project Administration; Investigation; Writing – Review & Editing; MBWF, TANNAB, MBJ, HV, FS, TF, ANM, FM, NSC, HIP, LHN, KD, BWL, ES, MLO, GKP, CMN, ESR, MP, SZ, KK, AE, and EN: Investigation; Writing – Review & Editing.

References

Abramovitz, T., Thybo, H. & MONA LISA Working Group 1998: Seismic structure across the Caledonian Deformation Front along MONA LISA profile 1 in the southeastern North Sea. Tectonophysics **288**, 153–176. *https://doi.org/10.1016/s0040-1951(97)00290-4*

Abramovitz, T., Thybo, H. & MONA LISA Working Group 2000: Seismic images of Caledonian, lithosphere-scale collisional structures in the southeastern North Sea along Mona Pisa Profile 2. Tectonophysics **317**, 27–54. *https://doi.org/10.1016/S0040-1951(99)00266-8*

Abramovitz, T. *et al.* 2024: CCS2022–2024 WP1: The Rødby structure. Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2024/18**, 143 pp. *https://doi.org/10.22008/gpub/34739*

Ahlrichs, N., Hübscher, C., Noack, V., Schnabel, M., Damm, V. & Krawczyk, C.M. 2020: Structural evolution at the northeast North German Basin margin: From initial Triassic salt movement to Late Cretaceous-Cenozoic remobilization. Tectonics **39**, e2019TC005927. *https://doi.org/10.1029/2019TC005927*

Anthonsen, K.L., Aagaard, P., Bergmo, P.E.S., Gislason, S.R., Lothe, A.E., Mortensen, G.M. & Snæbjörnsdóttir, S.Ó. 2014: Characterisation and selection of the most prospective CO_2 storage sites in the Nordic region. Energy Procedia **63**, 4884–4896. *https://doi.org/10.1016/j.egypro.2014.11.519*

BABEL Working Group. 1993: Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. Geophysical Journal International **112**, 325–343. *https://doi.org/10.1111/j.1365-246x.1993.tb01173.x*

Bachmann, G.H. *et al*. 2010: Triassic. In: Doornenbal, J.C. & Stevenson, A.G. (eds): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten), 149–173.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P.C. & Mathiassen, O.M. 2007: CO_2 storage capacity estimation: Methodology and gaps. International Journal of Greenhouse Gas Control **1**(4), 430–443. ISSN 1750-5836. *https://doi.org/10.1016/S1750-5836(07)00086-2*

Bertelsen, F. 1978: The Upper Triassic – Lower Jurassic Vinding and Gassum Formations of the Norwegian–Danish Basin. Danmarks Geologiske Undersøgelse Serie B **3**, 26 pp. *https://doi.org/10.34194/serieb.v3.7058*

Bertelsen, F. 1980: Lithostratigraphy and depositional history of the Danish Triassic. Danmarks Geologiske Undersøgelse Serie B **4**, 59 pp. *https://doi.org/10.34194/serieb.v4.7059*

Bjerager, M. *et al.* 2024: CCS2022–2024 WP1: The Thorning structure – Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2024/**27**, 188 pp. + Appendix A & B. *https://doi.org/10.22008/gpub/34748*

Boldreel, L.O. 1985: On the structural development of the salt dome province in NW Jutland, Denmark, based on seismic studies. First Break **3**(8), 15–21. *https://doi.org/10.3997/1365-2397.1985015*

Bredesen, K., Lorentzen, M., Smit, F.W.H. & Gregersen, U. 2022: Quantitative seismic interpretation of the Gassum Formation at the Stenlille aquifer gas storage. GHGT-16 Conference Proceedings (2022); SSRN Electronic Journal, November 2022, 12 pp. *https://doi.org/10.2139/ssrn.4276697*

Bredesen, K., Smit, F.W.H., Lorentzen, M. & Gregersen, U. 2023: Improved delineation of the Gassum Formation reservoir zones using seismic impedance inversions: Implications for exploiting the Stenlille aquifer gas storage facility as a CO_2 storage demonstration site, onshore Denmark. Geological Society Publications. Geoenergy geoenergy2022–002. *https://doi.org/10.1144/geoenergy2022-002*

Burruss, R.C. *et al.* 2009: Development of a probabilistic assessment methodology for evaluation of carbon dioxide storage: U.S. Geological Survey Open-File Report **2009–1035**, 81 pp. *https://pubs.usgs.gov/of/2009/1035/*

Chadwick, R.A., Zweigel, P., Gregersen, U., Kirby, G.A., Holloway, S. & Johannesen, P.N. 2004: Geological reservoir characterization of a CO_2 storage site: The Utsira Sand, Sleipner, northern North Sea. Energy **29**, 1371–1381. *https://doi.org/10.1016/j.energy.2004.03.071*

Clark, C.E. 1962: The PERT model for the distribution of an activity Time. Operations Research **10**, 405–406. *https://doi.org/10.1287/opre.10.3.405*

Clausen, O.R. & Pedersen, P.K. 1999: Late Triassic structural evolution of the southern margin of the Ringkøbing–Fyn High, Denmark. Marine and Petroleum Geology **16**(7), 653–665. *https://doi.org/10.1016/S0264-8172(99)00026-4*

Clemmensen, L.B. 1986: Desert sand plain and sabkha deposits from the Bunter Sandstone Formation (L. Triassic) at the northern margin of the German Basin. Geologische Rundschau **74**, 519–536. *https://doi.org/10.1007/bf01821209*

Erlström, M. & Sivhed, U. 2012: Pre-Rhaetian Triassic strata in Scania and adjacent offshore areas – Stratigraphy, petrology and subsurface characteristics. SGU – Geological Survey of Sweden. ISSN 0349-2176. ISBN 978-91-7403-157-7. Rapporter och Meddelanden **132**, 74 pp.

Erlström, M., Thomas, S.A., Deeks, N. & Sivhed, U. 1997: Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. Tectonophysics **271** (3–4), 191–215. *https://doi.org/10.1016/S0040-1951(96)00247-8*.

Fuchs, S., Balling, N. & Mathiesen, A. 2020: Deep basin temperature and heat-flow field in Denmark – New insights from borehole analysis and 3D geothermal modelling. Geothermics **83**, 101722. *https://doi.org/10.1016/j.geothermics.2019.101722*

Funck, T. & Nørmark, E. 2023: CCS2022–2024 WP1: The Havnsø structure – Marine acquisition report. Offshore seismic acquisition Havnsø-Nekselø 2022, with seismic source from the onshore acquisition. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2023/22**, 48 pp. *https://doi.org/10.22008/gpub/34689*

Funck, T. *et al.* 2023: Acquisition of marine seismic data in Jammerbugt in 2023. CCS2022–2024 WP1: Seismic data acquisition across the Jammerbugt structure on research vessel Jákup Sverri. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2023/39**, 120 pp. *https://doi.org/10.22008/gpub/34706*

Fyhn, M.B.W. *et al*. 2024: CCS2022–2024 WP1: The Jammerbugt structure. Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2024/11**, 82 pp. *https://doi.org/10.22008/gpub/34732*

Geil, K. 1991: The development of salt structures in Denmark and adjacent areas: The role of basin floor dip and differential pressure. First Break **9**(10), 458–466. *https://doi.org/10.3997/1365-2397.1991022.*

Goodman, A. *et al.* 2011: U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control **5**(4), 952–965. *https://doi.org/10.1016/j.ijggc.2011.03.010*

Gorecki, C.D., Holubnyak, Y.I., Ayash, S.C., Bremer, J.M., Sorensen, J.A., Steadman, E.N. & Harju, J.A. 2009: A new classification system for evaluating CO_2 storage resource/capacity estimates. Paper presented at the SPE International Conference on CO_2 Capture, Storage, and Utilization, San Diego, California, USA, November 2009. ISBN: 978-1-55563-267-0. *https://doi.org/10.2118/126421-MS*

Gregersen, U. & Johannessen, P.N. 2007: Distribution of the Neogene Utsira Sand and the succeeding deposits in the Viking Graben area, North Sea. Marine and Petroleum Geology **24**(10), 591–606. *https://doi.org/10.1016/j.marpetgeo.2007.04.006*

Gregersen, U., Vosgerau, H., Laghari, S., Bredesen, K., Rasmussen, R. & Mathiesen, A. 2020: Capture, Storage and Use of CO_2 (CCUS): Seismic interpretation of existing 2D and 3D seismic data around the Havnsø structure (Part of work package 5 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport **2020/33**, 60 pp. *https://doi.org/10.22008/gpub/34530*

Gregersen, U., Smit, F.W.H., Lorentzen, M., Vosgerau, H., Bredesen, K., Hjelm, L., Mathiesen, A. & Laghari, S. 2022: Tectonostratigraphy and structural evolution of the stenlille structure in Zealand, Denmark – A site for natural gas and CO_2 storage. GHGT-16 Conference Proceedings (2022); SSRN Electronic Journal Nov. 2022 & Geophysics eJournal **4**(85), 12 pp. *https://doi.org/10.2139/ssrn.4275875*

Gregersen, U. *et al.* 2023a: CCS2022-2024 WP1: The Stenlille structure – Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2022/26**. 164 pp. *https://doi.org/10.22008/gpub/34661*

Gregersen, U. *et al.* 2023b: CCS2022-2024 WP1: The Havnsø structure – Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2023/38**. 200 pp. *https://doi.org/10.22008/gpub/34705.*

Hall, G. 2008: Carbon storage Atlas of the United States and Canada, 2014-07-01. *https://edx.netl.doe.gov/dataset/2008-carbon-storage-atlas-of-the-united-states-and-canada* (Accessed September 2023).

Heidug, W.K., Brennan, S.T., Holloway, S., Warwick, P.D., McCoy, S.T. & Yoshimura, T. 2013: Methods to assess geological CO_2 storage capacity: Status and best practice. International Energy Agency Workshop Report. *https://www.iea.org/reports/methods-to-assess-geological-co2-storage-capacity-status-and-best-practice* (Accessed September 2023)

Heilmann-Clausen, C. 1995: Palæogene aflejringer over Danskekalken. In: Nielsen, O.B. (ed.): Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier **1**, 69–114.

Hjelm, L., Anthonsen, K.L., Dideriksen, K., Nielsen, C.M., Nielsen, L.H. & Mathiesen, A. 2022: Capture, Storage and Use of CO_2 (CCUS). Evaluation of the CO_2 storage potential in Denmark. Vol.1: Report & Vol 2: Appendix A and B [Published as 2 separate volumes both with Series number 2020/46]. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2020/46**, 141 pp. *https://doi.org/10.22008/gpub/34543*

Houmark-Nielsen, M. 1987: Pleistocene stratigraphy and glacial history of the central part of Denmark. Bulletin of the Geological Society of Denmark **36**(1–2), 1–189. *https://doi.org/10.37570/bgsd-1988-36-01.*

Houmark-Nielsen, M. 2004: The Pleistocene of Denmark: A review of stratigraphy and glaciation history. Developments in Quaternary Sciences **2**(1), 35–46. *https://doi.org/10.1016/S1571-0866(04)80055-1.*

IPCC. 2005: IPCC special report on carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Metz, B. *et al.* (eds). Cambridge University Press, 442 pp. *https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/*

Japsen, P. & Bidstrup, T. 1999: Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. Bulletin of the Geological Society of Denmark **46**, 79–99. *https://doi.org/10.37570/bgsd-1999-46-08*

Japsen, P., Green, P.F., Nielsen, L.H., Rasmussen, E.S. & Bidstrup, T. 2007: Mesozoic–Cenozoic exhumation events in the eastern North Sea Basin: A multi-disciplinary approach based on palaeothermal, palaeoburial, stratigraphic and seismic data. Basin Research **19**, 451–490. *https://doi.org/10.1111/j.1365-2117.2007.00329.x*

Keiding, M. *et al.* 2024: CCS2022–2024 WP1: The Gassum structure. Seismic data and interpretation to mature potential geological storage of CO_2. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2024/25**, 160 pp. *https://doi.org/10.22008/gpub/34746*

Konstantinidis, E., Kucinskaite, K., Malehmir, A., Westgate, M., Gregersen, U. & Keiding, M. 2023: Velocity model building and seismic imaging of the Gassum structure for potential CO_2 storage in Denmark. 4th EAGE Global Energy Transition Conference & Exhibition, GET2023, Paris, 5 pp. *https://doi.org/10.3997/2214-4609.202321050*

Kucinskaite, K., Papadopoulou, M., Zappalà, S., Malehmir, A., Westgate, M., Gregersen, U. & Funck, T. 2023: Near-surface effect on geological CO_2 storage site characterization in Denmark. Conference paper. 4th EAGE Global Energy Transition Conference & Exhibition, GET2023, European Association of Geoscientists & Engineers, Paris, Nov 14–17, 2023, 5 pp. *https://doi.org/10.3997/2214-4609.202321026*

Larsen, M., Bidstrup, T. & Dalhoff, F. 2003: Mapping of deep saline aquifers in Denmark with potential for future CO_2 storage. A GESTCO contribution. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/39**, 83 pp. *https://doi.org/10.22008/gpub/19006*

Lassen, A., Thybo, H. & Berthelsen, A. 2001: Reflection seismic evidence for Caledonian de-formed sediments above Sveconorwegian basement in the southwestern Baltic Sea. Tectonics **20**, 268–276. *https://doi.org/10.1029/2000tc900028*

Lindström, S., Erlström, M., Piasecki, S., Nielsen, L.H. & Mathiesen, A. 2017: Palynology and terrestrial ecosystem change of the Middle Triassic to lowermost Jurassic succession of the eastern Danish Basin. Review of Palaeobotany and Palynology **244**, 65–95. *https://doi.org/10.1016/j.revpalbo.2017.04.007*

Lorentzen, M., Bredesen, K., Gregersen, U., Smit, F.W.H. & Laghari, S. 2022: Fault mapping of the Gassum Formation Reservoir and the Fjerritslev Formation Caprock Interval at the Stenlille gas storage site using a pre-trained convolutional neural network. GHGT-16 Conference Proceedings (2022); Geophysics eJournal, **4**(86), 12 pp. *https://doi.org/10.2139/ssrn.4277405*

Malehmir, A. & Markovic, M. 2024: GEUS2023-ROEDBY seismic survey. Acquisition, processing and results. In collaboration with Geological Survey of Denmark and Greenland (GEUS). Uppsala University: Uppsala. 22 pp. GEUS report file no. **44504**. *https://data.geus.dk/sambawebrpc/get_report?id=151937* (accessed April 2025)

Malehmir, A. & Papadopoulou, M. 2022: Innovative land seismic data acquisition for geological CO_2 storage in Stenlille, Denmark. In collaboration with Geological Survey of Denmark and Greenland (GEUS). Uppsala University: Uppsala. 42 pp. GEUS report file no. **43166**. *https://data.geus.dk/sambawebrpc/get_report?id=143896* (accessed April 2025)

Malehmir, A. & Papadopoulou, M. 2023: GEUS2022-HAVNSOE seismic survey: Acquisition and processing report. In collaboration with Geological Survey of Denmark and Greenland (GEUS). Uppsala University: Uppsala. 45 pp. GEUS report file no. **43809**. *https://data.geus.dk/sambawebrpc/get_report?id=148104* (accessed April 2025)

Malehmir, A. & Westgate, M. 2023: GEUS2023-GASSUM seismic survey. Acquisition, processing and results. In collaboration with Geological Survey of Denmark and Greenland (GEUS). Uppsala University: Uppsala. 25 pp. GEUS report file no. 43844: *https://data.geus.dk/sambawebrpc/get_report?id=149325* (accessed April 2025)

Malehmir, A. *et al*. 2022: Fault intersections control short period intraplate start-stop seismicity in the Korean Peninsula. Tectonophysics **834**, 229387. *https://doi.org/10.1016/j.tecto.2022.229387*

Malehmir, A., Markovic, M., Abramovitz, T. & Gregersen, U. 2025: Geological carbon storage site characterization using a dual element seismic recording technology. Scientific Reports **15**, 12937. *https://doi.org/10.1038/s41598-025-96012-8*

Michelsen, O. & Clausen, O.R. 2002: Detailed stratigraphic subdivision and regional correlation of the southern Danish Triassic succession.

Marine and Petroleum Geology **19**, 563–587. *https://doi.org/10.1016/S0264-8172(02)00028-4*

Michelsen, O. & Nielsen, L.H. 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark: Hans-1, Sæby-1, and Terne-1 wells. Geological Survey of Denmark – DGU Serie A, **29**, 38 pp. *https://doi.org/10.34194/seriea.v29.7049*

Michelsen, O. & Nielsen, L.H. 1993: Structural development of the Fennoscandian Border Zone, offshore Denmark. Marine and Petroleum Geology **10**, 124–134. *https://doi.org/10.1016/0264-8172(93)90017-m*

Michelsen, O., Nielsen, L.H., Johannessen, P.N., Andsbjerg, J. & Surlyk, F. 2003: Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 145–216. *https://doi.org/10.34194/geusb.v1.4651*

Nielsen, L.H. 2003: Late Triassic – Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, J.R. & Surlyk, F. (eds): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin **1**, 459–526. *https://doi.org/10.34194/geusb.v1.4681*

Nielsen, L.H. & Japsen, P. 1991: Deep wells in Denmark 1935-1990. Lithostratigraphic subdivision. Danmarks Geologiske Undersøgelse, DGU Serie A, **31**, 177 pp. *https://doi.org/10.34194/seriea.v31.7051*

Nielsen, A.T. & Klitten, K. 2023: Wireline log stratigraphy of the lower Cambrian Læså Formation, Bornholm, Denmark. Bulletin of the Geological Society of Denmark **72**, 175–205.

Nielsen, A.T. & Schovsbo, N.H. 2011: The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth-Science Reviews **107**, 207–310. *https://doi.org/10.1016/j.earscirev.2010.12.004*

Nielsen, A.T. & Schovsbo, N.H. 2015: The regressive Early–Mid Cambrian 'Hawke Bay Event' in Baltoscandia: Epeirogenic uplift in concert with eustasy. Earth Science Reviews **151**, 288–350. *https://doi.org/10.1016/j.earscirev.2015.09.012*

Olsen, H. 1988: Sandy braidplan deposits from the Triassic Skagerrak Formation in the Thisted-2 well, Denmark. Danmarks Geologiske Undersøgelse Serie B **11**, 1–26. *https://doi.org/10.34194/serieb.v11.7078*

Papadopoulou, M., Malehmir, A., Zappalá, S., Gregersen, U., Nielsen, L. & Hjelm, L. 2022: Innovative land seismic data acquisitions for CO_2 and energy storage applications. NSG2022 28th European Meeting of Environmental and Engineering Geophysics **2022**, 1–5. European Association of Geoscientists & Engineers. *https://doi.org/10.3997/2214-4609.202220098*

Papadopoulou, M., Zappalá, S., Malehmir, A., Gregersen, U., Hjelm, L., Nielsen, L. & Haspang, M.P. 2023: Innovative land seismic investigations for CO_2 geological storage in Denmark. Geophysics **88**, B251–B266. *https://doi.org/10.1190/geo2022-0693.1*

Papadopoulou, M. *et al*. 2024: Advancements in seismic imaging for geological carbon storage: Study of the Havnsø structure, Denmark. International Journal of Greenhouse Gas Control **137**, 10204. *https://doi.org/10.1016/j.ijggc.2024.104204*.

Peryt, T.M., Geluk, M.C., Mathiesen, A., Paul, J. & Smith, K. 2010: Zechstein. In: Doornenbal, J.C. & Stevenson, A.G. (eds): Petroleum geological atlas of the Southern Permian Basin area. Houten, the Netherlands, European Association of Geoscientists and Engineers, 123–147.

Putnaite, J. & Malehmir, A. 2024: GEUS2023-Thorning seismic survey. Acquisition, processing and results. In collaboration with Geological Survey of Denmark and Greenland (GEUS). Uppsala University: Uppsala. 18 pp. GEUS report file no. **44505**. *https://data.geus.dk/sambawebrpc/get_report?id=152005* (accessed April 2025)

Putnaite, J., Malehmir, A., Bjerager, M., Abramovitz, T., Vosgerau H. & Keiding, M. 2025: The role of a salt pillow in deep saline aquifer integrity and shallow groundwater resources. Science Reports **15**, 15074. *https://doi.org/10.1038/s41598-025-99721-2*

Rasmussen, E.S. 2009: Neogene inversion of the Central Graben and Ringkøbing–Fyn High, Denmark. Tectonophysic **465**, 84–97. *https://doi.org/10.1016/j.tecto.2008.10.025*

Rasmussen, E.S., Vejbæk, O.V., Bidstrup, T., Piasecki, S. & Dybkjær, K. 2005: Late Cenozoic depositional history of the Danish North Sea Basin: Implications for the petroleum systems in the Kraka, Halfdan, Siri and Nini fields. In: Dore, A.G. & Vining, B.A. (eds): Petroleum geology: North-West Europe and global perspectives. Proceedings of the 6th Petroleum Geology Conference I, 1347–1358. London: Geological Society. *https://doi.org/10.1144/0061347*

Rasmussen, E.S., Heilmann-Clausen, C., Waagstein, R. & Eidvin, T. 2008: The tertiary of Norden. Episodes **31**, 66–72. *https://doi.org/10.18814/epiiugs/2008/v31i1/010*

Rasmussen, E.S., Dybkjær, K. & Piasecki, S. 2010: Lithostratigraphy of the Upper Oligocene – Miocene succession of Denmark. Geological Survey of Denmark and Greenland Bulletin **22**, 1–92. *https://doi.org/10.34194/geusb.v22.4733*

Realtimeseismic 2023a: GEUS2022_HAVNSOE-RE2023. Reprocessing of the GEUS2022-HAVNSOE 2D Seismic Survey for the Geological Survey of Denmark and Greenland. 57 pp. Realtime Seismic Pty. Ltd.: Pau. GEUS report file no. **43833**. *https://data.geus.dk/sambawebrpc/get_report?id=149107* (accessed April 2025)

Realtimeseismic 2023b: Geological Survey of Denmark and Greenland Stenlille. Data processing report. 69 pp. Realtime Seismic Pty. Ltd.: Pau. GEUS report file no. **43743**. *https://data.geus.dk/sambawebrpc/get_report?id=149305* (accessed April 2025)

Realtimeseismic 2024a: GEUS2023-ROEDBY-RE2023. Reprocessing of the GEUS2023-ROEDBY 2D seismic survey for the Geological Survey of Denmark and Greenland. 68 pp. Realtime Seismic Pty. Ltd.: Pau. GEUS report file no. **43848**. *https://data.geus.dk/sambawebrpc/get_report?id=152285* (accessed April 2025)

Realtimeseismic 2024b: Final report – Reprocessing [GEUS2023-THORNING-RE2024, PSTM] of the GEUS2023-THORNING 2D Seismic Survey. Reprocessing report for the Geological Survey of Denmark and Greenland. Realtime Seismic Pty. Ltd.: Pau. GEUS report file no. **44503**.

Realtimeseismic 2024c: Final report – GEUS2023-GASSUM-RE2023. Reprocessing of the GEUS2023-GASSUM 2D Seismic Survey for the Geological Survey of Denmark and Greenland. Realtime Seismic Pty. Ltd.: Pau. 63 pp. GEUS report file no.**43854**. *https://data.geus.dk/sambawebrpc/get_report?id=152286* (accessed April 2025)

Realtimeseismic 2024d: GEUS2023-JAMMERBUGT-RE2023. Reprocessing of the GEUS2023-Jammerbugt 2D seismic survey for the Geological Survey of Denmark and Greenland. 93 pp. Realtime Seismic Pty. Ltd.: Pau. 93 pp. GEUS report file no. **43856**. *https://data.geus.dk/sambawebrpc/get_report?id=149645* (accessed April 2025)

Schiøler, P. *et al*. 2007: A revised lithostratigraphy for the Palaeogene – Lower Neogene of the Danish North Sea. Geological Survey of Denmark and Greenland Bulletin **7**, 21–24. *https://doi.org/10.34194/geusb.v7.4825*

Schovsbo, N.H., Nielsen, A.T. & Erlström, M. 2016: Middle–Upper Ordovician and Silurian stratigraphy and basin development in southernmost Scandinavia. Geological Survey of Denmark and Greenland Bulletin **35**, 39–42. *https://doi.org/10.34194/geusb.v35.4907*

Schovsbo, N.H., Holmslykke, H.D., Mathiesen, A. & Nielsen, C.M. 2025: Assessment of formation brine salinity, pressure and temperature in selected structures in eastern Denmark and implications for CO_2 storage. GEUS Bulletin **60**, 8383. *https://doi.org/10.34194/62417j08*

Smit, F.W.H., Gregersen, U., Lorentzen, M., Bredesen, K., Pedersen, G.K., Hovikoski, J. & Vosgerau, H. 2022: Seismic Geomorphology of the Upper Triassic – Lower Jurassic Gassum Formation – Improved reservoir characterization in the Stenlille (Denmark) CCS demonstration site. GHGT-16 Conference Proceedings (2022). Geophysics eJournal, **4**(83), 11 pp. *https://papers.ssrn.com/abstract=4277360*

Sorgenfrei, T. & Bertelsen, O. 1954: Geologi og vandboring. Danmarks Geologiske Undersøgelse III. Række **31**, 106 pp. *https://doi.org/10.34194/raekke3.v31.6936*

Span, R. & Wagner, W. 1996: A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100K at pressures up to 800 MPa. Journal of Physical and Chemical Reference Data **25**, 1509–1596. *https://doi.org/10.1063/1.555991*

Stemmerik, L. & Frykman, P. 1989: Stratigraphy and sedimentology of the Zechstein carbonates of southern Jylland, Denmark. GEUS. Danmarks Geologiske Undersøgelse Serie A **26**, 32 pp. *https://doi.org/10.34194/seriea.v26.7046*

Stemmerik, L., Ineson, J. & Mitchell, J. 2000: Stratigraphy of the Rotliegend Group in the Danish part of the Northern Permian Basin, North

Sea. Journal of The Geological Society **157**, 1127–1136. *https://doi.org/10.1144/jgs.157.6.1127*

Szabados, A. & Poulsen, S.R. 2023: The CCS greensand project: CO_2 pilot injection and monitoring. Baltic Carbon Forum **2**, 11–12. *https://doi.org/10.21595/bcf.2023.23608*

Sørensen, K. 1998: The salt pillow to diapir transition; evidence from unroofing unconformities in the Norwegian–Danish Basin. Petroleum Geoscience **4**(3), 193–202. *https://doi.org/10.1144/petgeo.4.3.193*.

Vejbæk, O.V. 1997: Dybe strukturer i danske sedimentære bassiner. Geologisk Tidsskrift **1997**(4), 1–31.

Wang, Y., Zhangb, K. & Wua, N. 2013: Numerical Investigation of the Storage Efficiency Factor for CO_2 Geological Sequestration in Saline Formations. Energy Procedia **37**, 5267–5274. *https://doi.org/10.1016/j.egypro.2013.06.443*

Westgate, M., Malehmir, A., Konstantinidis, E., Kucinskaite, K., Hjelm, L., Gregersen, U., Keiding, M. & Bjerager, M. 2023: Seismic imaging of the Gassum Formation in Denmark for CO_2 storage potential using a dual-recording method. NSG2023 29th European Meeting of Environmental and Engineering Geophysics **2023**, 5 pp. *https://doi.org/10.3997/2214-4609.202320051*

Westgate, M., Malehmir, A., Konstantinidis, E., Kucinskaite, K., Keiding, M., Gregersen, U. & Bjerager, M. 2024: High-resolution, large-scale seismic imaging of halokinetic-induced structures for geological carbon storage: Results from East Jutland, Denmark. NSG2024 30th European Meeting of Environmental and Engineering Geophysics **2024**, 5 pp. *https://doi.org/10.3997/2214-4609.202420063*

Westgate, M., Kucinskaite, K., Konstantinidis, E., Malehmir, A., Papadopoulou, M., Gregersen, U., Keiding, M. & Bjerager, M. 2025: Seismic imaging of halokinetic sequences and structures with high-resolution, dual-element acquisition, and processing: Applications to the Gassum Structure in eastern Jutland, Denmark. Earth and Space Science **12**(1), 1–15. *https://doi.org/10.1029/2024EA004014*

Wischnewski, B. 2007: Peace software for calculation of thermodynamic state variables of carbon dioxide. *http://www.peacesoftware.de/einigewerte/co2_e.html*

Zappalá, S. *et al*. 2022: Crustal-scale fault systems in the Korean Peninsula unraveled by reflection seismic data. Earth and Space Science **9**, e2022EA00246. *https://doi.org/10.1029/2022EA002464*

Zappalá, S., Malehmir, A., Papadopoulou, M., Gregersen, U., Funck, T., Clausen, O.R. & Nørmark, E. 2024: Combined onshore and offshore wide-scale seismic data acquisition and imaging for carbon capture and storage exploration in Havnsø, Denmark. Geophysics **89**(4), B257–B272. *https://doi.org/10.1190/geo2023-0503.1*

Ziegler, P.A. 1990. Geological atlas of western and central Europe. 2nd Edition, Shell Internationale Petroleum Maatschappij B.V., Hague, distributed by Geological Society, London, Publishing House, Bath, 239 pp.