Subsurface CO_2 Storage Potential of the Central Åsta Graben – Norwegian North Sea

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Summary

The central Åsta Graben is large structural element on the flank of the Central Graben that is characterized by a regional monoclinal dip of the sedimentary section but where main reservoir sections are modified by halokinesis of the Zechstein salt. Petroleum exploration activity has ceased in the 1980s after a few unsuccessful wells which proved reservoir presence but also a lack of petroleum charge. However, CCS related activity in the larger area should revive interest in the Åsta Graben as a potential CO_2 subsurface storage site. There are multiple proven reservoirs in favourable depth range present which are covered by fine grained and largely unfaulted overburden. Modest halokinesis and induced salt anticlines without piercing salt provide a number of low structural height traps. Because of the regional monoclinal dip the Åsta Graben area may be considered an open aquifer system when considering the main Middle Jurassic section but potentially also for other reservoir units proven in the wells.

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Introduction

Development of CO_2 subsurface storage sites is imperative to reach Net Zero goals and will require significant reservoir and trap capacity (IEA, 2021). Norway is at the forefront of subsurface CO_2 storage development and a number of CCS licenses have been awarded in the last years to develop offshore injection sites (https://www.sodir.no/en/facts/carbon-storage/licences-for-carbon-storage/), most of them located in Norway's southern North Sea. The Sleipner project in the southern of the Viking Graben is an open aquifer system and operates since 1996 (Furre et al. 2019). As part of the Norwegian Longship CCS project hub multiple CO_2 storage sites on the Horda Platform are being investigated in the Northern Lights CO_2 storage cluster (https://www.equinor.com/energy/northern-lights).

High quality seismic data are essential for the evaluation of storage sites to ensure CO_2 can safely be stored in the subsurface without leaking back to the surface. Data needs to cover areas sufficient to evaluate potential sites that allow storage of significant quantities of CO_2 particularly if open saline aquifer storage is considered. Open saline aquifer storage concepts rely on residual and solution trapping and offer potentially more CO_2 storage capacity than structural and stratigraphic trapping mechanisms (https://www.pgs.com/new-energy/gigaton-storage-required-to-reach-net-zero---the-elephant-in-the-room/part-3--aquifer-characterization/).

Large areas of the Norwegian North Sea Central and Viking Graben and flanking structures are covered by vintage and modern 3D seismic data which were acquired for petroleum exploration purposes. However, marginal areas distal to the main petroleum field trends and closer to the Norwegian mainland have received limited interest in conventional E&P ventures largely because of petroleum charge risk due to immature Upper Jurassic source rocks (Badics 2023). These areas are only locally covered by 3D seismic data and over large areas only 2D seismic data with variable spacing exists. Accordingly, well density is low and drilling activity has ceased with few exceptions. These marginal areas may become of interest in the light of energy transition ventures and specifically subsurface storage of CO_2 because of proven reservoir sections and presence of multiple trap styles. Closeness to coast, and infrastructure, vicinity CO2 point emitters and planned CCS hubs, and existing and proposed CCS licenses provide additional impetus to revisit these areas (Bøe et al. 2002).

Central Åsta Graben - Overview

One of the areas orphaned in conventional E&P ventures on the Norwegian Continental Shelf is the central Åsta Graben, south of the petroliferous Egersund Basin and flanked to the west by the Sørvestlandet High. Generally, the stratigraphy (Figure 1) is equivalent but the Jurassic and Triassic section in the Åsta Graben is thicker and positioned shallower than in neighbouring areas. The Lower Cretaceous on the other hand is reduced in thickness. Structural style is dominated by movement of Permian Zechstein salt, which caused partition of the Triassic-Jurassic section of the area into mini-basins with locally thick Triassic and internal reflector configuration related to salt movement separated by salt domes, pillows and swells. Halokinesis is less severe compared to the Egersund Basin (Sørensen and Tangen 1995), and piercing salt domes (penetrating the overburden over the top Jurassic) occur only in the neighbouring structural elements.

Only a limited number of wells were drilled in the late 1960 to 80s to explore an area of approximately 8700 km^2. Out of this area about 3400 km^2 is not covered by 3D data. The wells drilled have multiple proven reservoir levels and accompanying trapping potential but were dry for oil and gas. The main reservoir section is the same as in the Egersund Basin to the north where oil was discovered in the middle Jurassic sandstones (Hansen et al. 2020). However, the equivalent reservoir section is shallower in the Åsta Graben and in depth ranges suitable for CO_2 storage (NPD 2011).

Deposition of Permian Zechstein salt and later salt movement provide various trap styles such as salt movement induced anticlines and salt flank traps. In addition, significant open saline aquifer potential may be present in shallow Cenozoic reservoir sands, largely unmodified in their structure by the underlying salt and trending up monoclinally towards the coast.

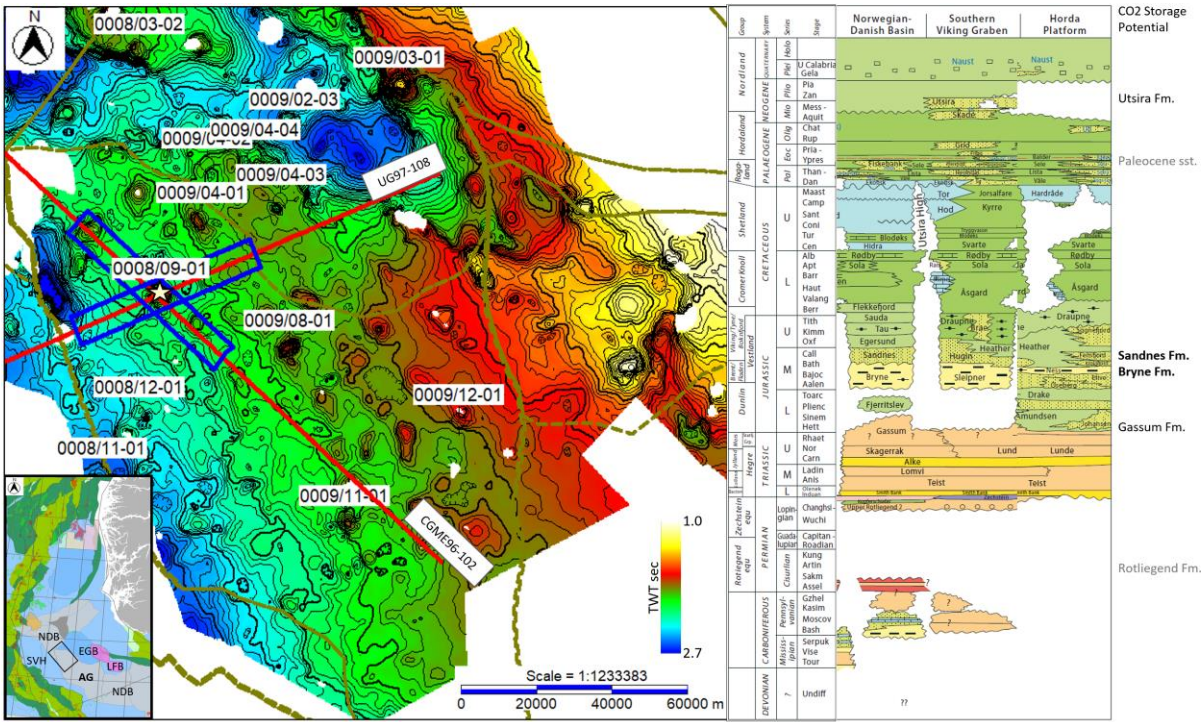

Figure 1 Top Upper Jurassic time structure map (c.i.: 0.035 ms TWT) showing location of salt structures. Red-blue 2D lines denote 2D seismic sections crossing well 8/9-1 and shown in Figure 2. Area lithostratigraphy (adopted from NPD https://www.sodir.no/en/facts/geology/lithostratigraphy/) and reservoir potential proven in fields and discoveries (bold), in wells and within the larger region (grey) shown to the right. Inset map for area location (coloured blocks are current CCS licenses), coloured areas are structural elements (AG: Åsta Graben, SVH: Sørvestlandet High, NDB: Norwegian_Danish Basin, EGB: Egersund Basin, LFB: Lista Fault Block, NPD Factmap https://factmaps.npd.no/factmaps/3_0/, boundaries shown in structural map as thick green lines).

Well Results, 2D Seismic and CO_2 Storage Potential

The limited number of vintage wells drilled in central Åsta Graben were mostly intended to test Middle Jurassic-Triassic reservoirs in 4-way closures over salt structures or at the flank of salt domes. Additional targets were seen in Miocene-Oligocene and Paleocene sands as well as in the Late Cretaceous Chalk. All wells drilled were dry (some with minor shows) but proved multi-level reservoir potential. Wells 8/9-1 and 9/4-1 report thick high porous Middle Jurassic Sandnes Formation sands, core data in 9/11-1 also indicate porous Bryne Formations sandstones. Triassic reservoir potential is reported in some of the wells (e.g. 9/12-1) but porosity measurements were available only from wells in adjacent structural element such as 17/10-1 in the Norwegian-Danish Basin. This well is unique as it specifically tested an inter-salt turtle structure and reports porous Middle Jurassic-Triassic (Gassum and Skagerrak) sandstones.

Non-piercing salt structures create undulating top Jurassic structure (Figure 1), where Triassic-Jurassic in 4-way and fault bounded closures give rise to structural trapping. The piercing salt dome in Figure 2 (top section) is located on the Sørvestlandet High and the section illustrates the decrease in intensity of halokinetic movements towards the northeast across the central Åsta Graben. The lower section in Figure 2 across the Åsta Graben also indicates limited salt movement and shows that well 8/9-1 has tested one of the more pronounced salt structures in the area.

Early Cretaceous seal thickness appears rather uniform over the central Åsta Graben area but can thin over salt induced anticlines (Figure 2). The well results indicate uniformly shale and marl present in the section. Thicker Upper Jurassic Tau in inter-salt areas off structure e.g. the gamma ray logs 9/4-3 at salt flank indicate >30 m of organic rich Tau and the well location suggests that the formation becomes thicker off the salt structures in the inter-salt basins. Together the Upper Jurassic and Lower Cretaceous should provide a continuous shale seal over the area. The Late Cretaceous Chalk may also function as a regional seal, although porous Tor Formation Chalk appears to be present e.g. in well 9/10-1.

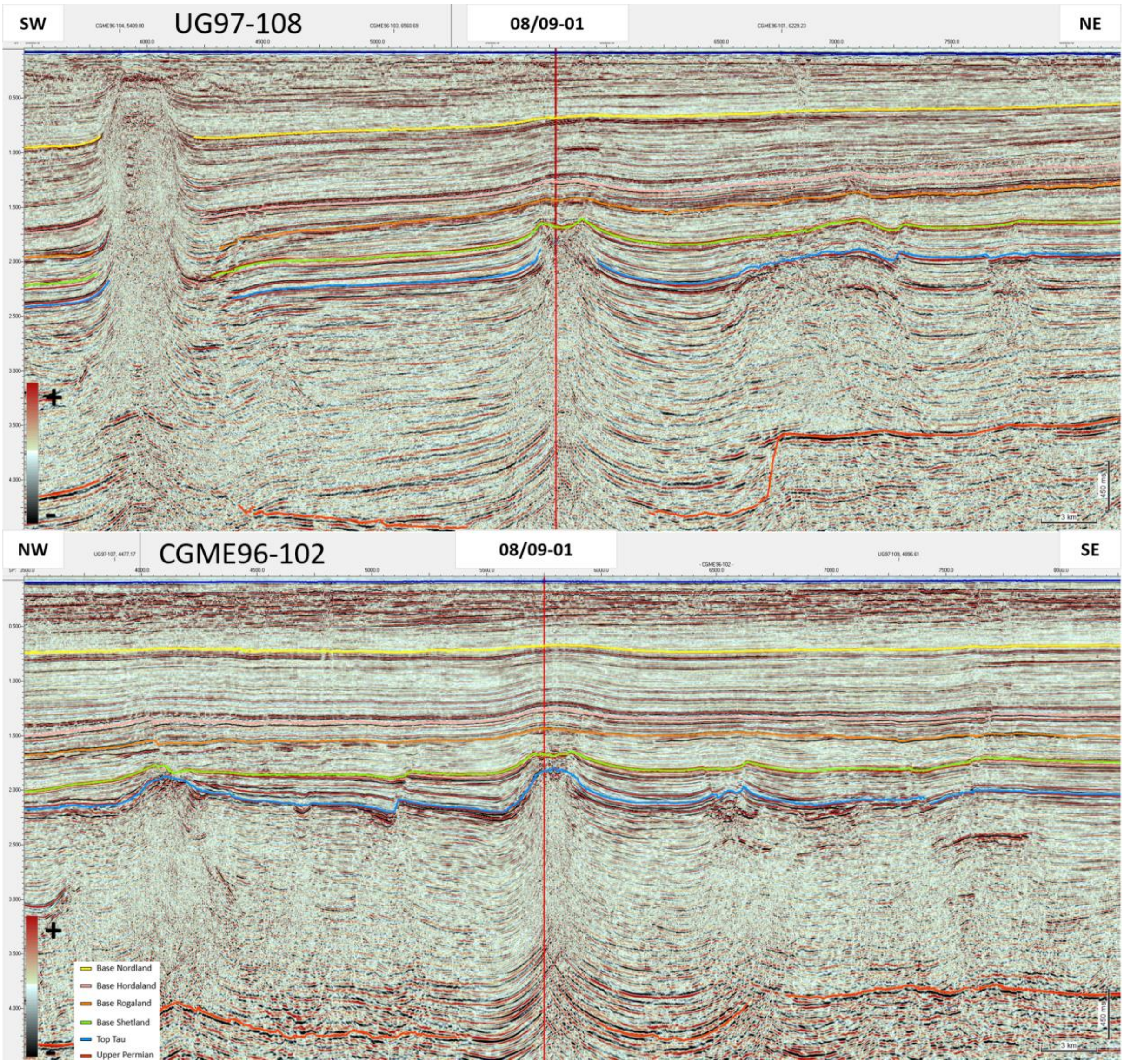

Figure 2 Example 2D seismic time sections illustrating the general stratigraphic configuration and structure of the central Åsta Graben. Tentative horizon interpretation shown.

Vintage 2D seismic data suggest a generally unfaulted overburden and structuration associated with salt movement is by and large limited to the Triassic-Jurassic. Larger salt structures such as shown in Figure 2 at well 8/9-1 appear not to produce faults that extend to near seabed, although an amplitude anomaly at around 1 sec. TWT in the Hordaland (top section UG97-108) indicates potential leakage over the salt anticline

Additional reservoir potential was found in Well 9/10-1 which explored specifically for Oligocene-Miocene sand that were found gas bearing over the Sørvestlandet High the west. No Late Tertiary sands were drilled but well 9/11-1 reported two of late Tertiary sand units of about 70 m combined gross thickness based on gamma ray log and cuttings description. These sands may be equivalent to the Vade/Skade sands reported in wells further to the West on the Sørvestlandet High (e.g. 2/2-2). Additional aquifer potential may be present, but the extent of the sands cannot be followed on the vintage 2D data. If the amplitude anomaly in the top section in Figure 2 is related to a gas accumulation, then additional evidence for porous sections is present in the seismic data.

Conclusion

The central Åsta Graben offers multiple reservoir units in a depth range appropriate for CO_2 injection and CO_2 phase consideration. In a regional sense the area can be considered an open aquifer system due to the regional dip towards the northeast. Numerous structural traps generated by Zechstein salt movement provide additional trapping potential for a buoyancy driven migrating CO_2 plume. Limited halokinesis left the overburden uncompromised by faulting and fracturing as opposed to the neighboring areas where salt domes often pierce into the younger sections and cause radial faulting above the salt structure crests. Fine grained Upper Jurassic-Late Cretaceous and a tight early Chalk provide sealing capacity. If CO_2 plumes did migrate laterally from the western Åsta Graben boundary over 60-70 km to reach the northern edge the Egersund Basin and Lista Fault Block provide structural barriers for continuous northward migration. Tertiary sands appear to be present locally, as they monoclinally dip upward towards northeast they may constitute additional open aquifer storage systems possibly with pinch out stratigraphic trapping potential.

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